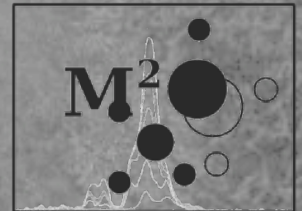
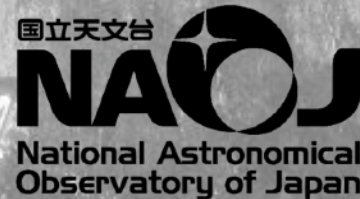
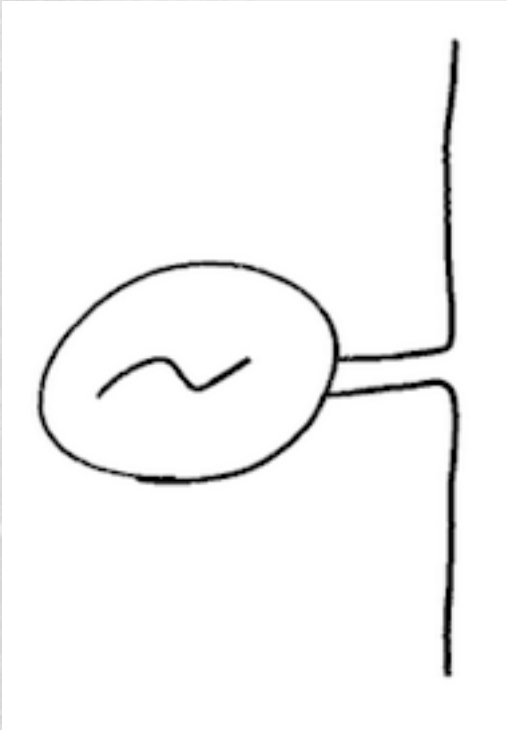


Polarisation

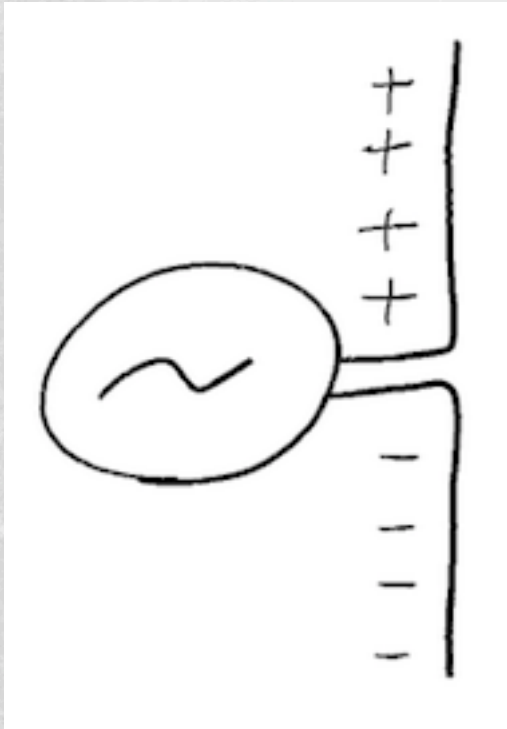
Ross Burns
DARA training, June 2021



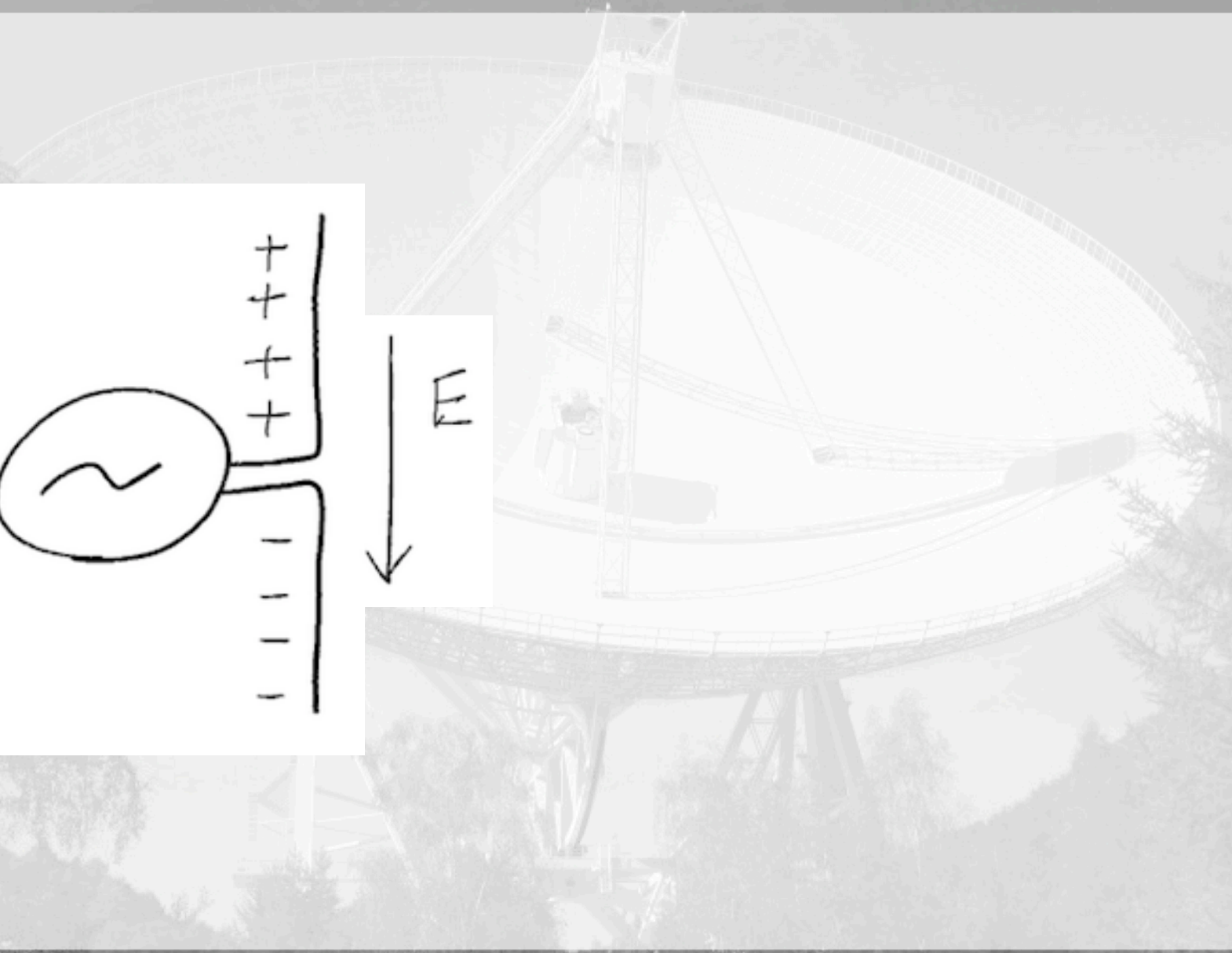
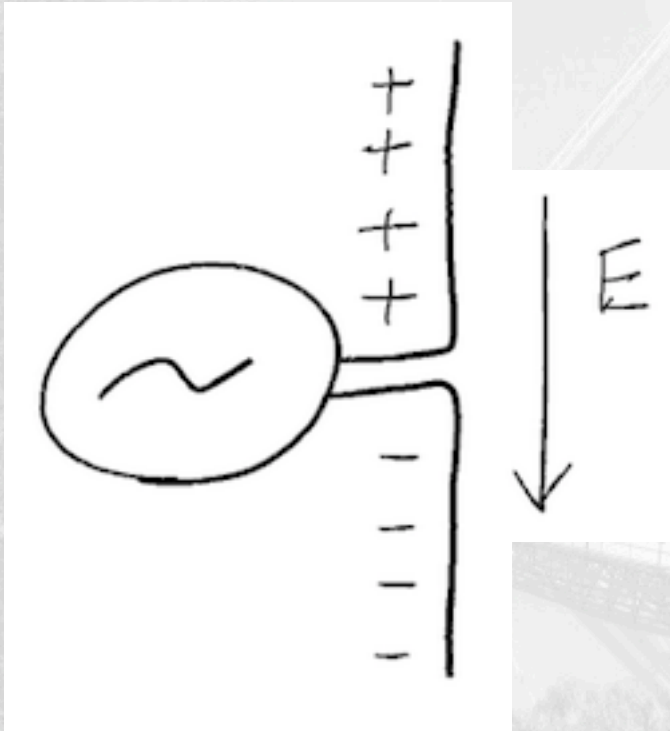
What is an EM wave?



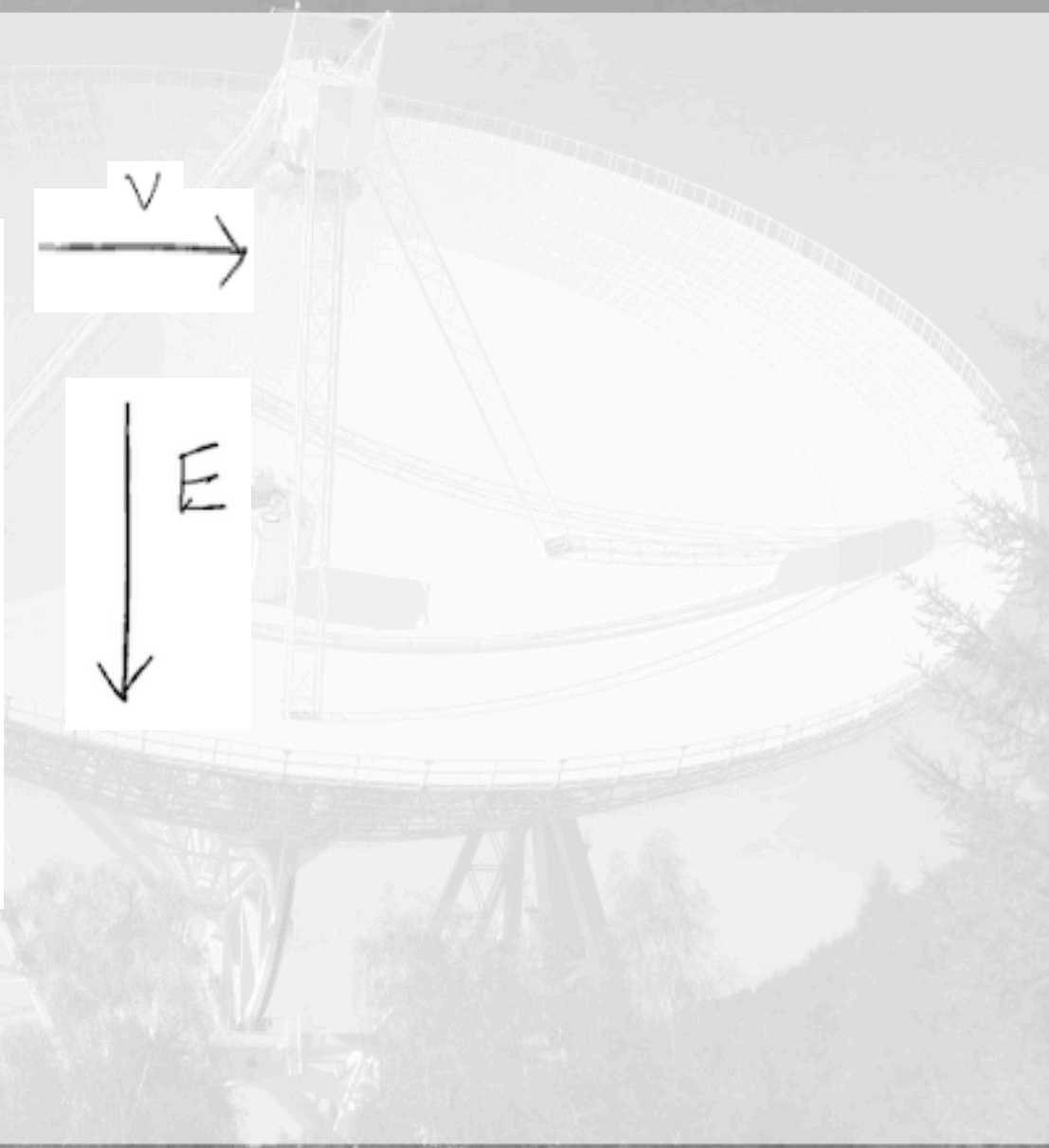
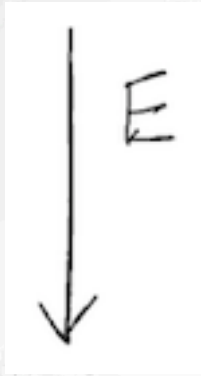
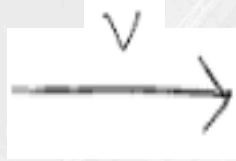
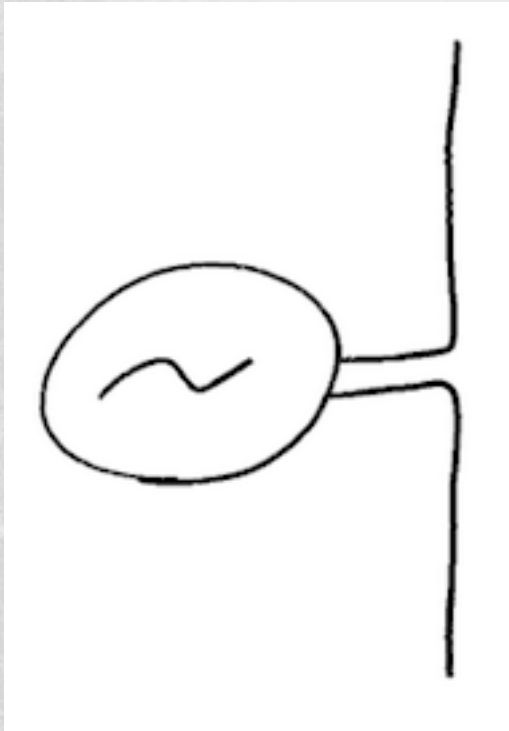
What is an EM wave?



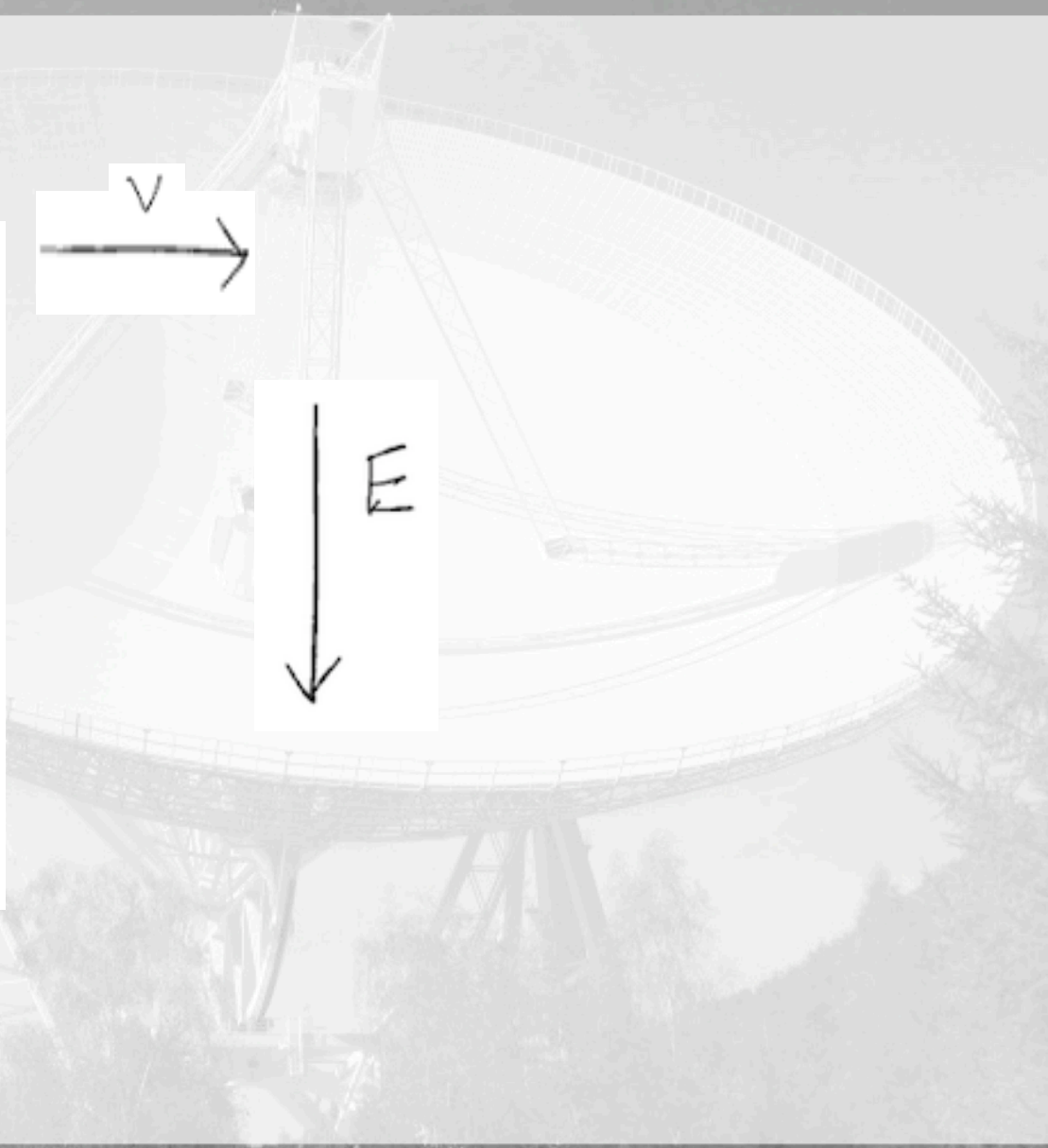
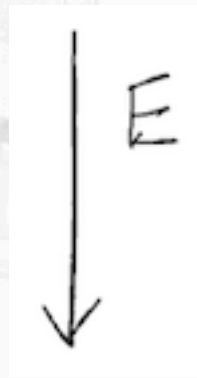
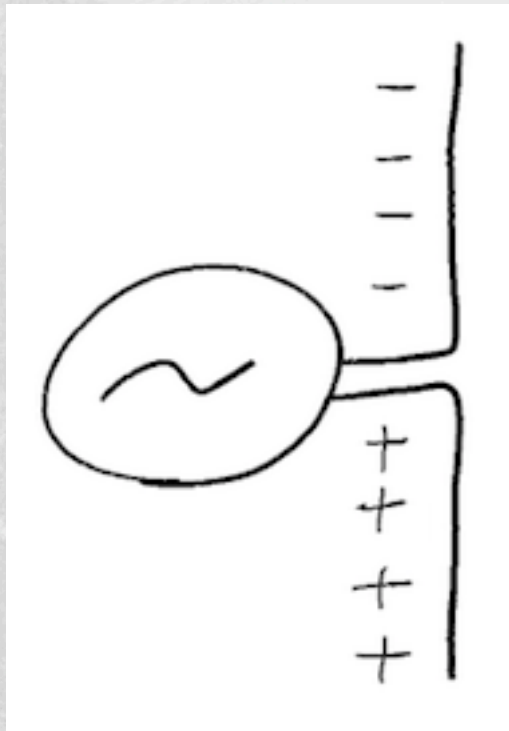
What is an EM wave?



