Low Frequency Radio-Interferometers for Radio-Astronomy/Cosmology

Patrice M. OKOUMA

NOMMO ASTRONOMIA

RHODES UNIVERSITY
Where leaders learn

Outline

Motivation

Low Frequency (< 1GHz) radio-interferometers (LFRi) for (West) Central Africa : A two-phased approach

How to make a radio-interferometer

(0th order) **Motivation**

Radio-Astronomer's nightmare,

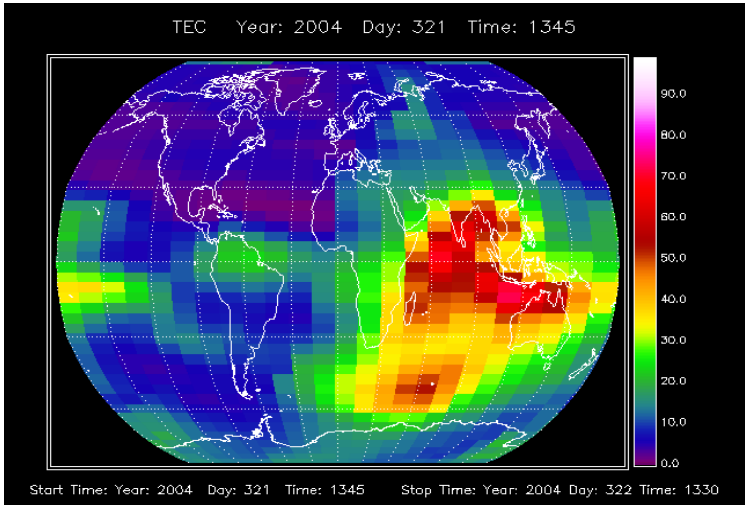
the **Ionosphere**,

is Space Scientists' Gem

==> Early Collaboration between

both communities is imperative.

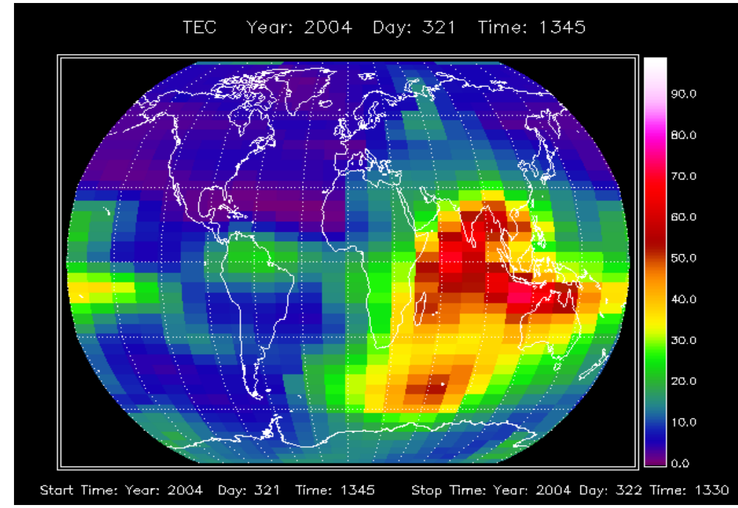
- Human Capital Gain(s)
-
- R&D
- Spin Off