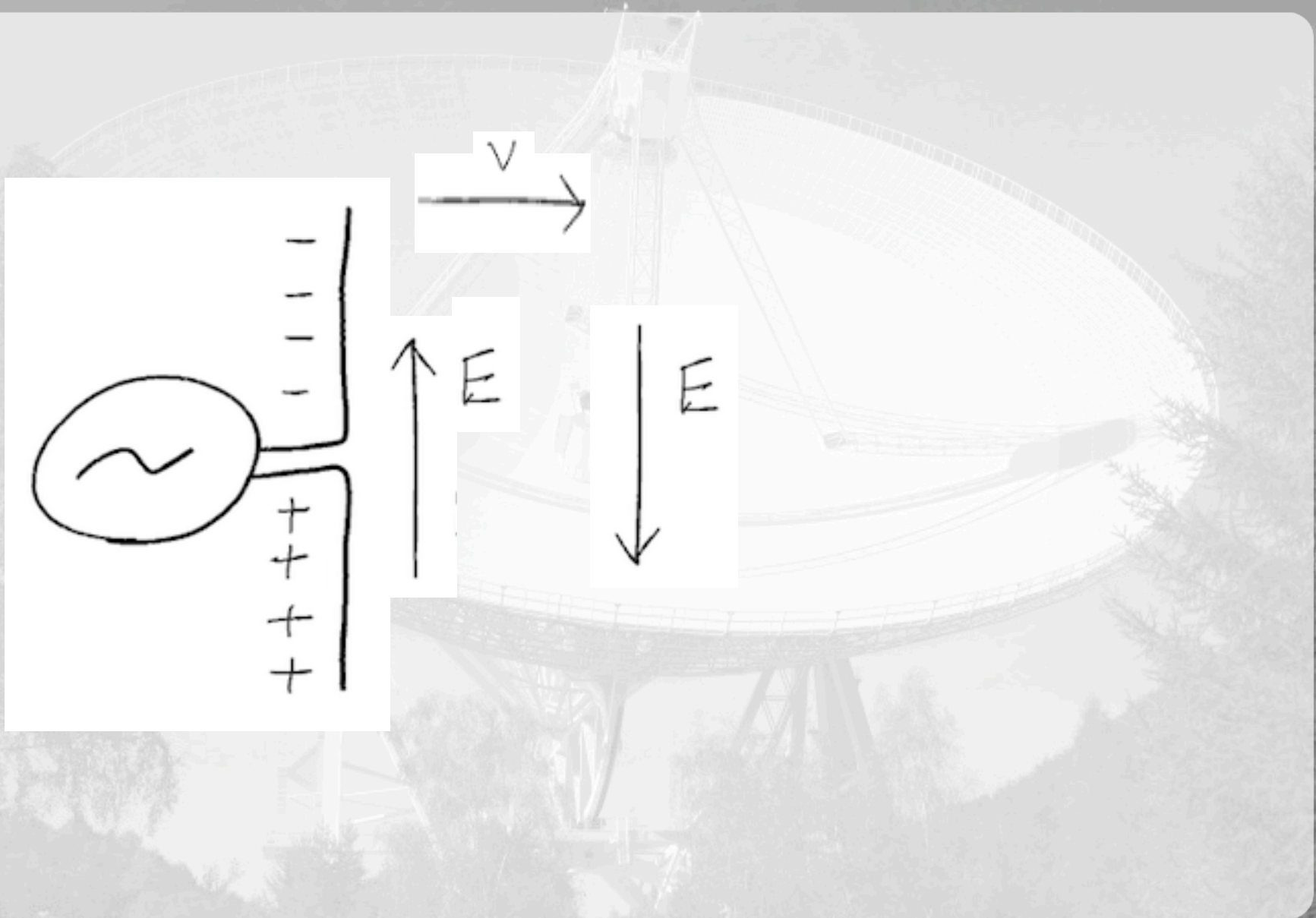
What is an EM wave?



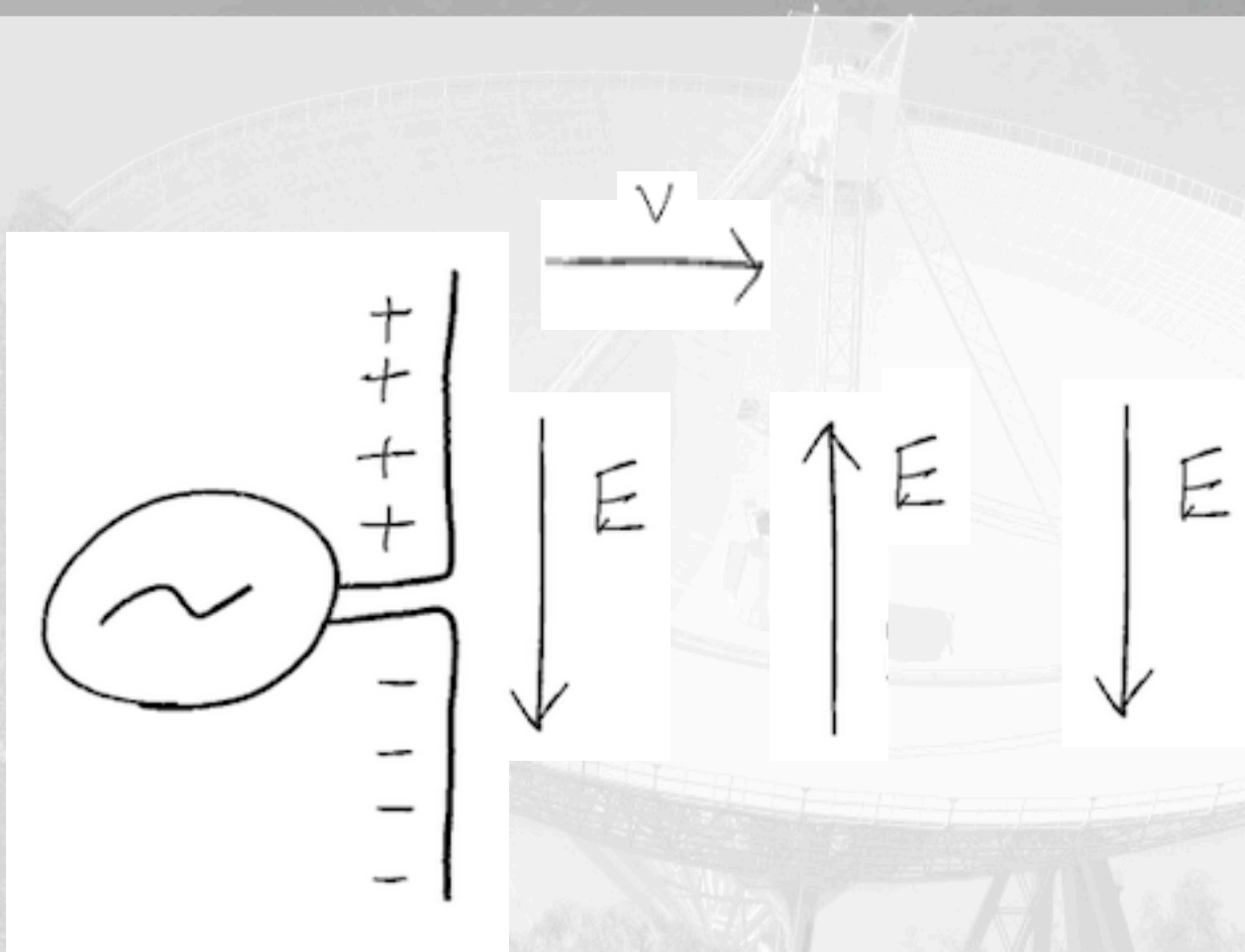
What is an EM wave?



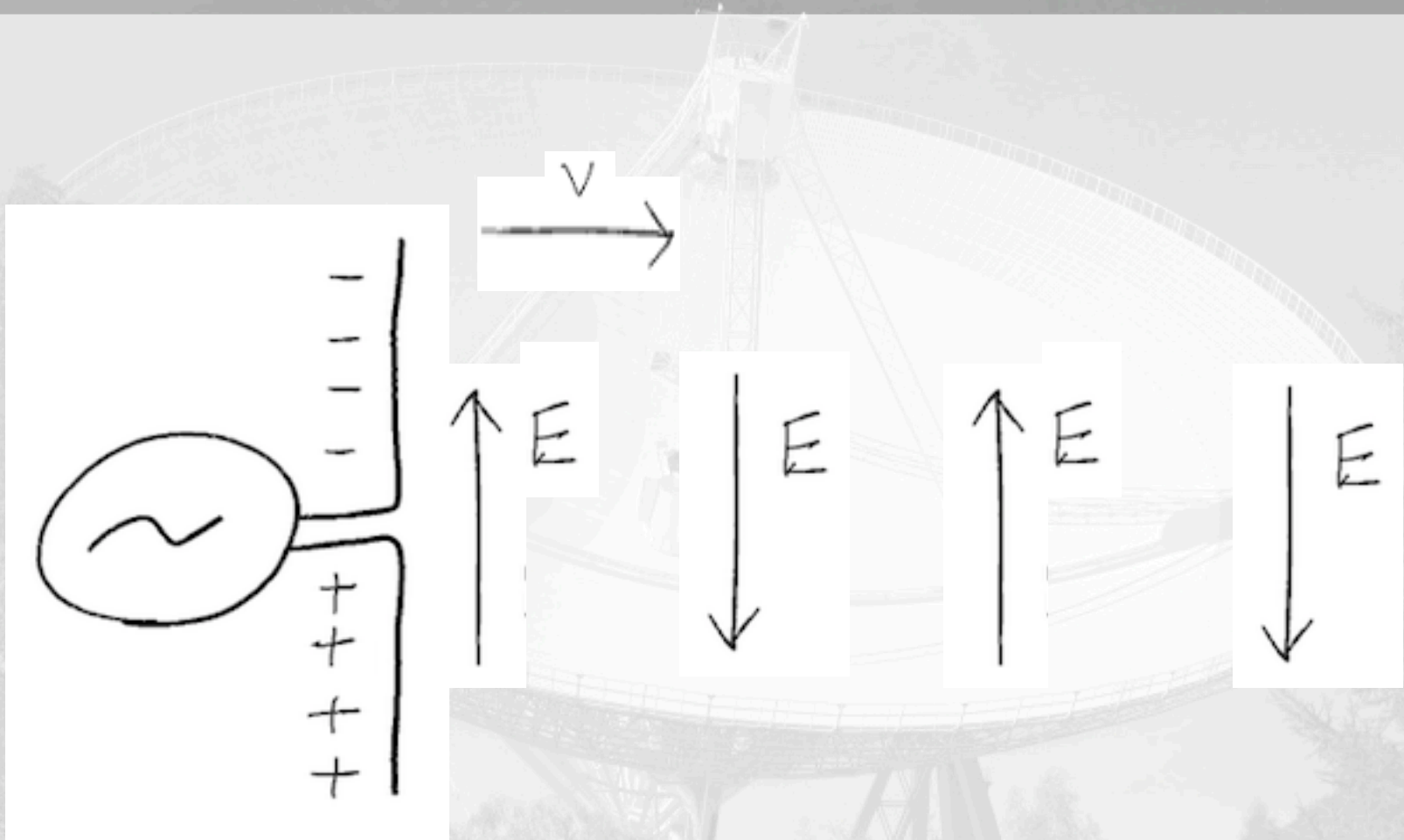
What is an EM wave?



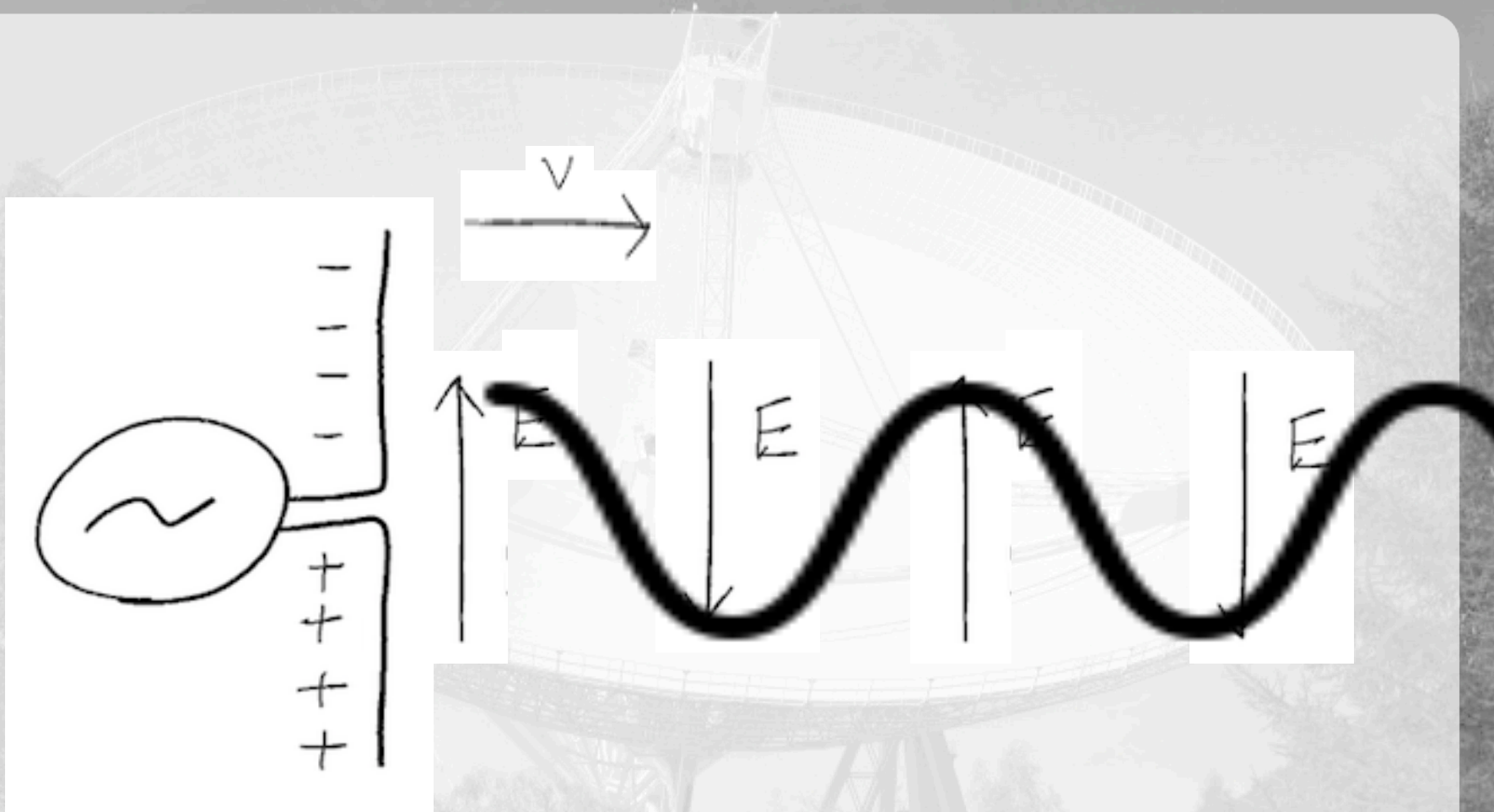
What is an EM wave?



What is an EM wave?



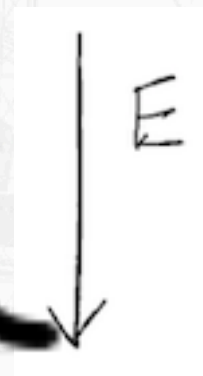
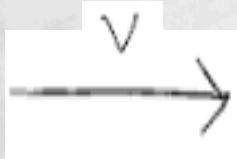
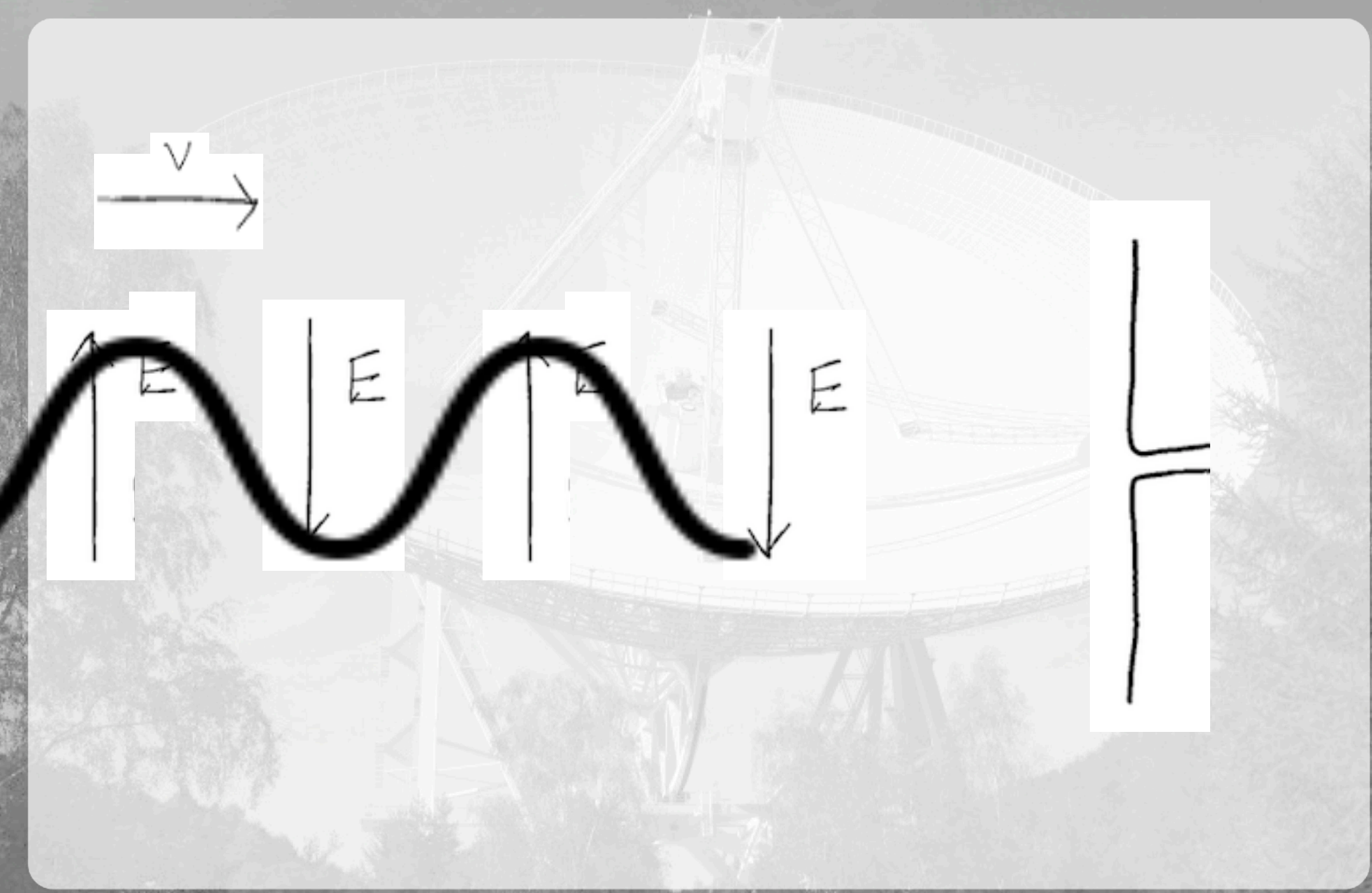
What is an EM wave?

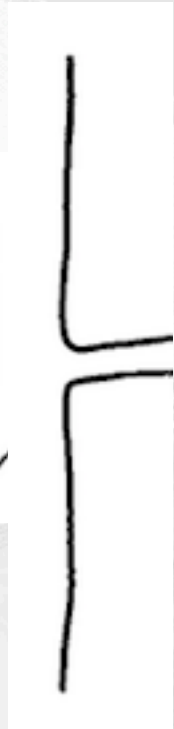
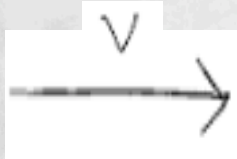


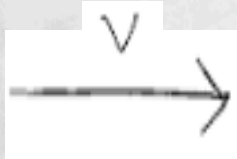
These are Electromagnetic (EM) waves.

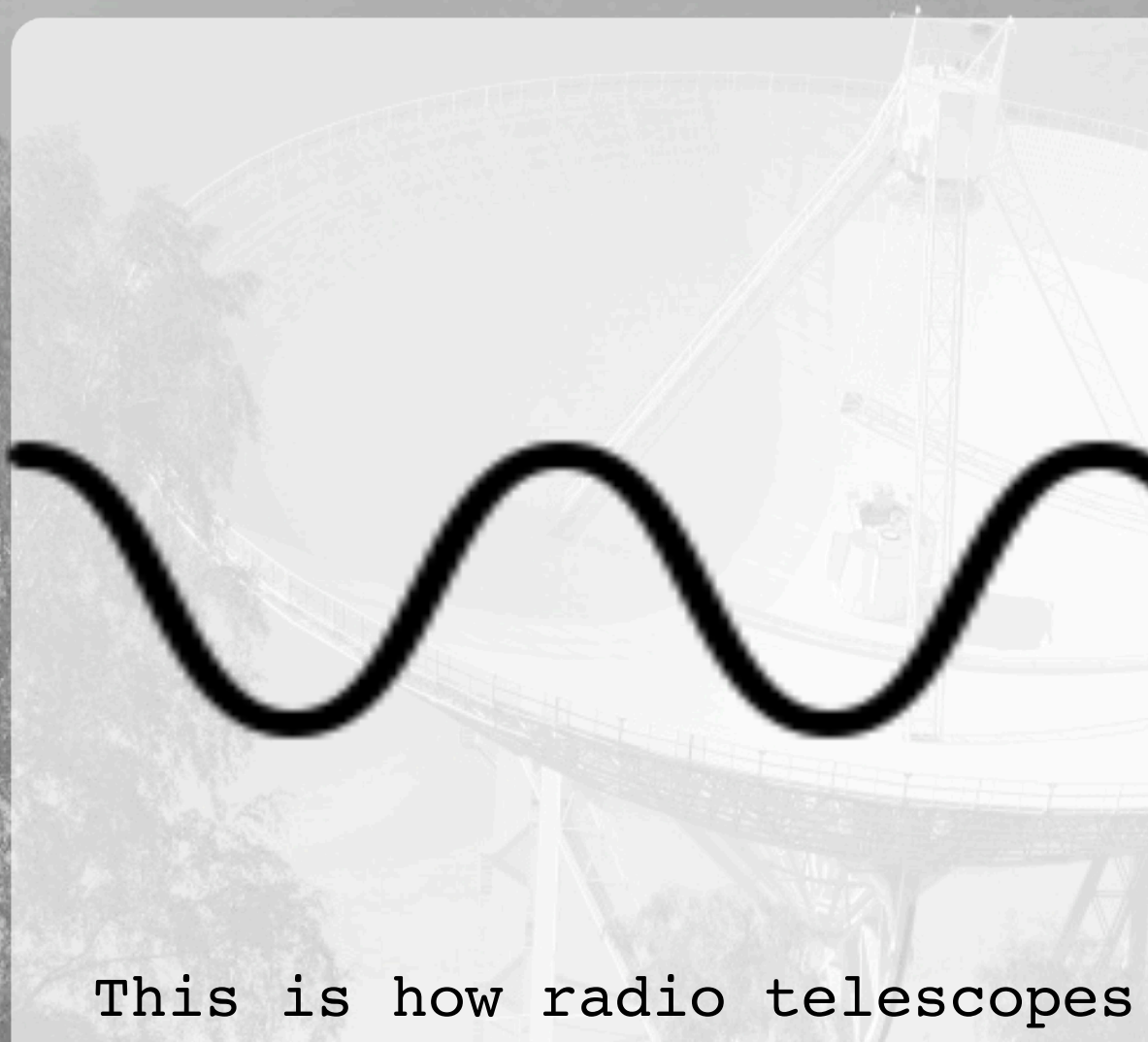


Lets invert the situation





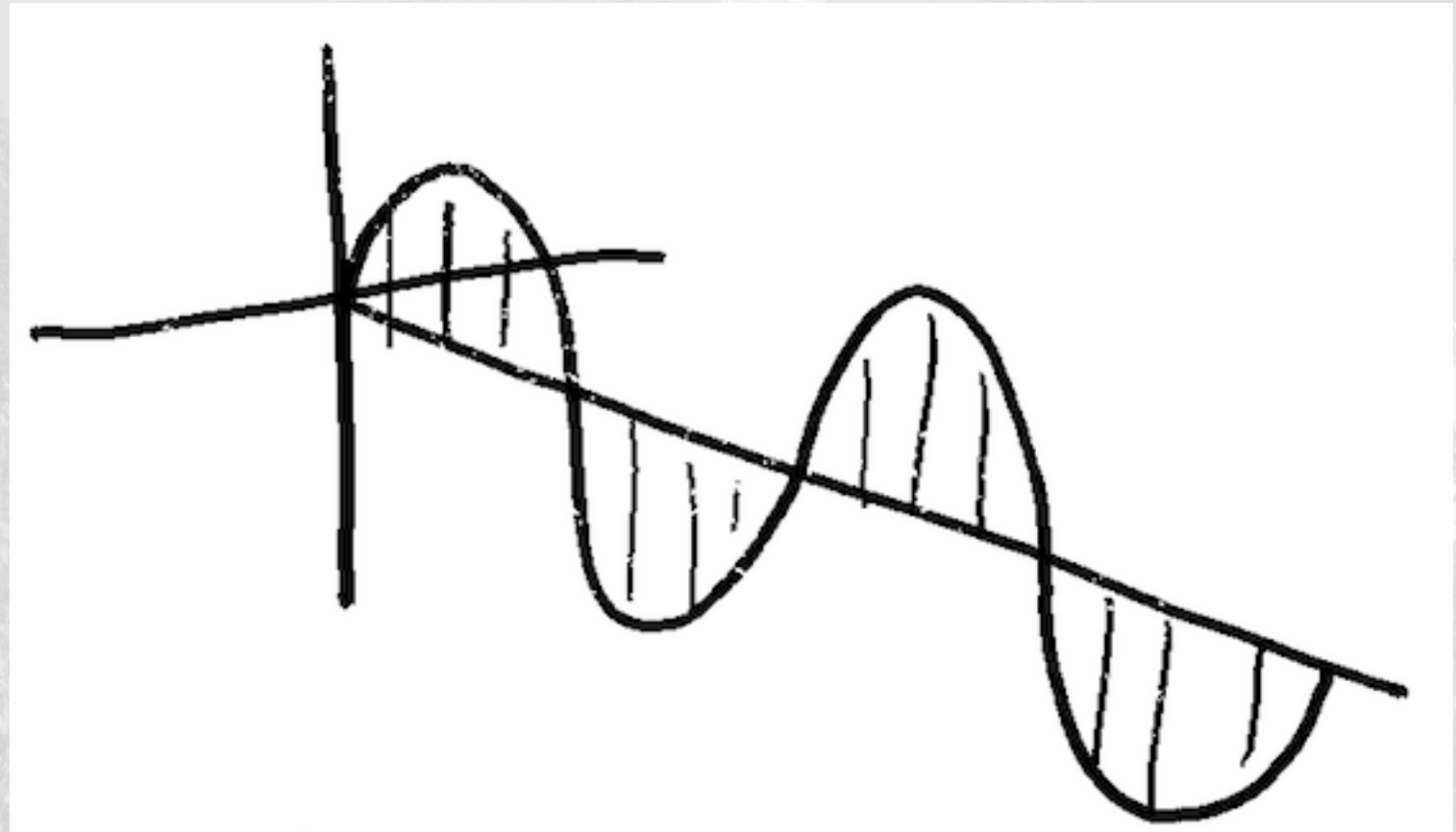


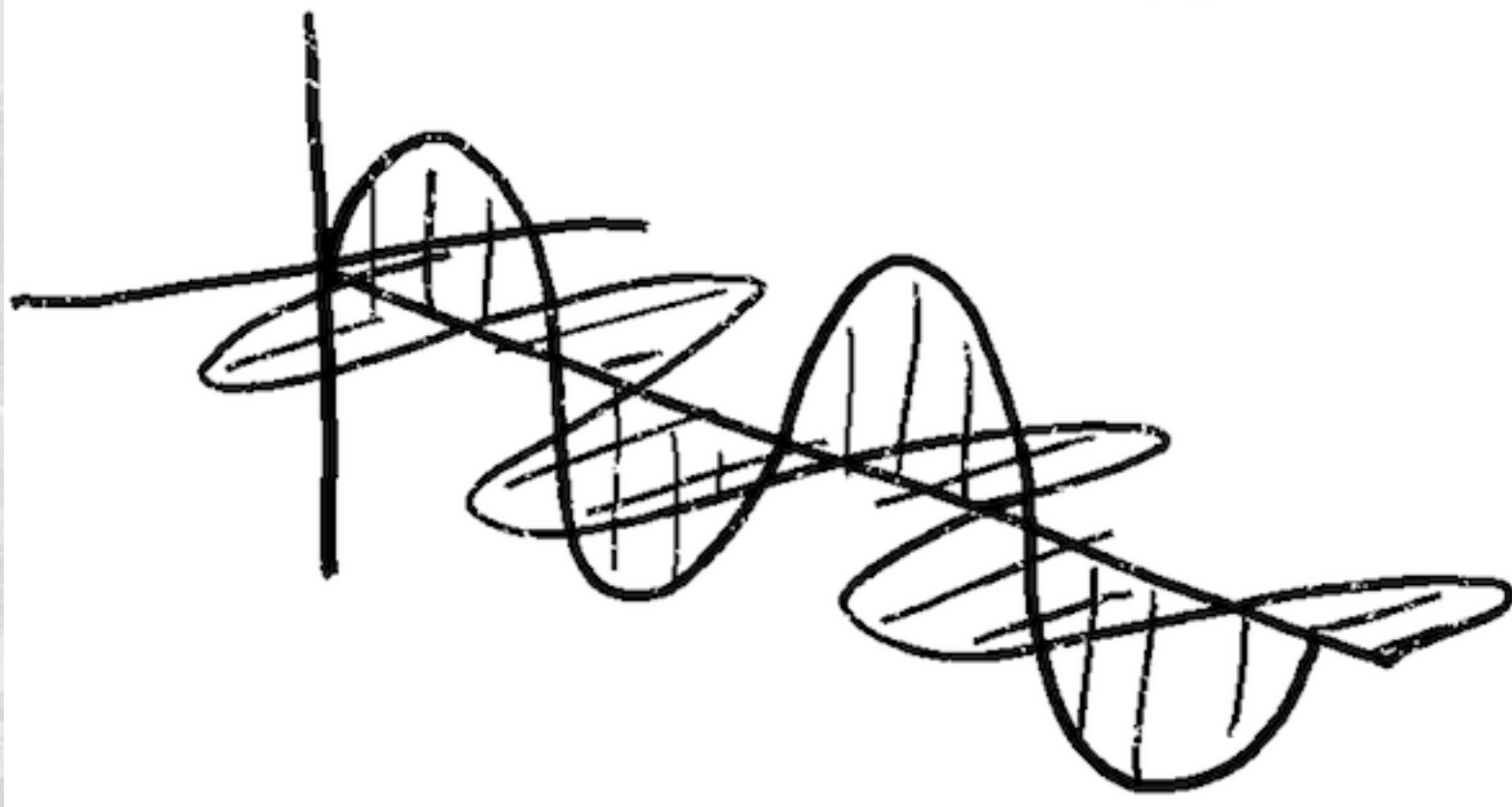


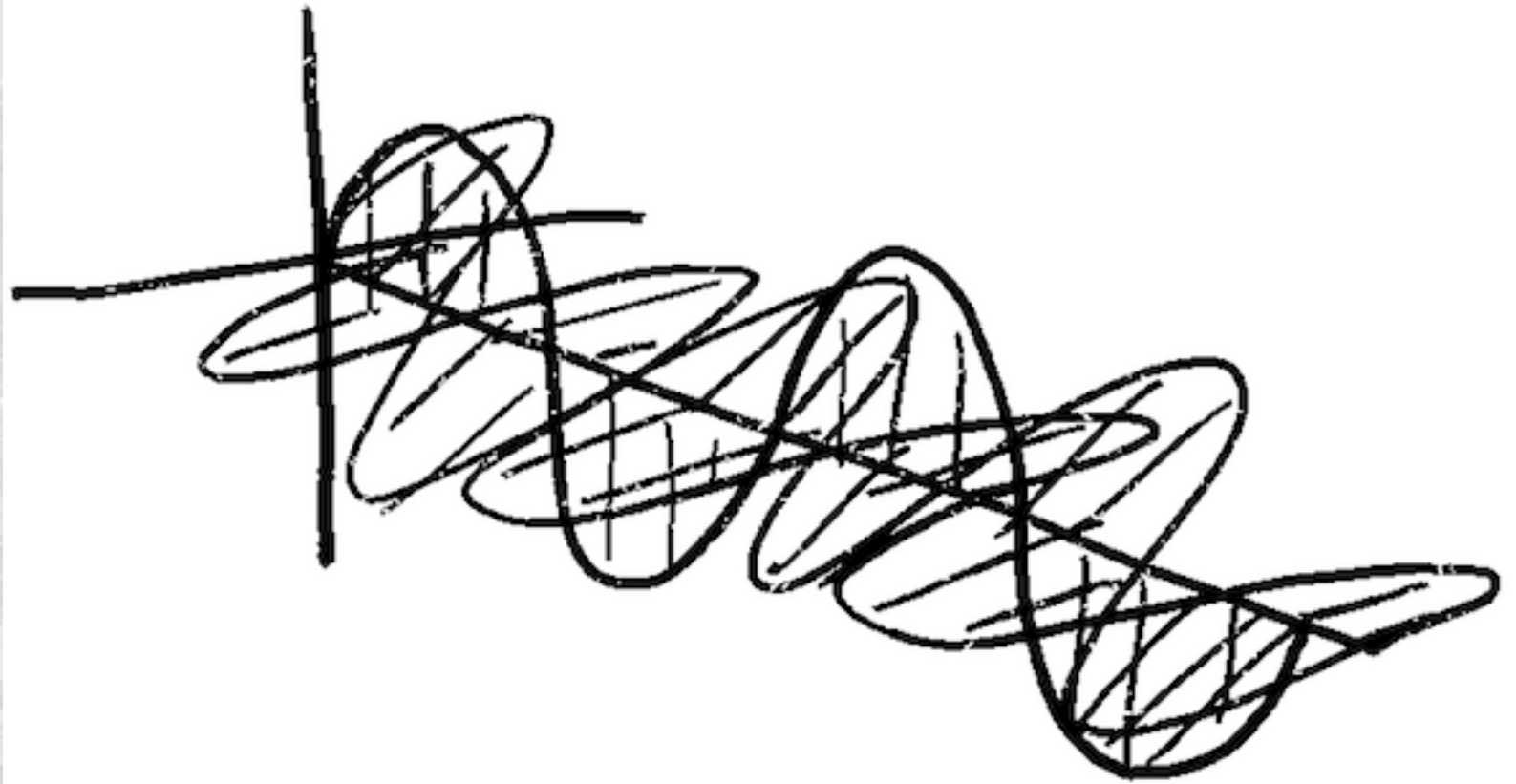
This is how radio telescopes receive EM wave signals (simplified)

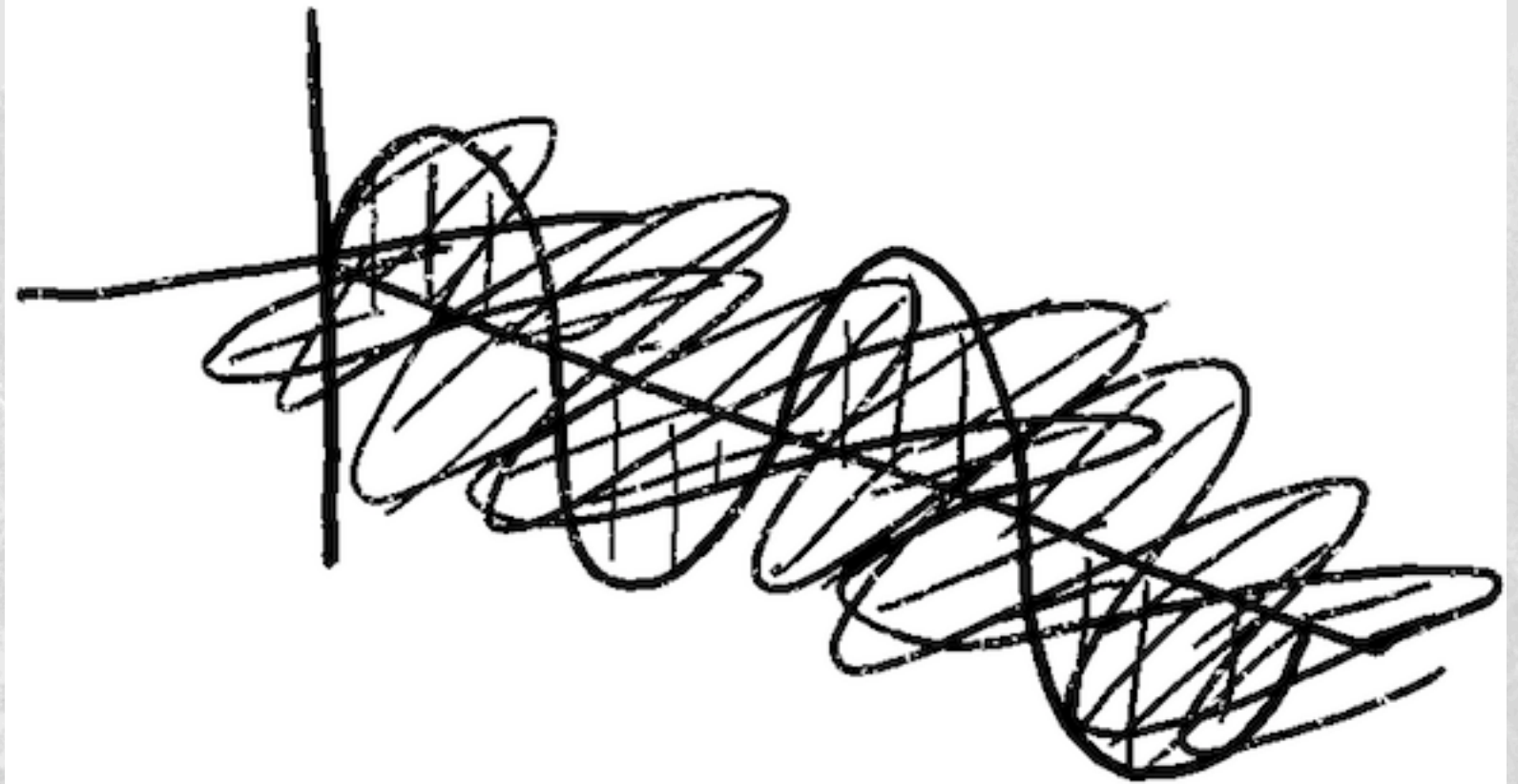


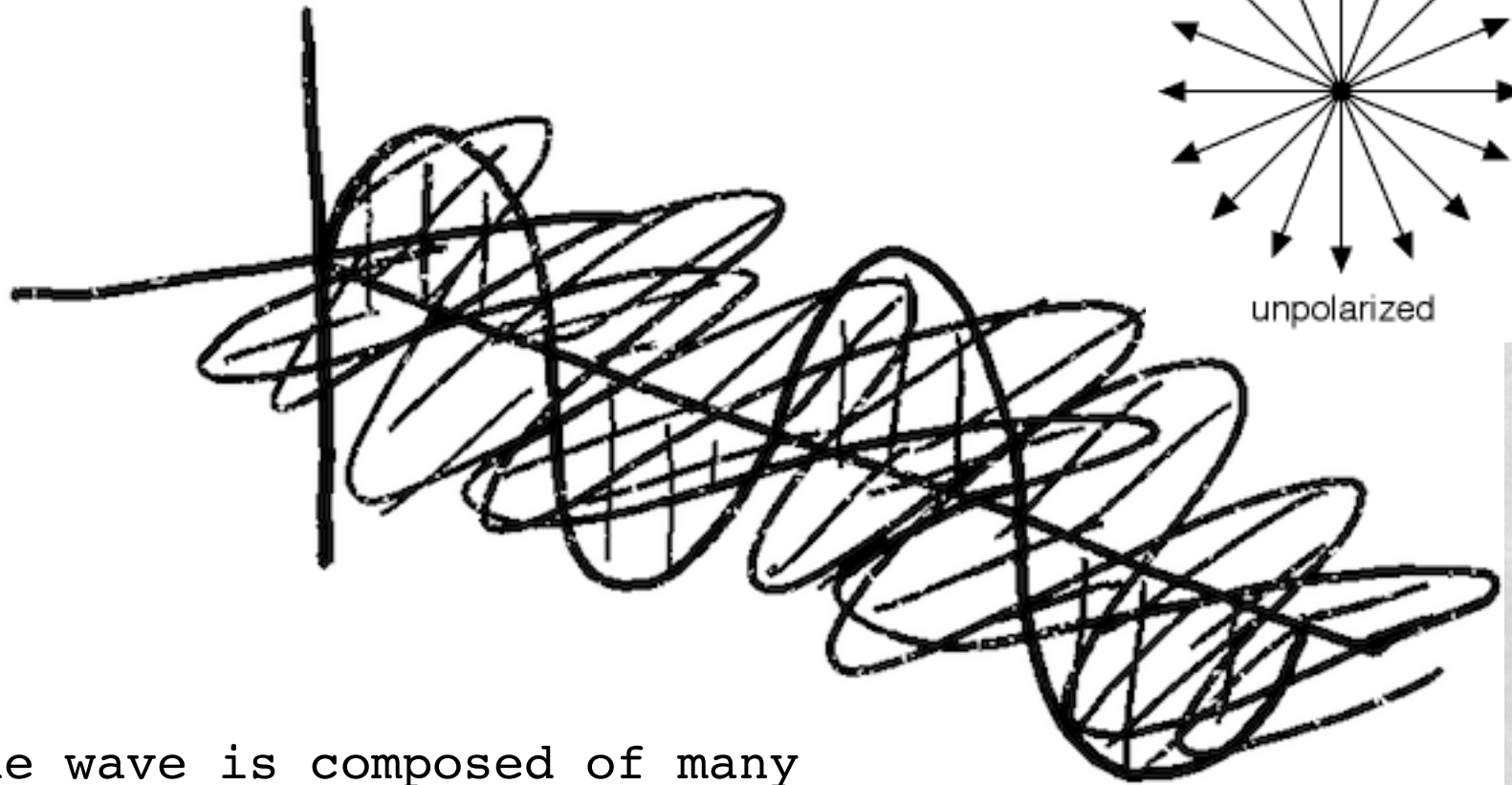
**We re-capped EM waves
now lets discuss
polarisation**







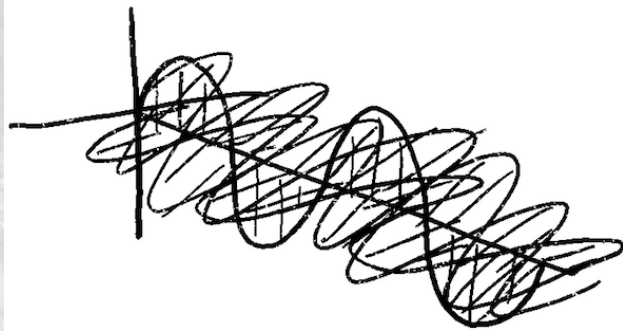




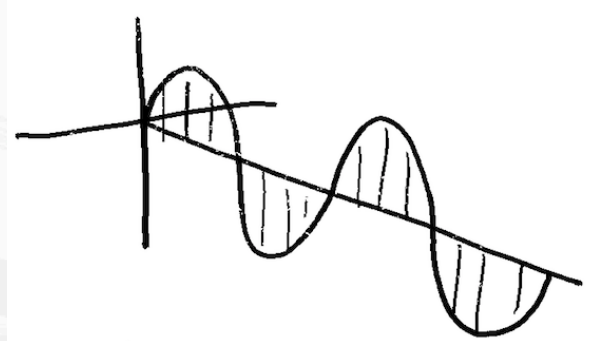
The wave is composed of many different waves of different angle and amplitude

There is **no preferential order**; it is 'unpolarised'

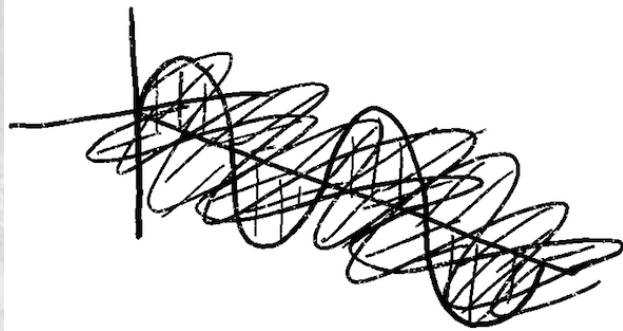
Unpolarised light has
no particular order;
it's a **mix** of all kinds
of waves



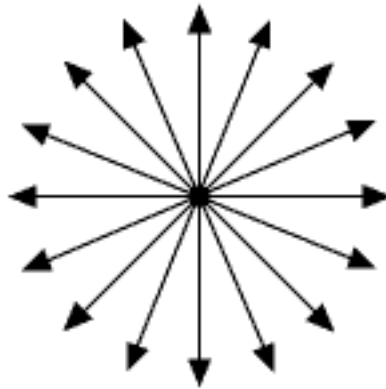
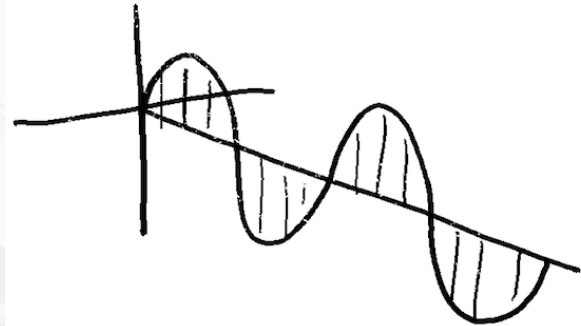
Plane-polarised light
has one preferred
oscillation orientation



Unpolarised light has
no particular order;
it's a mix of all kinds
of waves



Plane-polarised light
has one preferred
oscillation orientation

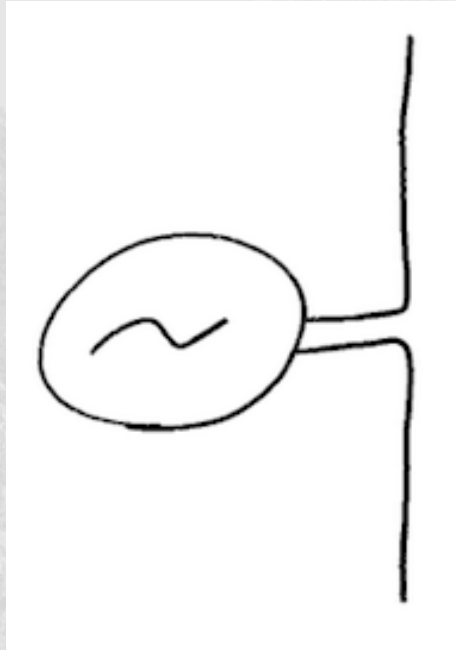


unpolarized



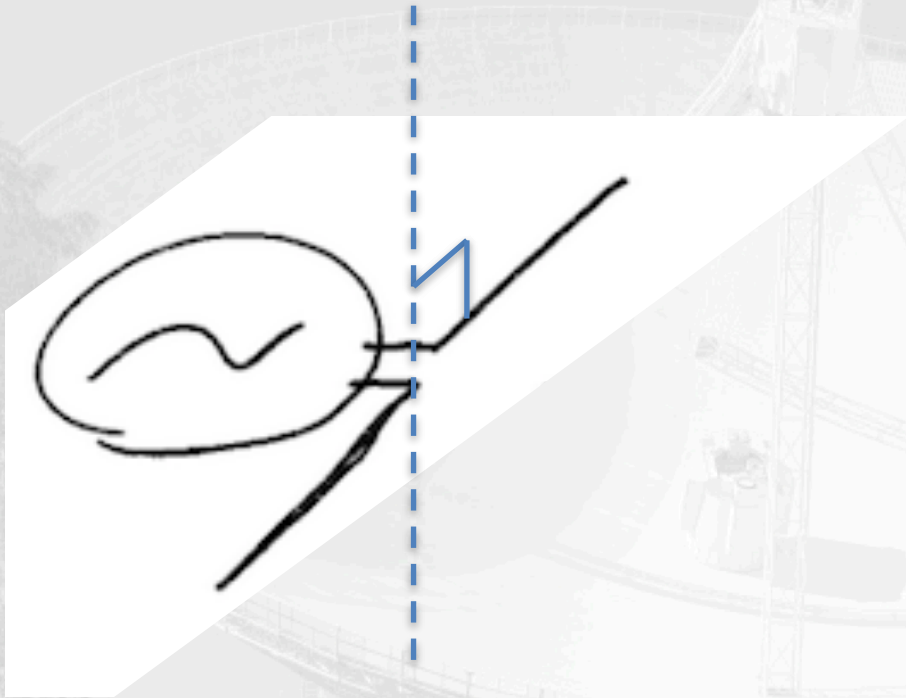
polarized

With preference in some direction...



Remember our transmitter?

It emits **one** polarisation,
but we can rotate the transmitter



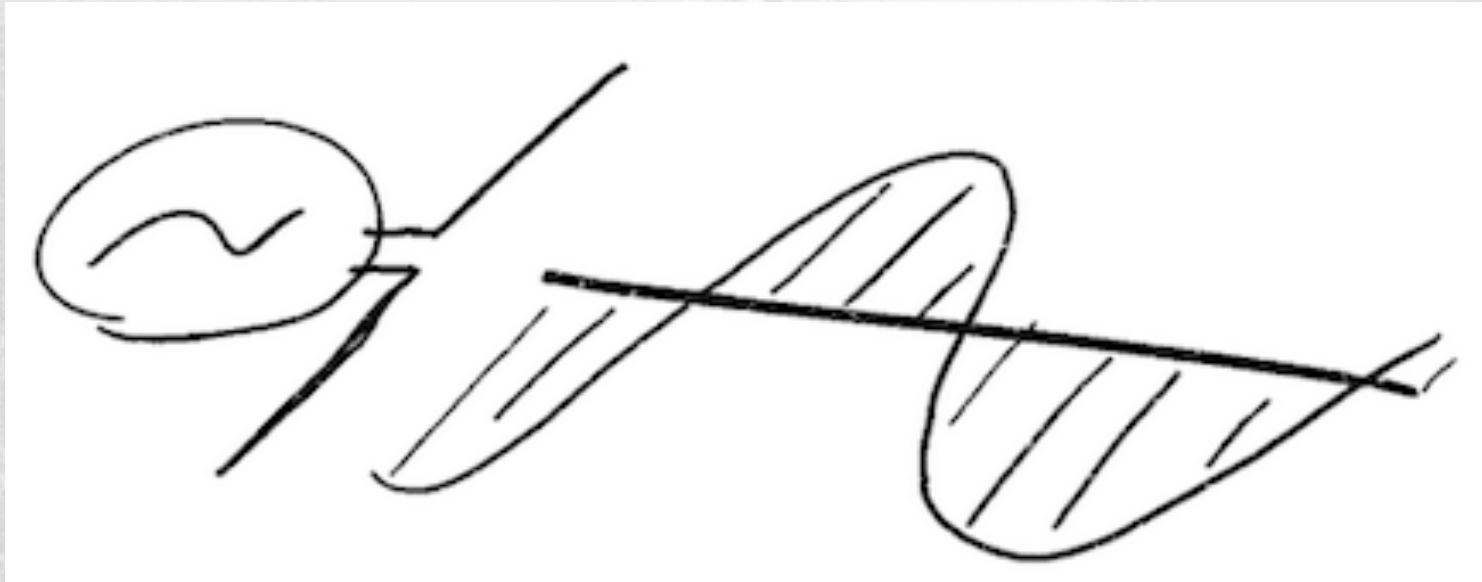
Remember our transmitter?

It emits **one** polarisation,
but we can rotate the transmitter



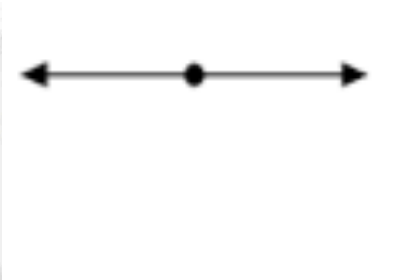
Remember our transmitter?

It emits **one** polarisation,
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Remember our transmitter?

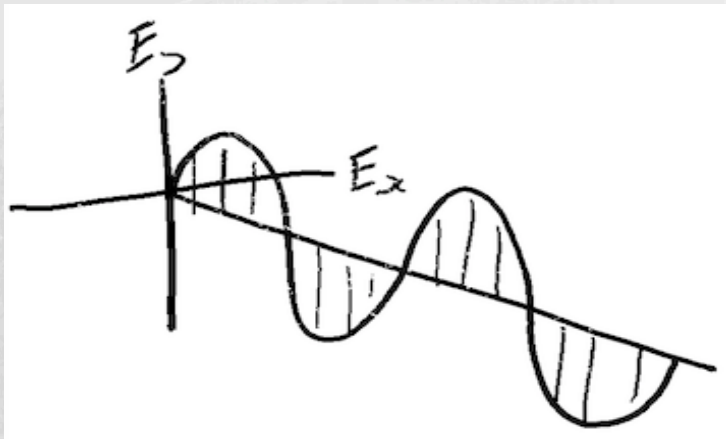
It emits **one** polarisation,
but we can rotate the transmitter



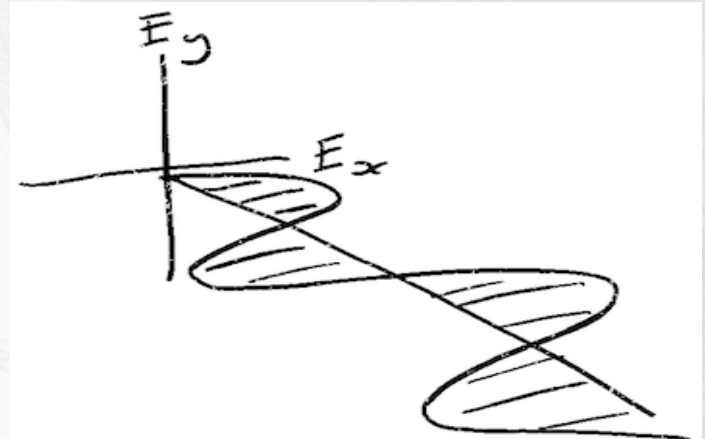
polarized

Linear polarisation

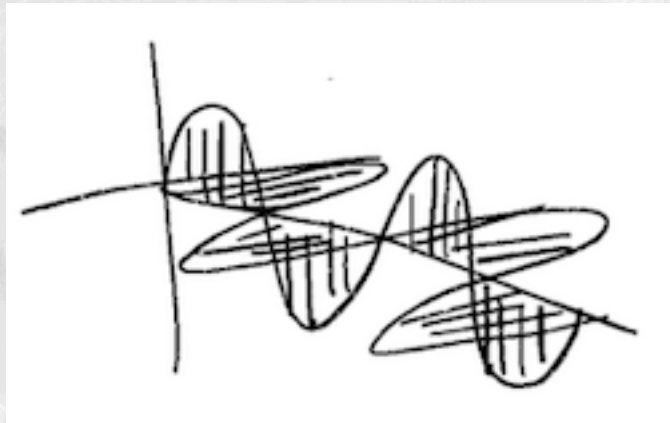
Vertical



Horizontal

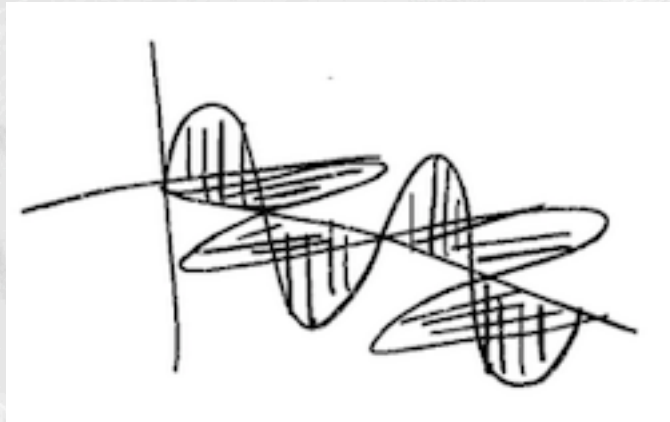


A linear polarised wave can be de-composed into orthogonal components: E_x and E_y



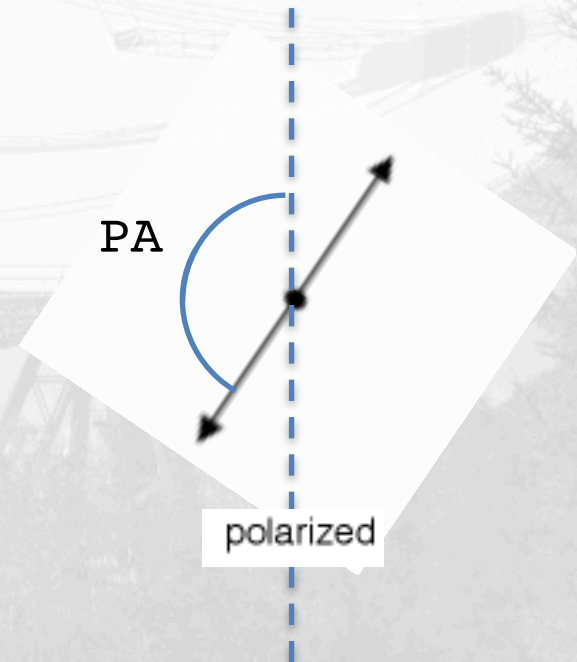
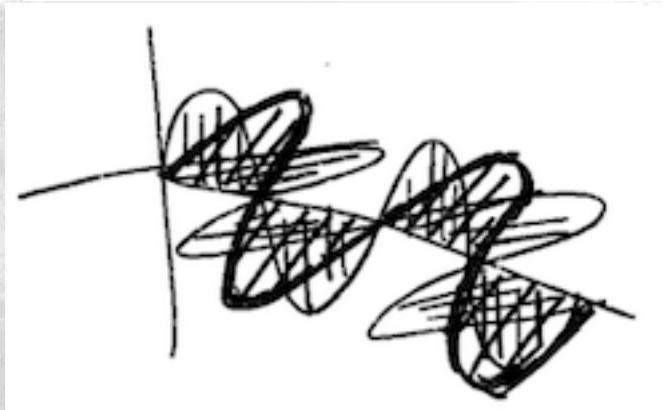
If we have a horizontal and vertical waves together we form a new wave.

The new wave is the sum of the orthogonal vector components ($E_x + E_y$)



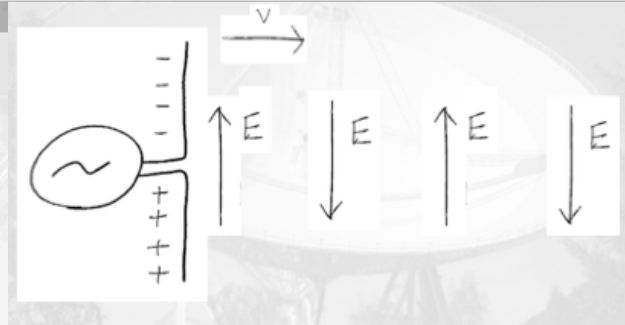
The angle of the wave is determined by:

$$PA = \tan^{-1}(E_x/E_y)$$

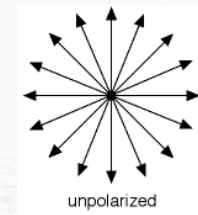


Take a minute to discuss:

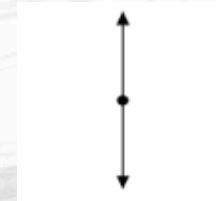
- What is an EM wave?



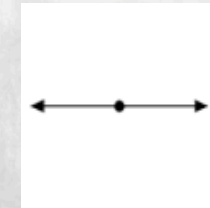
- What is unpolarised light?



- What is vertical polarisation?

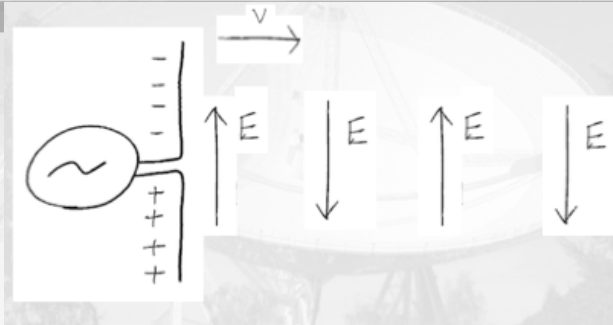


- What is horizontal polarisation?



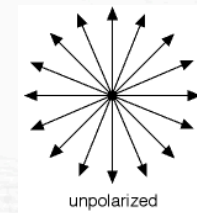
Take a minute to discuss:

- What is an EM wave?

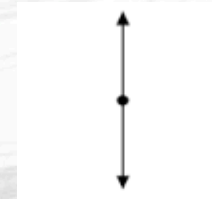


Oscillating electric field propagating at the speed of light

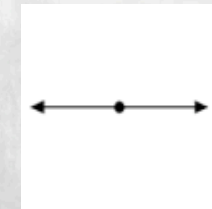
- What is unpolarised light?



- What is vertical polarisation?

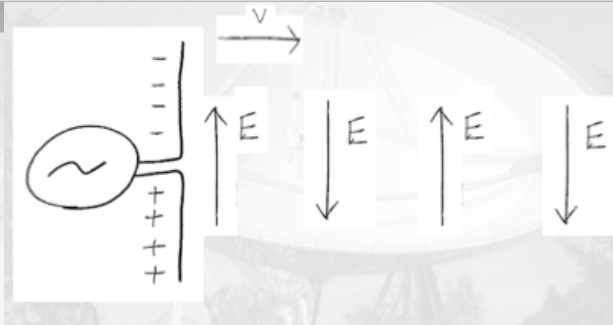


- What is horizontal polarisation?



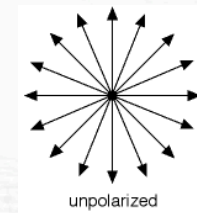
Take a minute to discuss:

- What is an EM wave?



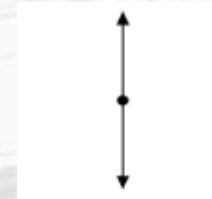
Oscillating electric field propagating at the speed of light

- What is unpolarised light?

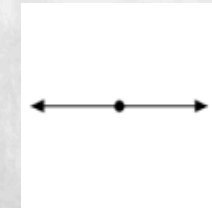


An unordered mix of light waves

- What is vertical polarisation?

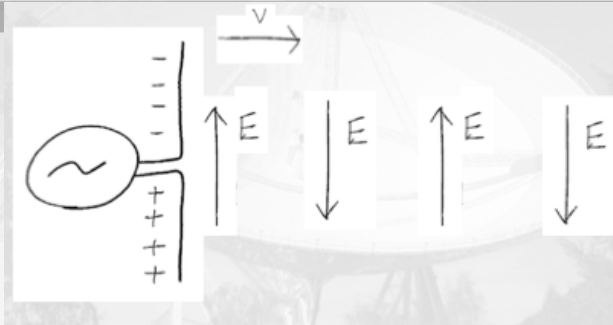


- What is horizontal polarisation?



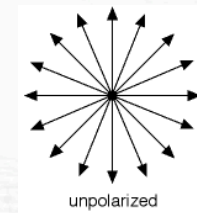
Take a minute to discuss:

- What is an EM wave?



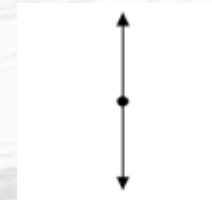
Oscillating electric field propagating at the speed of light

- What is unpolarised light?



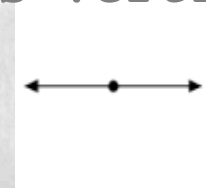
An unordered mix of light waves

- What is vertical polarisation?



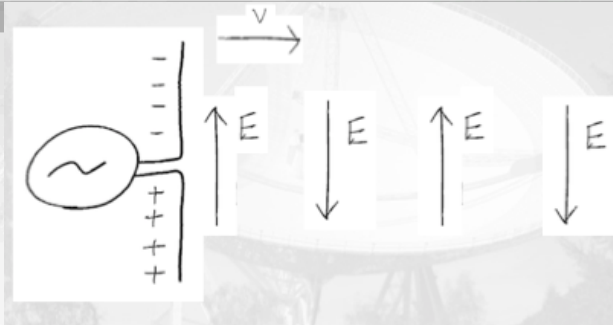
A wave whose electric field oscillates vertically

- What is horizontal polarisation?



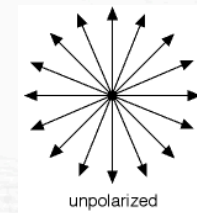
Take a minute to discuss:

- What is an EM wave?



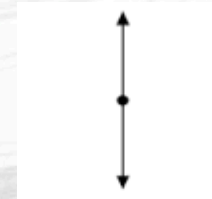
Oscillating electric field propagating at the speed of light

- What is unpolarised light?



An unordered mix of light waves

- What is vertical polarisation?

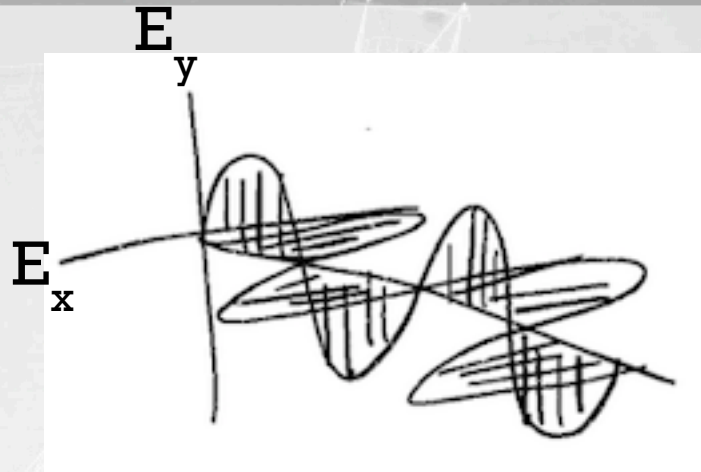


A wave whose electric field oscillates vertically

- What is horizontal polarisation?



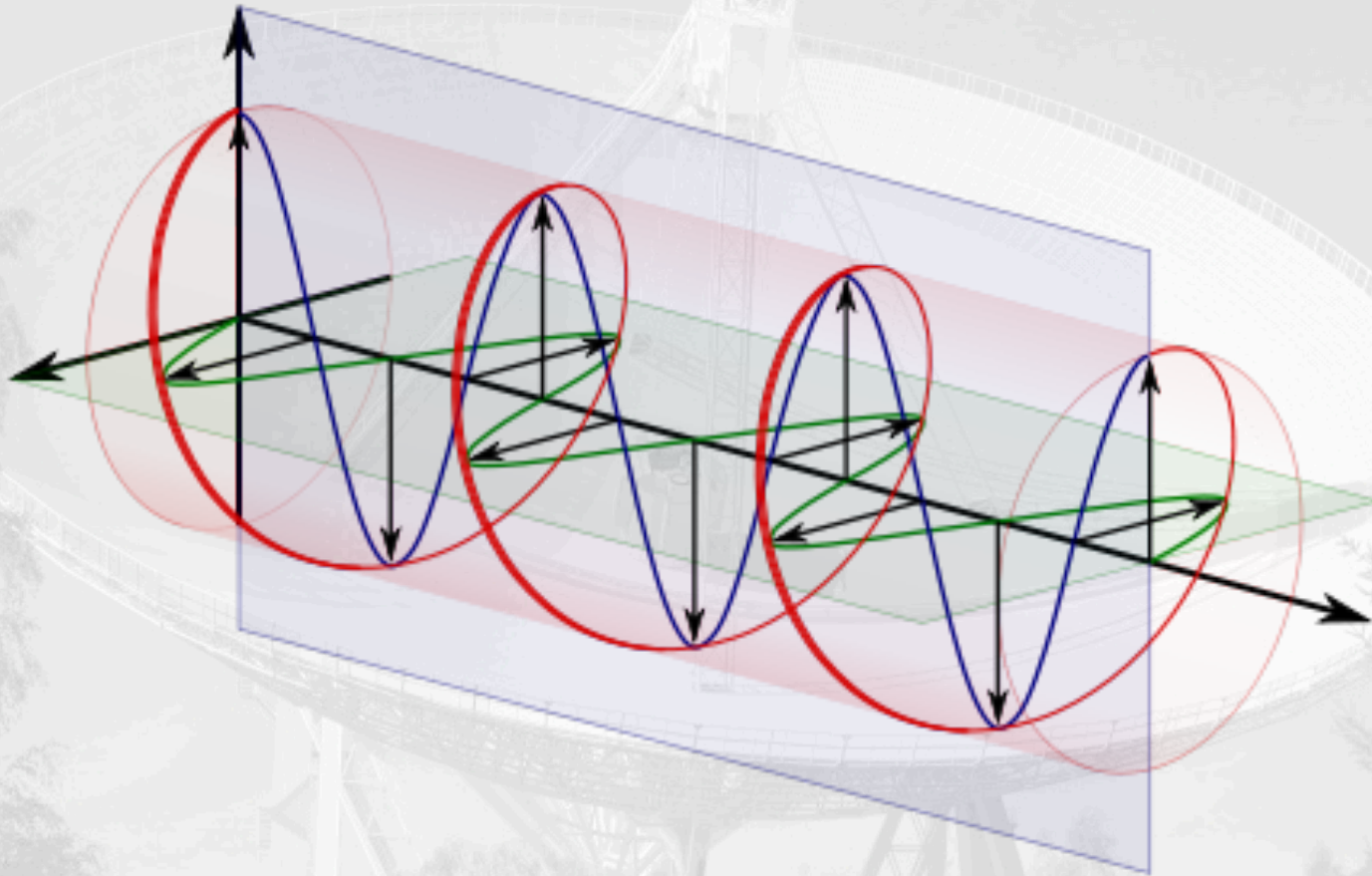
A wave whose electric field oscillates horizontally



In this example, the wave components in E_x and E_y oscillate in phase with each other

Lets consider when there is a phase difference between E_x and E_y

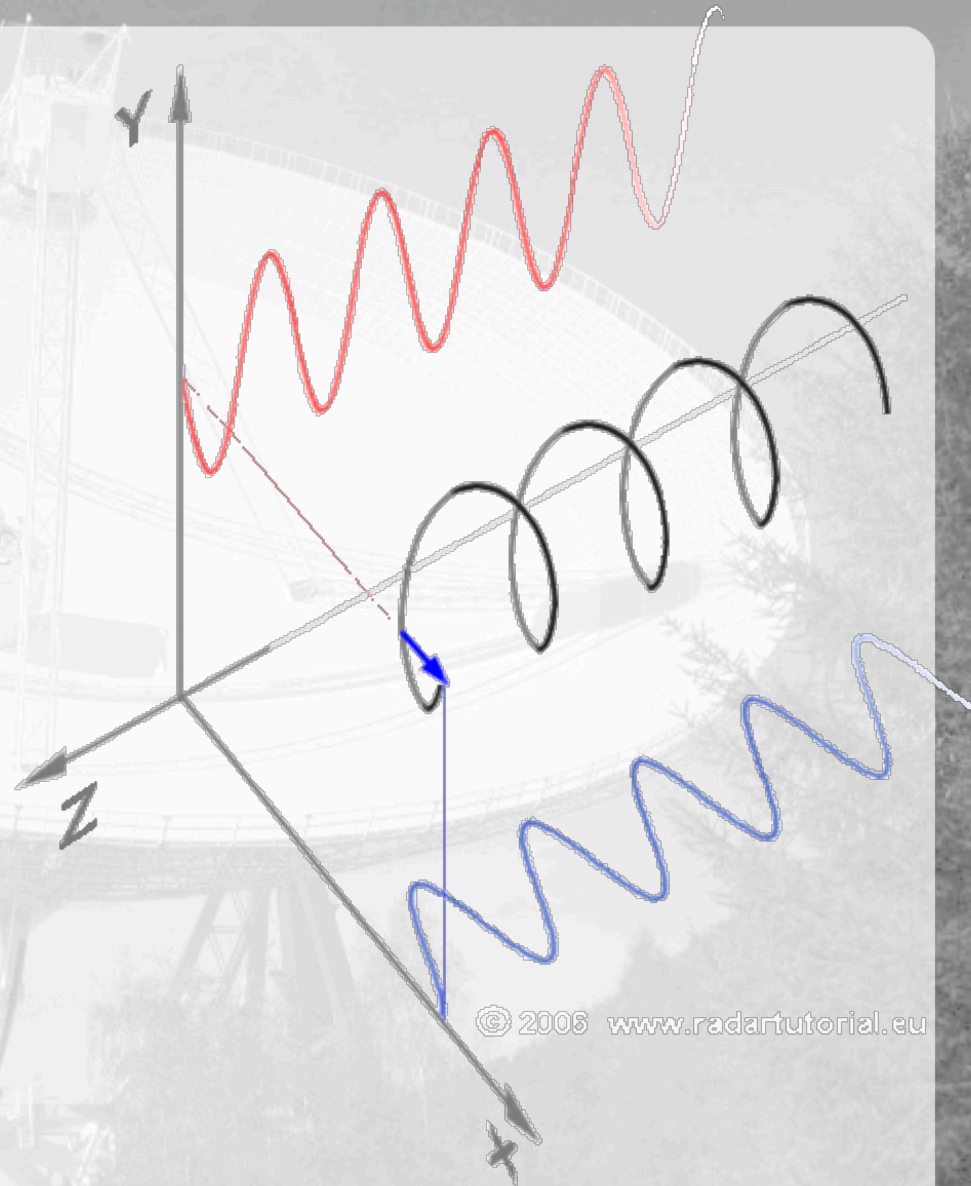
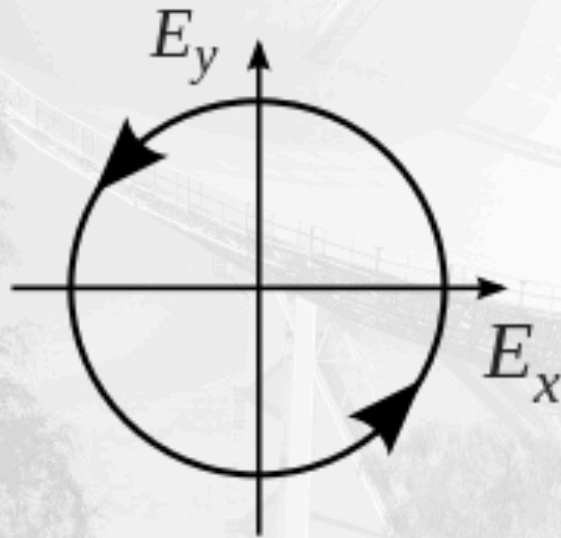
Circular polarisation



A $\pi/2$ phase offset in linear components creates **circular polarisation.**

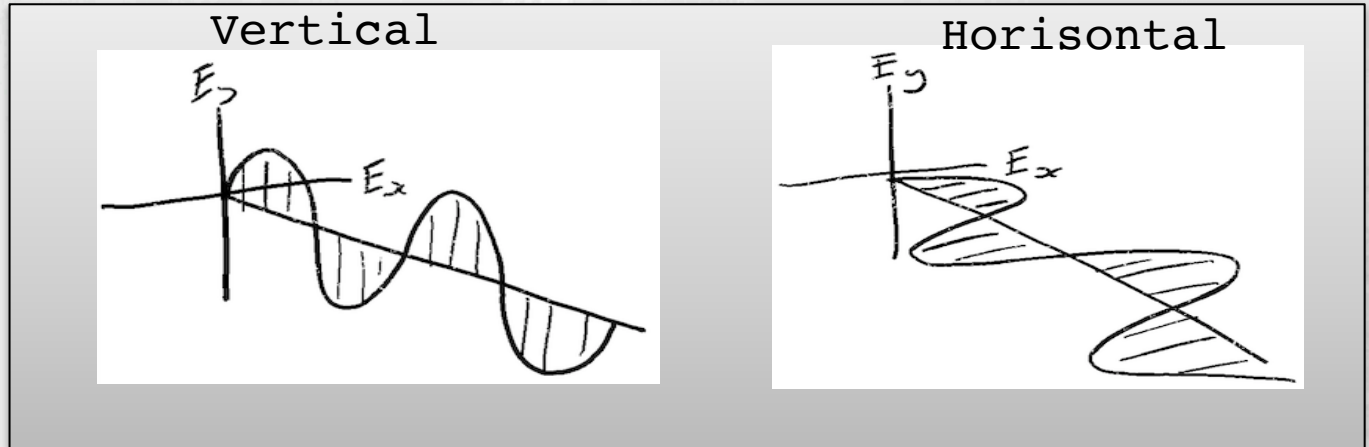
Circular polarisation

A $\pi/2$ phase offset in linear components creates **circular polarisation**.

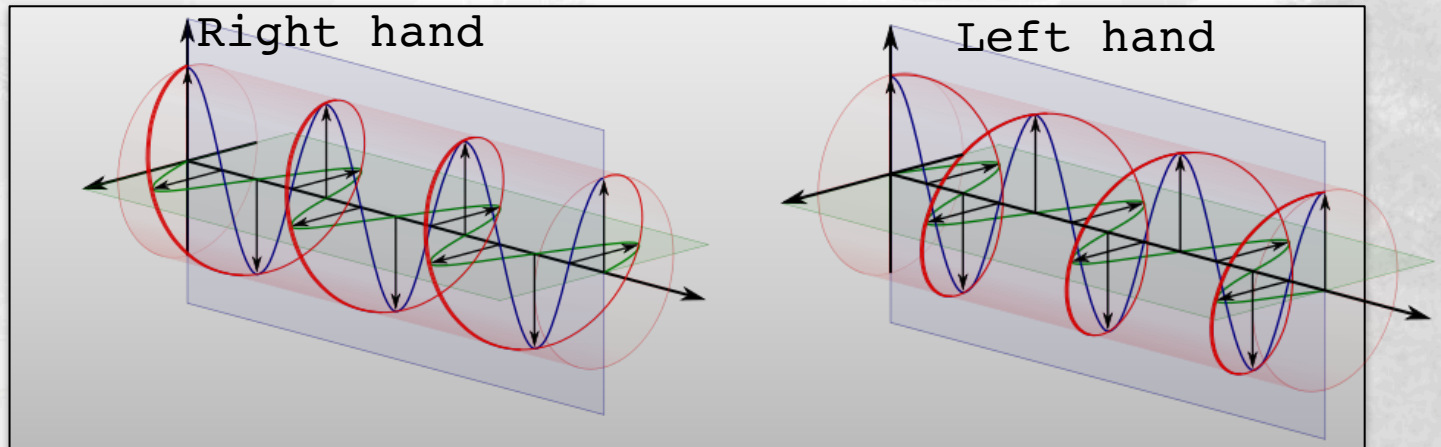


Polarised EM radiation

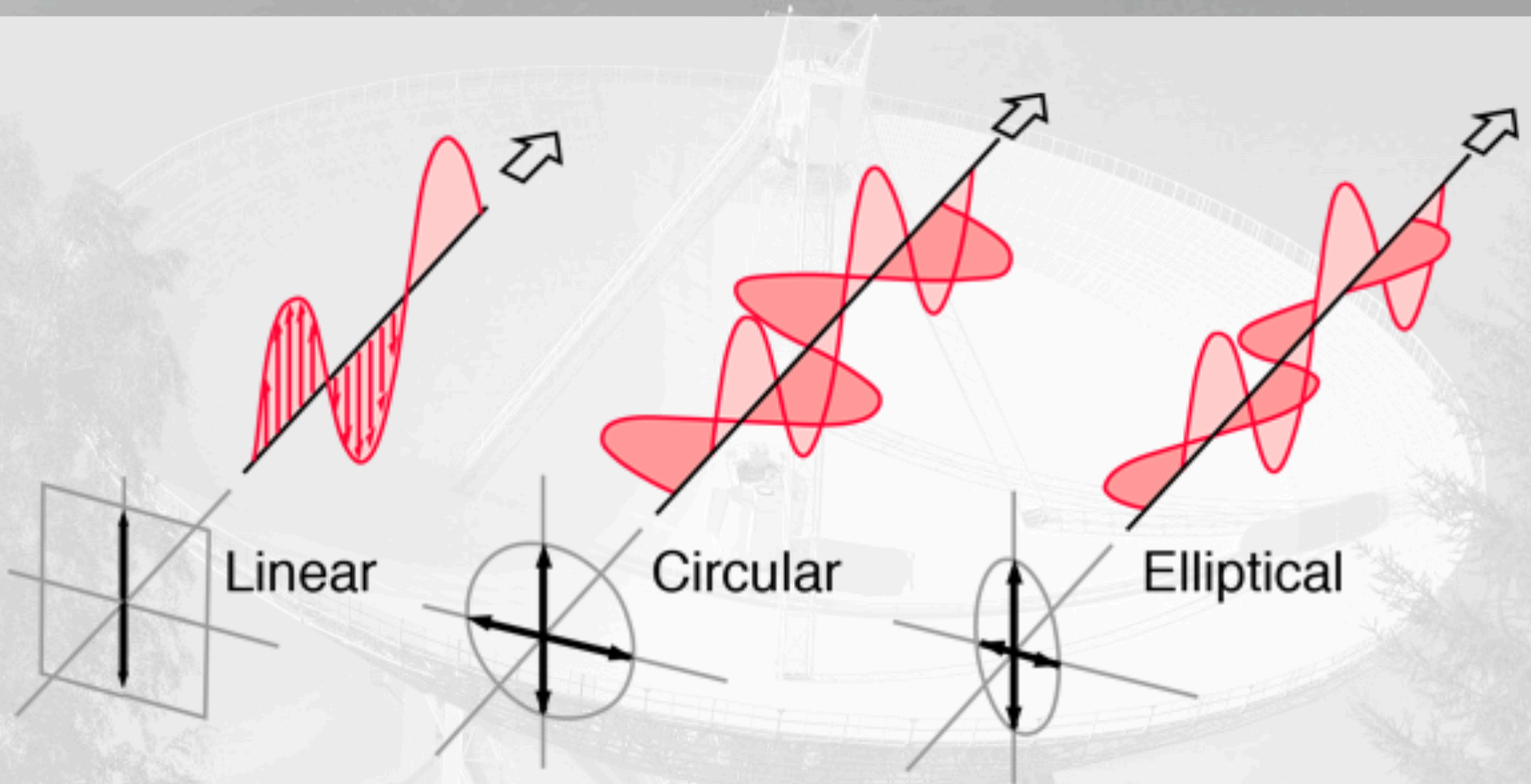
Linear



Circular



Elliptically polarised



Polarised light from astronomical sources are typically a mix of linear and circular polarisation

This is called elliptical polarisation

Stokes parameters

Linear

Circular

$$\begin{aligned} I &= \langle A_X^2 \rangle + \langle A_Y^2 \rangle &= \langle A_R^2 \rangle + \langle A_L^2 \rangle \\ Q &= \langle A_X^2 \rangle - \langle A_Y^2 \rangle &= \langle 2 A_R A_L \cos \delta_{RL} \rangle \\ U &= \langle 2 A_X A_Y \cos \delta_{XY} \rangle &= \langle 2 A_R A_L \sin \delta_{RL} \rangle \\ V &= \langle 2 A_X A_Y \sin \delta_{XY} \rangle &= \langle A_R^2 \rangle - \langle A_L^2 \rangle \end{aligned}$$

- Looks scary (the math, not the guy)
- Actually, quite simple and elegant
- Fully describe the polarisation state of any signal
(*Know you how much of each kind of pol. is present*)



Stokes parameters

Linear

Circular

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle = \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

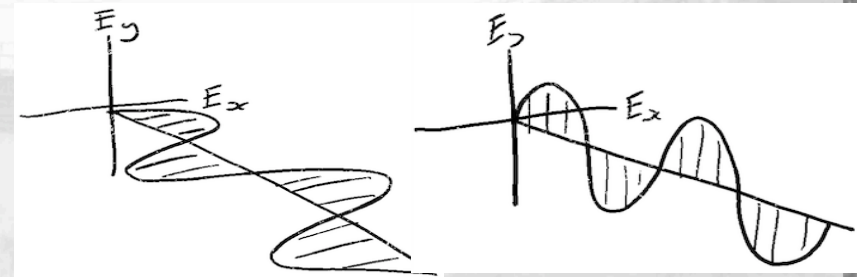
$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

I ->

Q ->

U ->

V ->



Stokes parameters

Linear

Circular

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle = \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

I -> Total intensity

Q ->

U ->

V ->



Stokes parameters

Linear

Circular

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle$$

$$= \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle$$

$$= \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

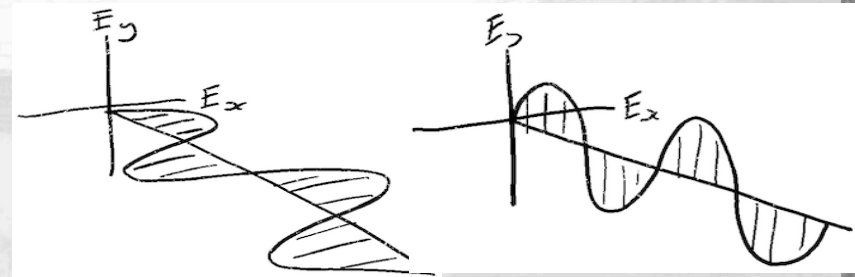
$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

I -> Total intensity

Q ->

U ->

V ->



Stokes parameters

Linear

Circular

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle = \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

I -> Total intensity

Q -> Linear polarisation (Hor=1, Ver=-1)

U ->

V ->



Stokes parameters

Linear

Circular

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle = \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

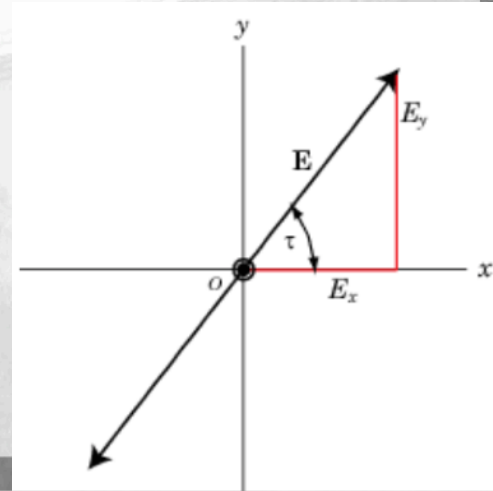
$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

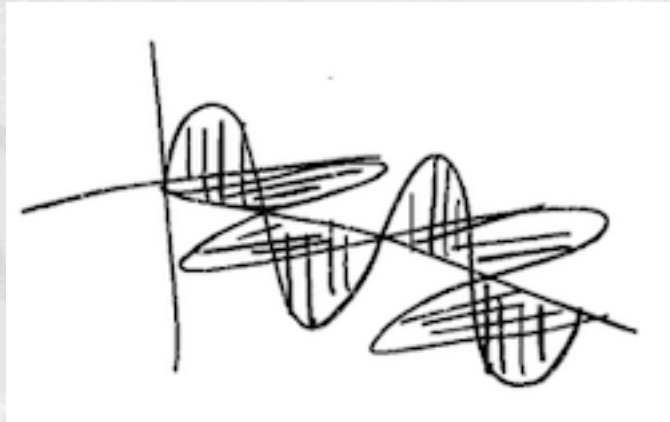
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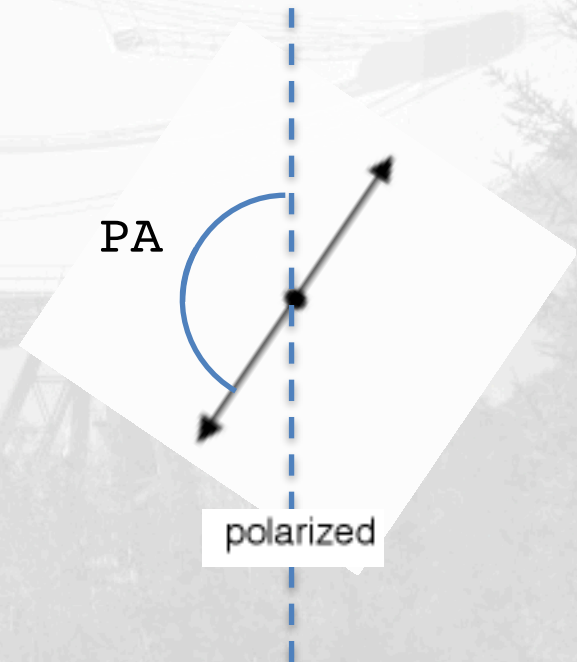
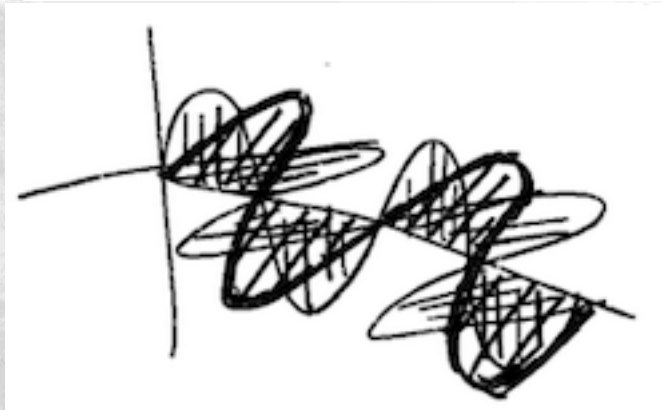
V ->





The angle of the wave is determined by:

$$PA = \tan^{-1}(E_x/E_y)$$



Stokes parameters

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Circular

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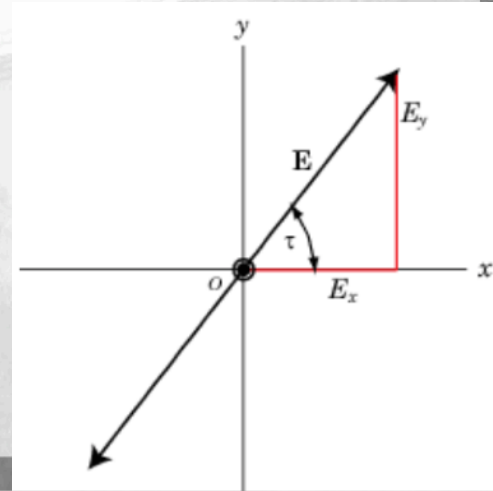
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Stokes parameters

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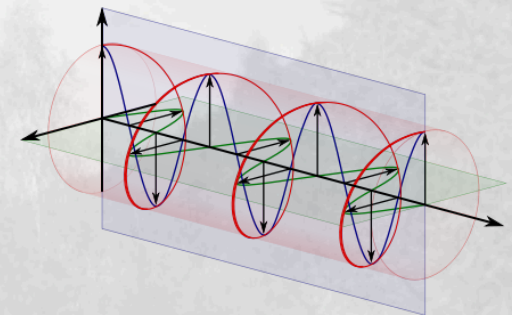
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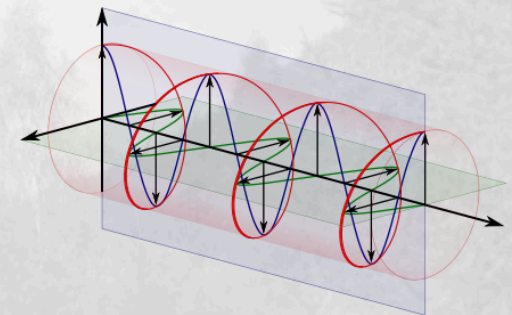
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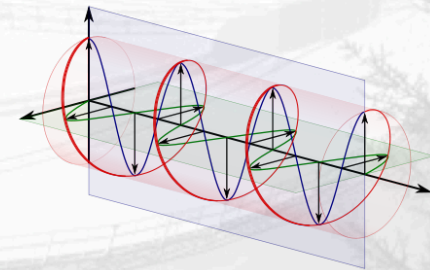
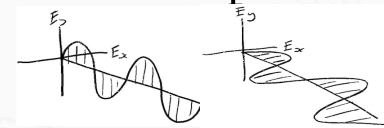
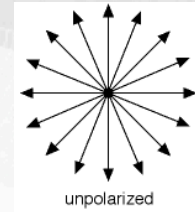
U -> Polarisation angle

V -> Circular polarisation (R=1, L=-1)



Take a minute to discuss:

- What is unpolarised light?
- What are the two linear polarisation components?
- What is circular polarisation?
- What is elliptical polarisation?
- What is the **purpose** of the Stokes parameters?



I, Q, U, V



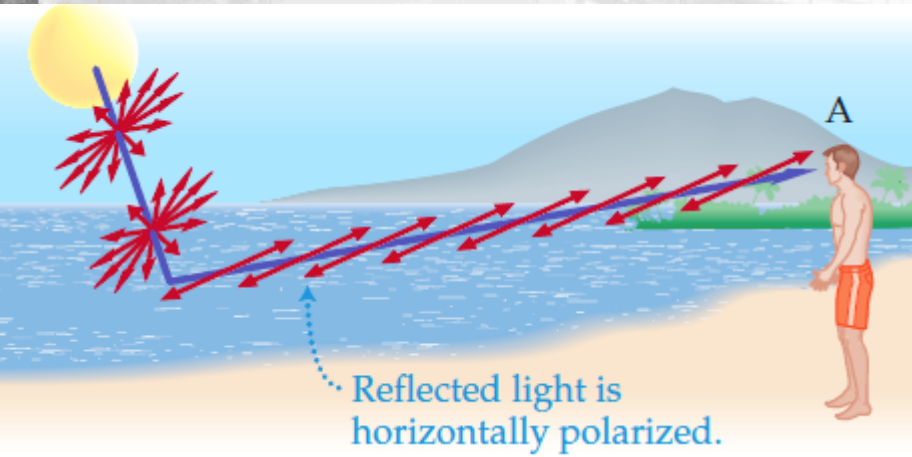
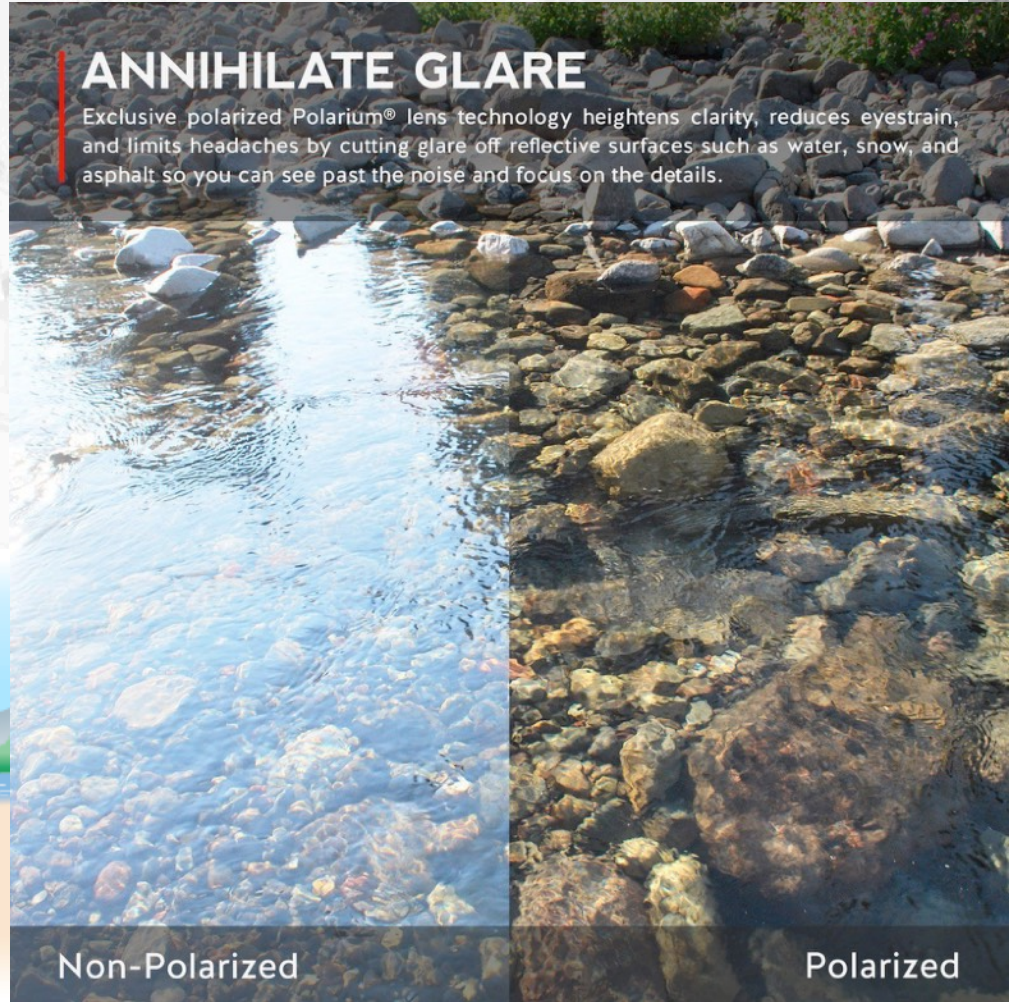
A large, white, parabolic satellite dish antenna is the central focus of the image. It is supported by a complex metal structure and is situated in a dense forest of tall evergreen trees. The dish is oriented towards the sky. The entire image is overlaid with a semi-transparent grey filter. The text 'Polarisation in nature' is centered over the dish.

Polarisation in nature

Polarisation in nature

Polarisation is everywhere

Reflections

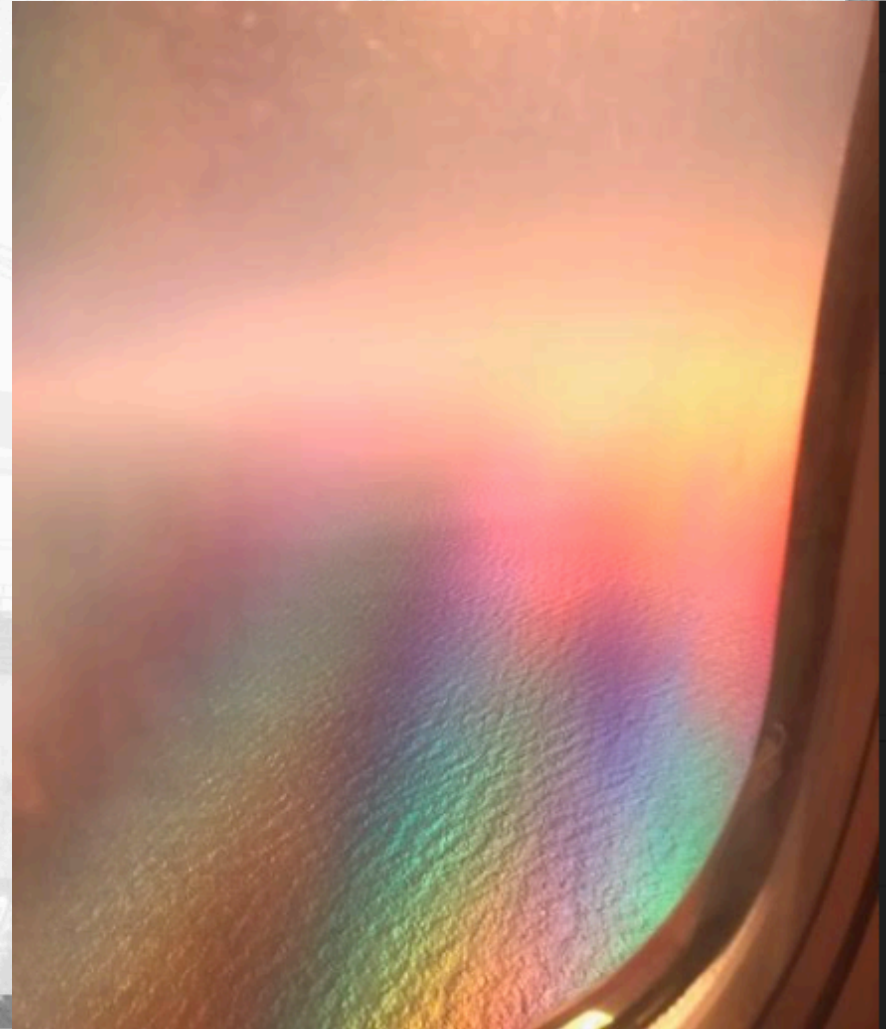


Polarisation in nature

Polarisation is everywhere

Reflections

Weird colours



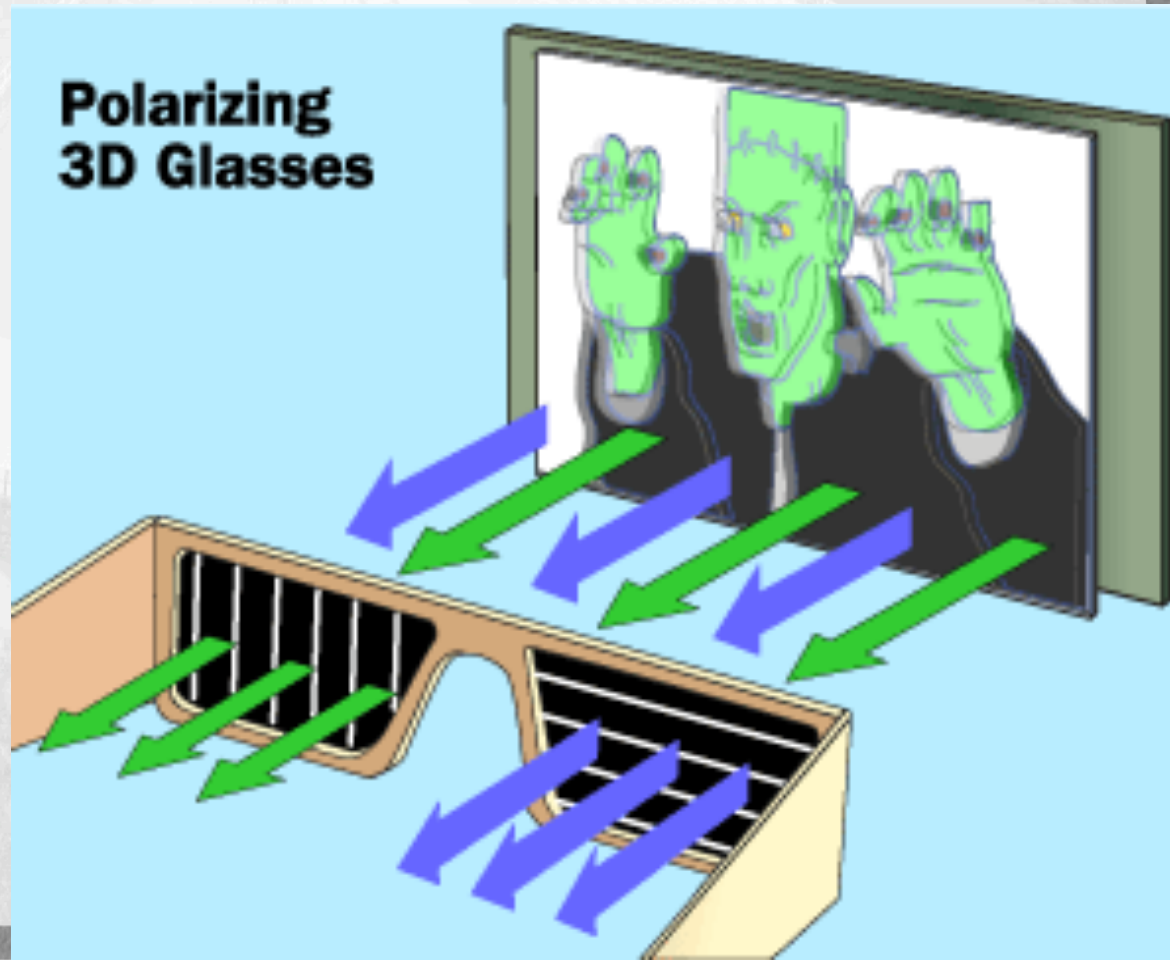
Polarisation in nature

Polarisation is everywhere

Reflections

Weird colours

3D movies



Polarisation in nature

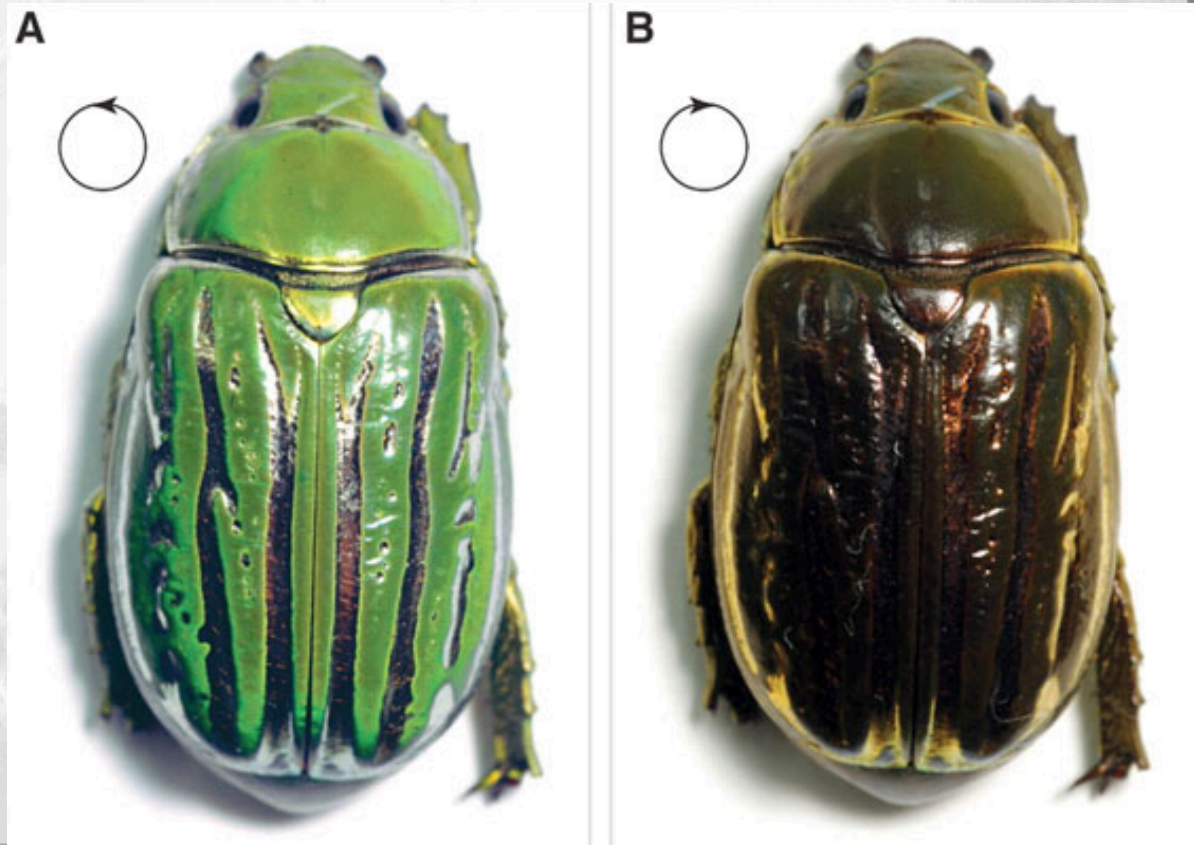
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Reflections

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3D movies

This beetle



Polarisation in nature

Polarisation is everywhere

Reflections

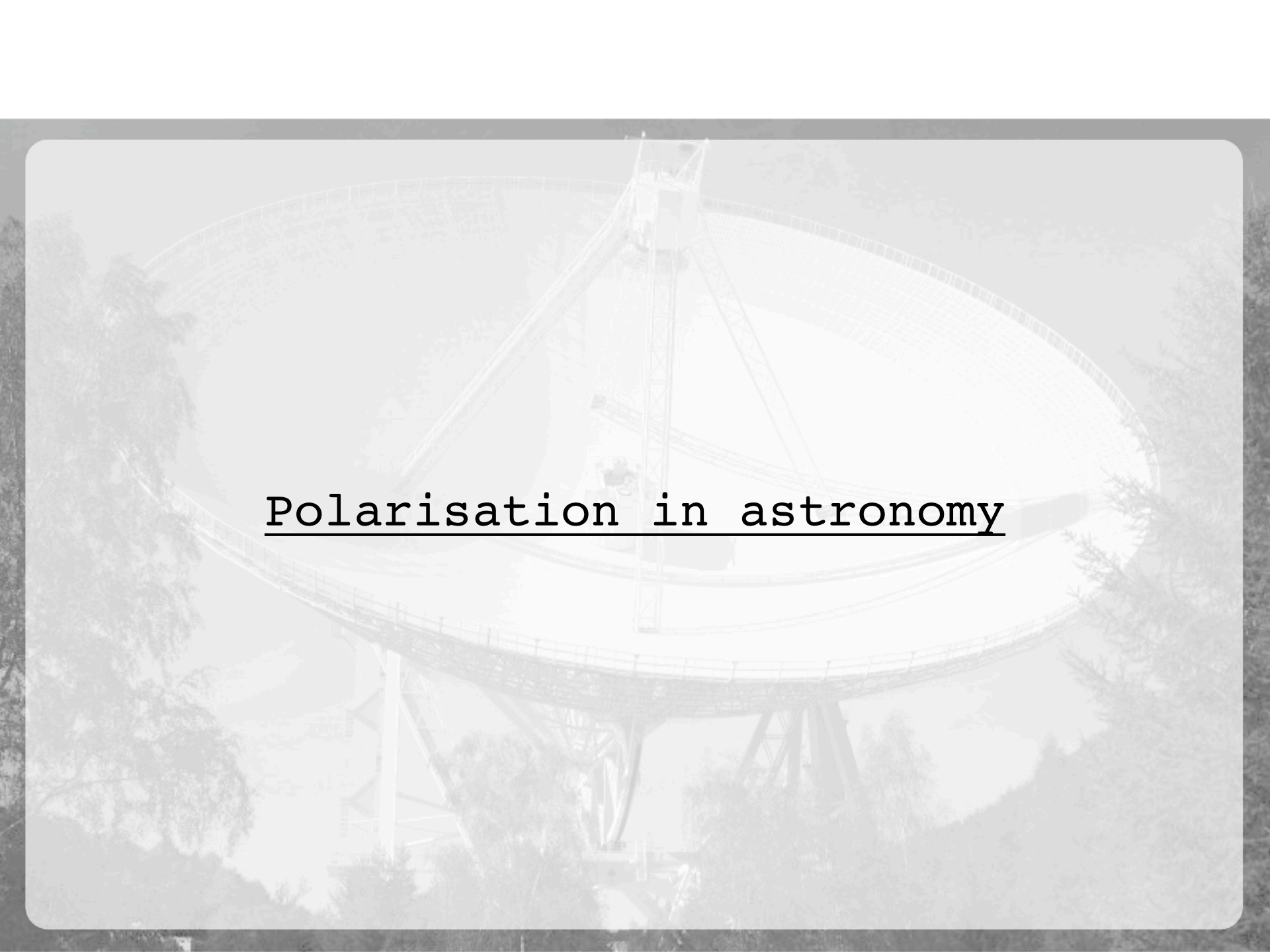
Weird colours

3D movies

This beetle

Bees and Vikings



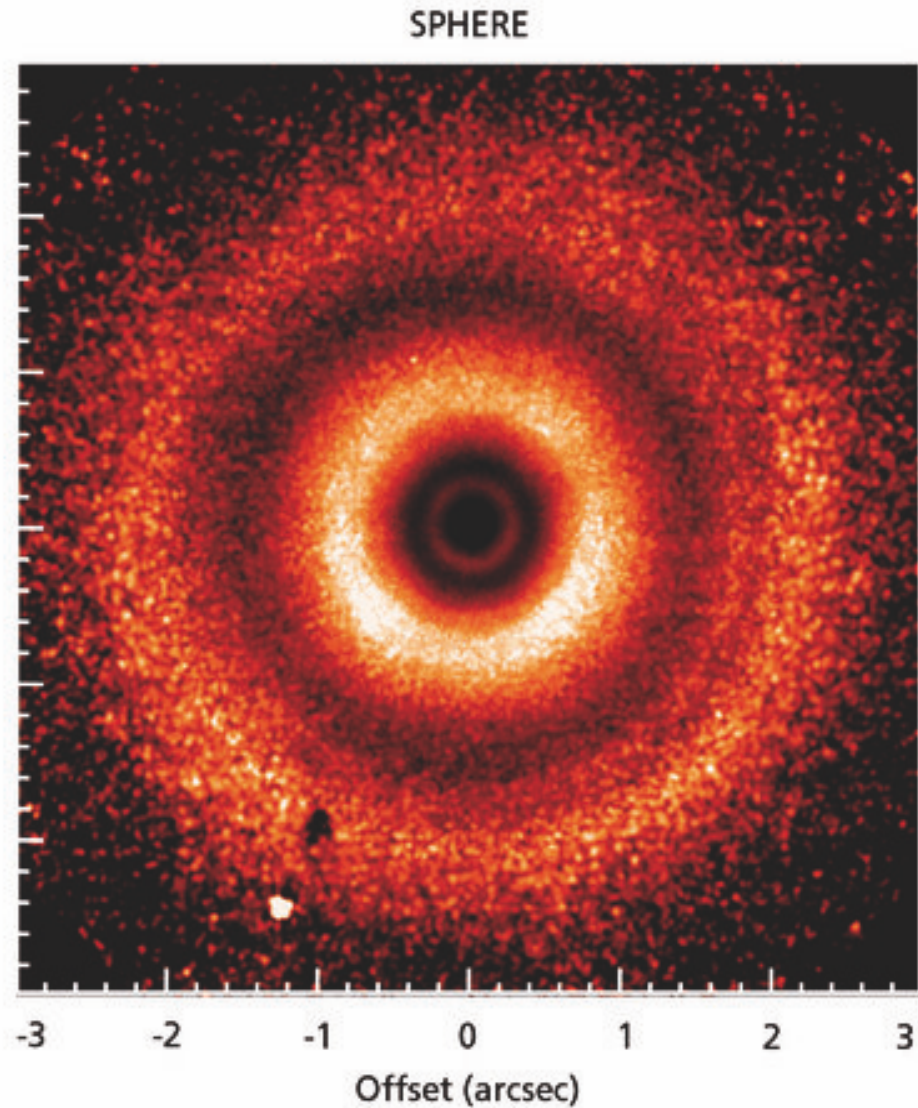


Polarisation in astronomy

Polarisation in astronomy

Polarisation is everywhere

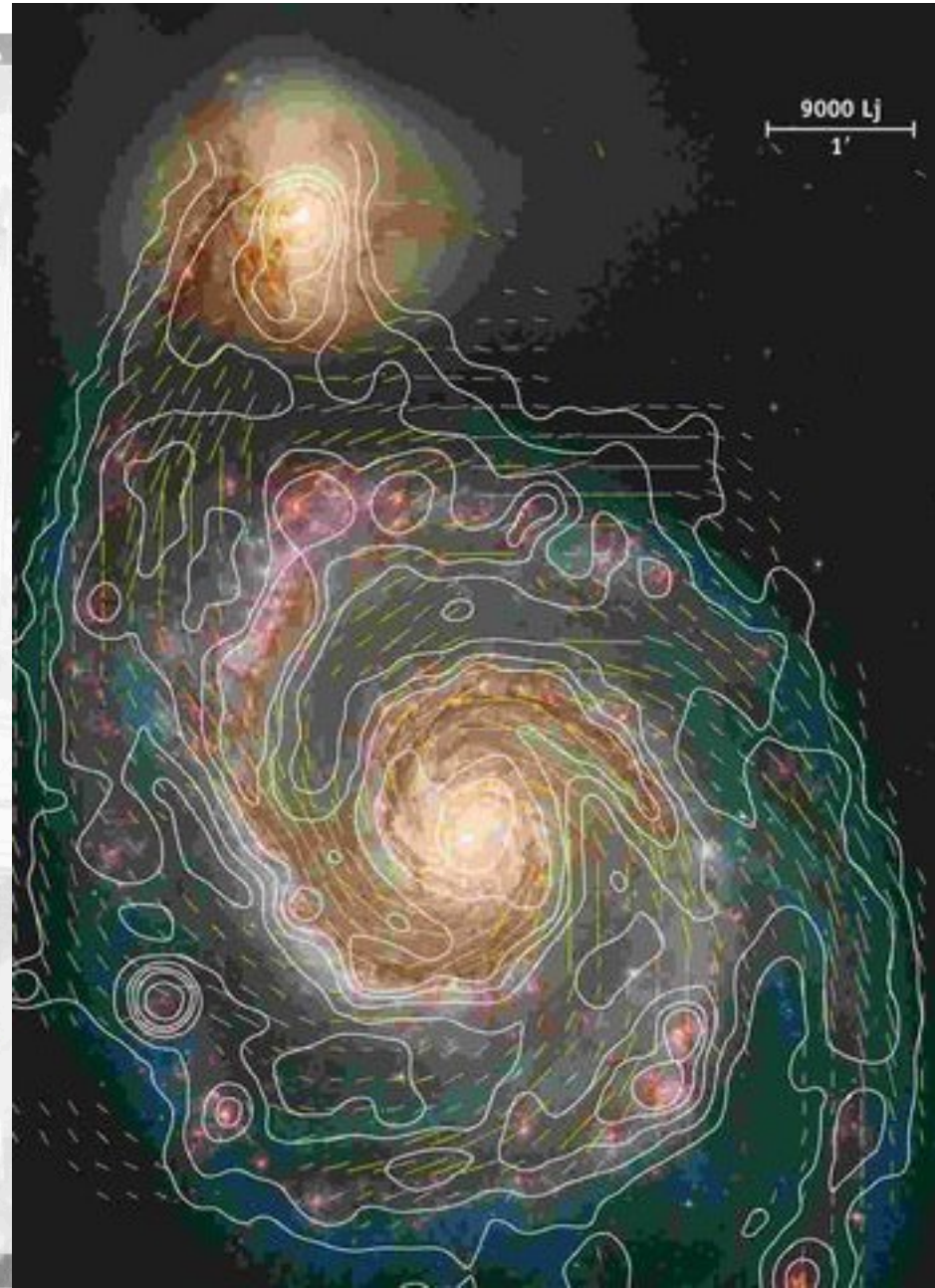
Reflections



Polarisation in astronomy

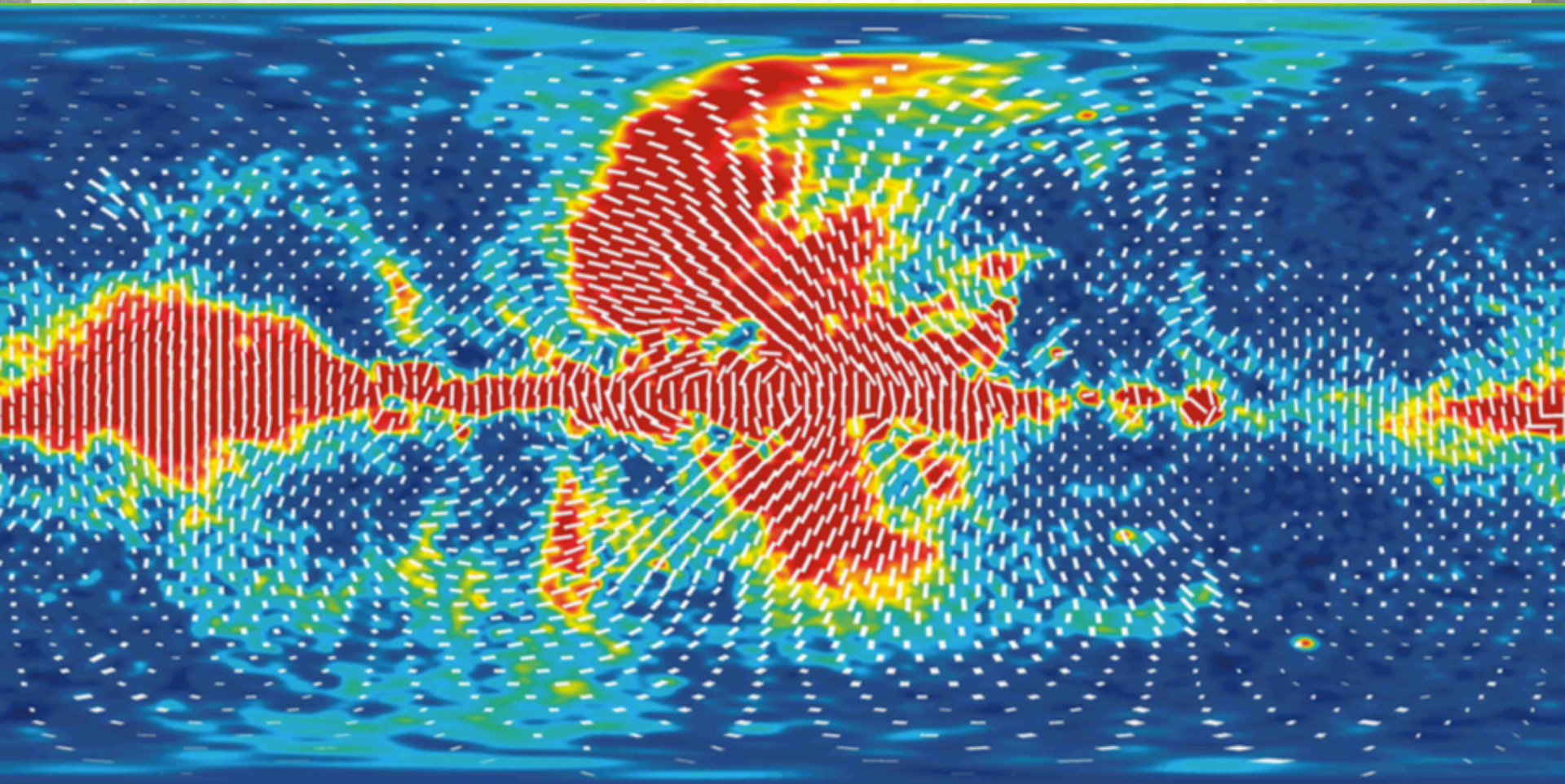
Polarisation is everywhere

Magnetic fields



Polarisation in astronomy

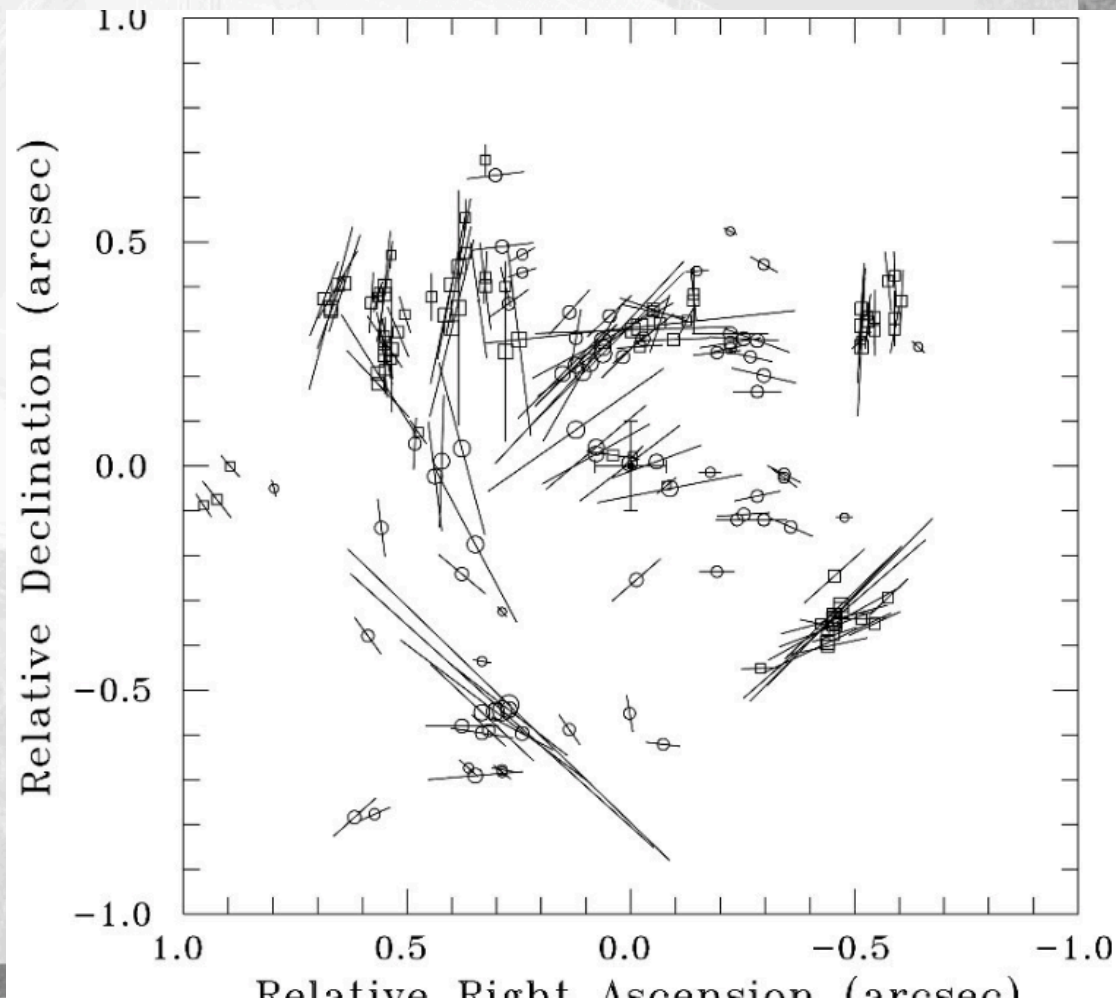
Polarisation is everywhere



Polarisation in astronomy

Polarisation is everywhere

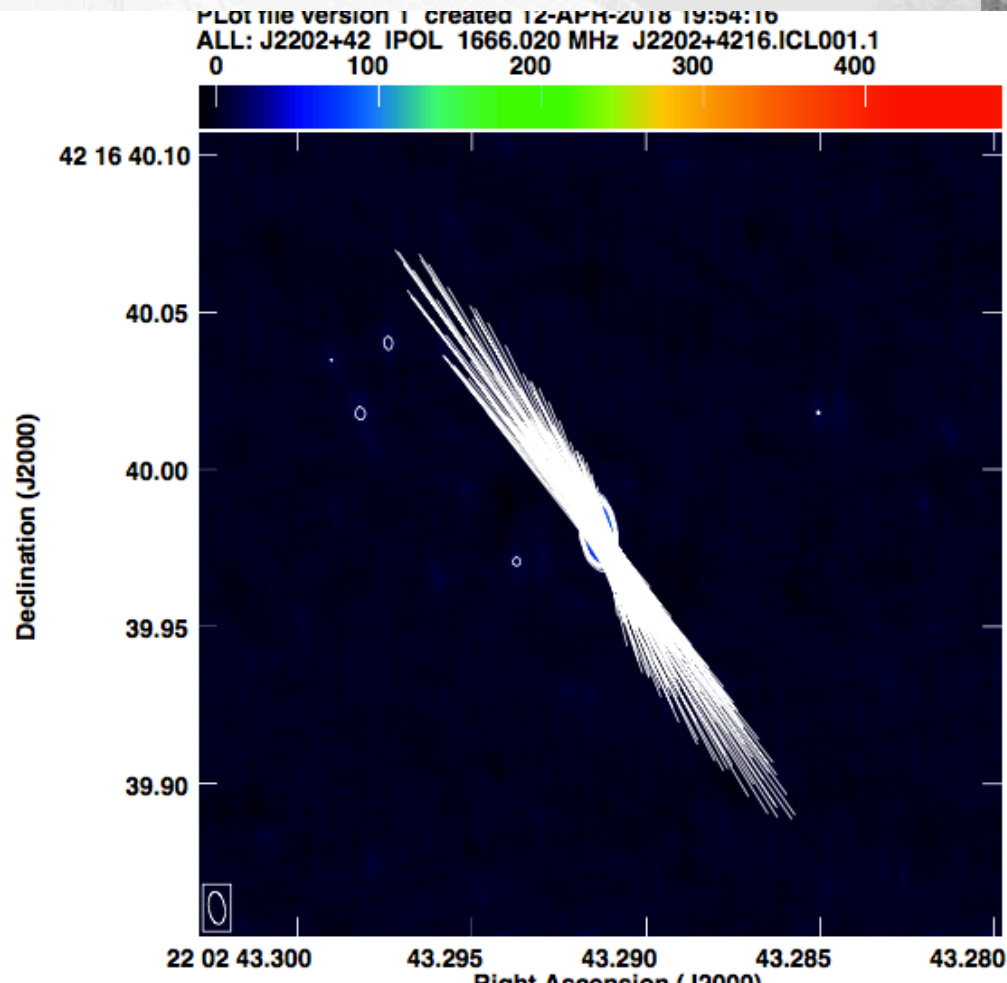
Magnetic fields



Polarisation in astronomy

Polarisation is everywhere

Magnetic fields



Polarisation in astronomy

Another use:

Increase your signal to noise by doubling your bandwidth; combine two polarisations

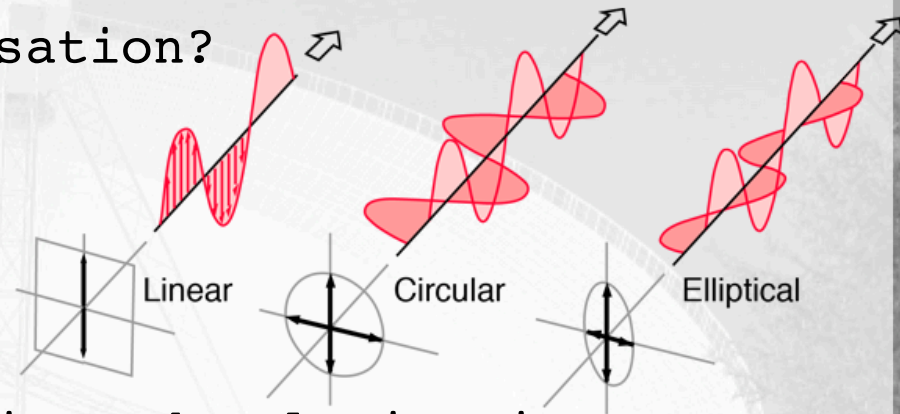
(for unpolarised sources).

Radiometer eq.

$$\sigma_T \approx \frac{T_{sys}}{\sqrt{\Delta\nu \cdot \tau}}$$

Take a minute to discuss:

- What is elliptical polarisation?



- When have you used/experienced polarisation in real life?
- What are some uses of polarisation in astronomy?
- What is the **purpose** of the Stokes parameters?

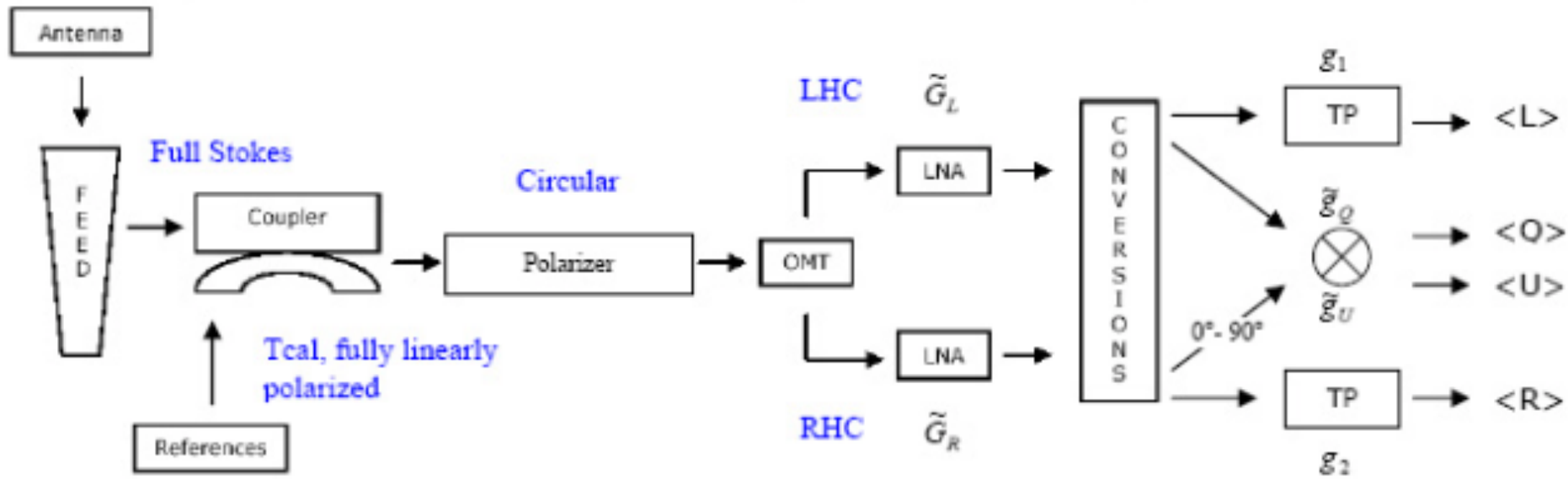
I, Q, U, V





How to measure
Polarisation in radio astronomy

Single-dish radio telescope



$$I = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

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Correlator products



“Direct” or “parallel”

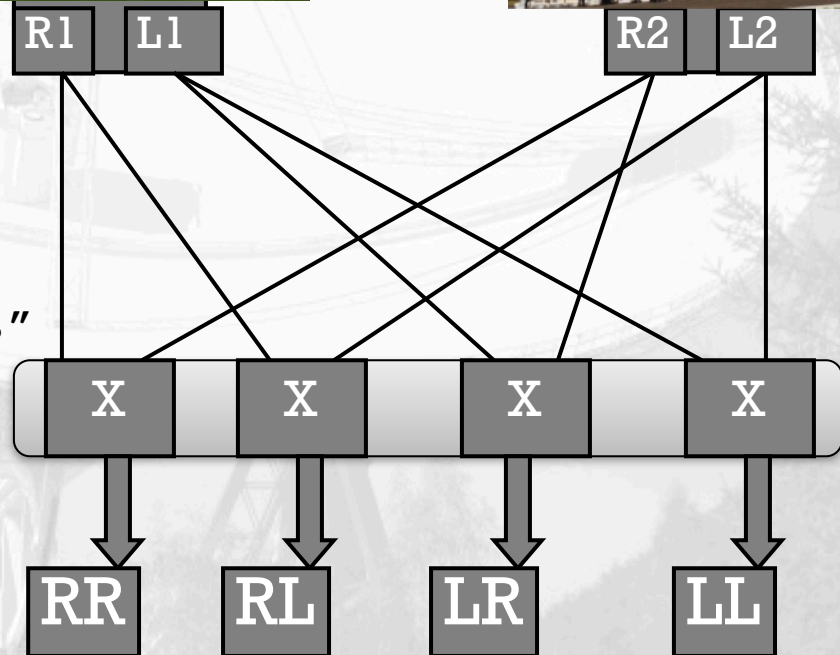
RR and LL

Strong correlation

“Cross Pol” or “cross hands”

RL and LR

Usually weak



Correlator products

$$I = R_{V_1V_2} + R_{H_1H_2}$$

$$Q = R_{V_1V_2} - R_{H_1H_2}$$

$$U = R_{V_1H_2} + R_{H_1V_2}$$

$$V = -i(R_{V_1H_2} - R_{H_1V_2})$$

$$I = R_{R_1R_2} + R_{L_1L_2}$$

$$Q = R_{R_1L_2} + R_{L_1R_2}$$

$$U = -i(R_{R_1L_2} - R_{L_1R_2})$$

$$V = R_{R_1R_2} - R_{L_1L_2}$$

Where R_{xx} is the 'correlator response'

- similar signals \rightarrow high R
- not similar signals \rightarrow small R

Interferometers using two polarisations are very effective at measuring pol. properties of a signal

Correlator products

$$I = R_{V_1 V_2} + R_{H_1 H_2}$$

$$Q = R_{V_1 V_2} - R_{H_1 H_2}$$

$$U = R_{V_1 H_2} + R_{H_1 V_2}$$

$$V = -i(R_{V_1 H_2} - R_{H_1 V_2})$$

$$I = R_{R_1 R_2} + R_{L_1 L_2}$$

$$Q = R_{R_1 L_2} + R_{L_1 R_2}$$

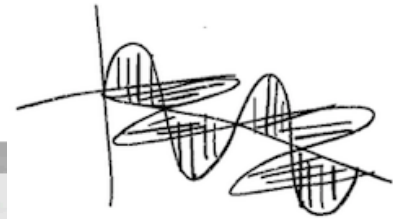
$$U = -i(R_{R_1 L_2} - R_{L_1 R_2})$$

$$V = R_{R_1 R_2} - R_{L_1 L_2}$$

Requires very careful data reduction!!

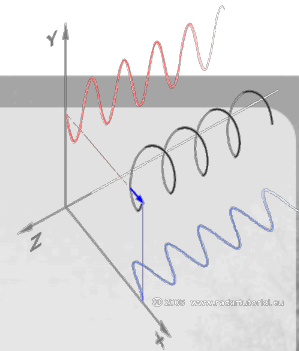
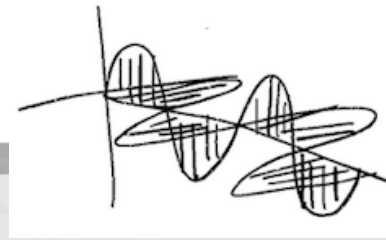
But if it works, it provides very valuable information

Summary



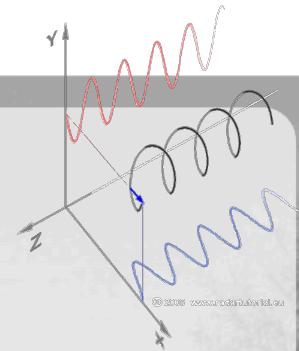
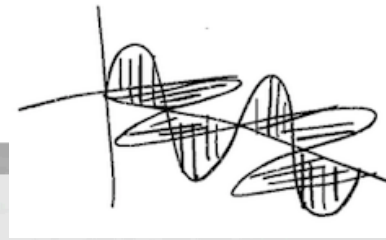
- EM waves can be decomposed into orthogonal E_x and E_y
- Linear polarisation can be Hor., Ver., or some PA
- When E_x and E_y are out of phase by $\pi/2$ we get circular polarisation
- Signals are usually elliptically polarised; a mix of linear and circular polarisation.
- The Stokes parameters fully describe the polarisation state of a signal
- Radio telescopes are well suited to measuring polarisation (correlator gives Stokes parameters)
- Polarisation reveals hidden information in astronomy

Summary

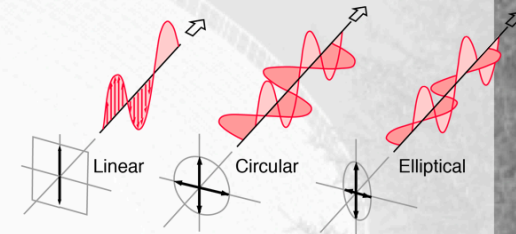


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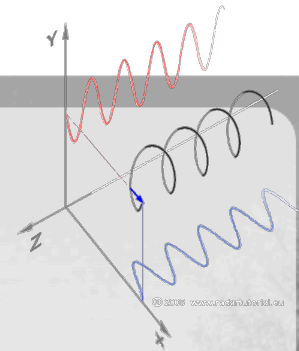
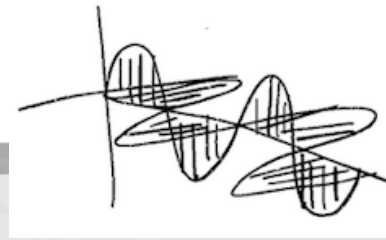
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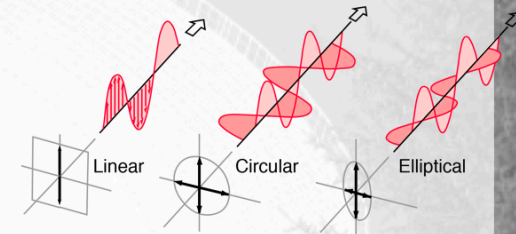
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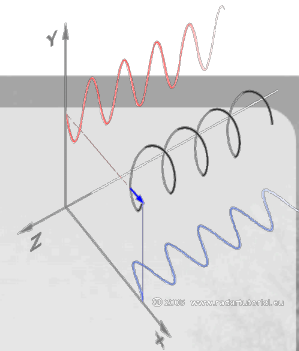
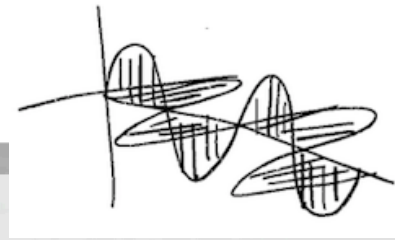
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