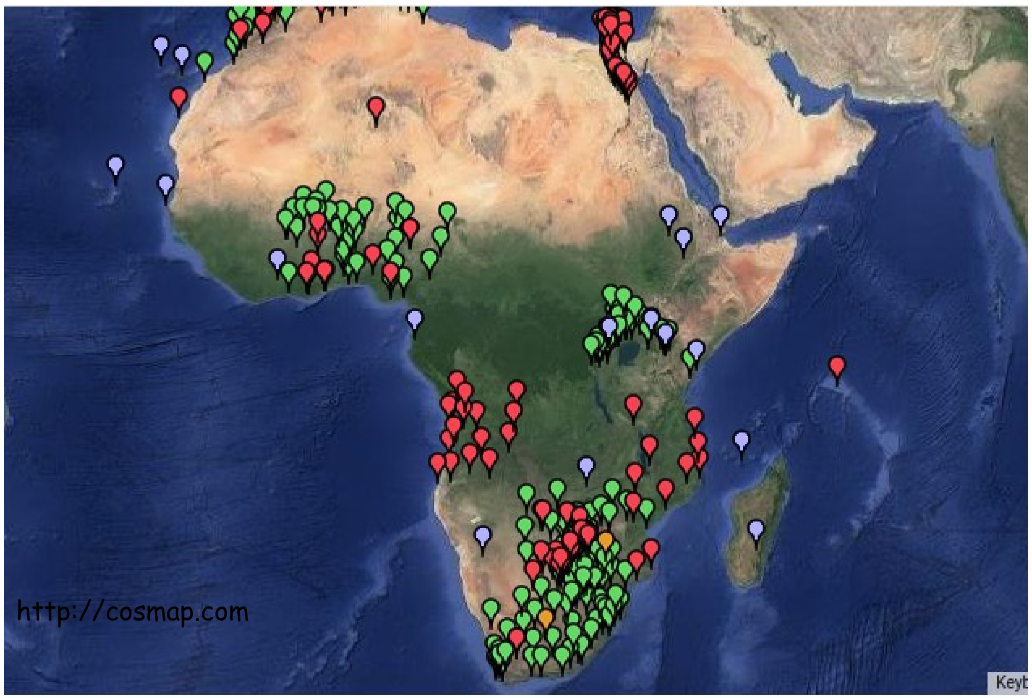
GAIM dynamic TEC model

(0th order) Motivation

Central Africa (incl. Gabon) is located where ….. is at its peak



GAIM dynamic TEC model



African GNSS CORS Network

- Sparse grid of stations
- Not all yet in real-time
- Accessibility
- *Most stations were donated*

Since some LFRi's can probe the Ionosphere,

What if we incrementally set up LFRi's while building up expertise in LFRi ?

Gabon as a test bed
For West Central Africa (WCA) ?

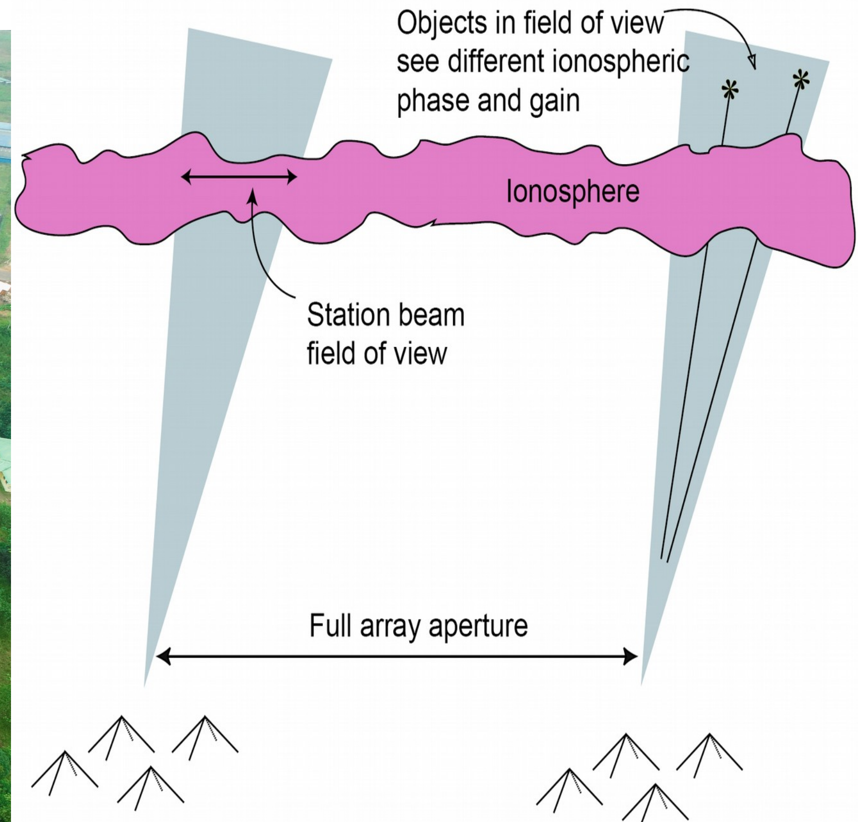
(Image courtesy of Gabon Space Agency (AGEOS : www.ageos.ga)

Gabon as a test bed
For West Central Africa (WCA) ?

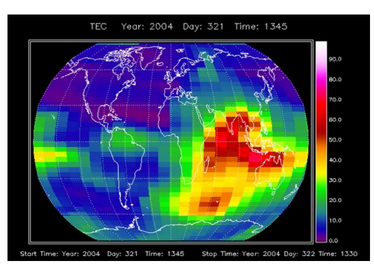
A number of GPS stations on their way to monitor Total Electron Content (TEC)
At this Unique Equatorial Latitute

Gabon as a Test Bed
For West Central Africa (WCA) ?

(Image courtesy of Gabon Space Agency (AGEOS : www.ageos.ga)



Images courtesy of C. Watts (LWA collaboration)



GAIM dynamic TEC model

- **Build and maintain Synergy (Space Science + radio-astro/cosmo) Within a world leading Niche area.**
- **Ownership of Value Chain (Human capital Dev + R&D + Spin Off)**

LFRi's for (West) Central Africa: A two-phased approach

Phase 1 : Proof-of-concept

The **T**ransient **A**rray **R**adio **T**elescope (TART)
- A Radio Interferometer operarting in the GPS L1 Band (centered at ~ 1575 MHz)

Phase 1 : Scale up

Nth iteration of TART

Phase 2 : Build **IT**

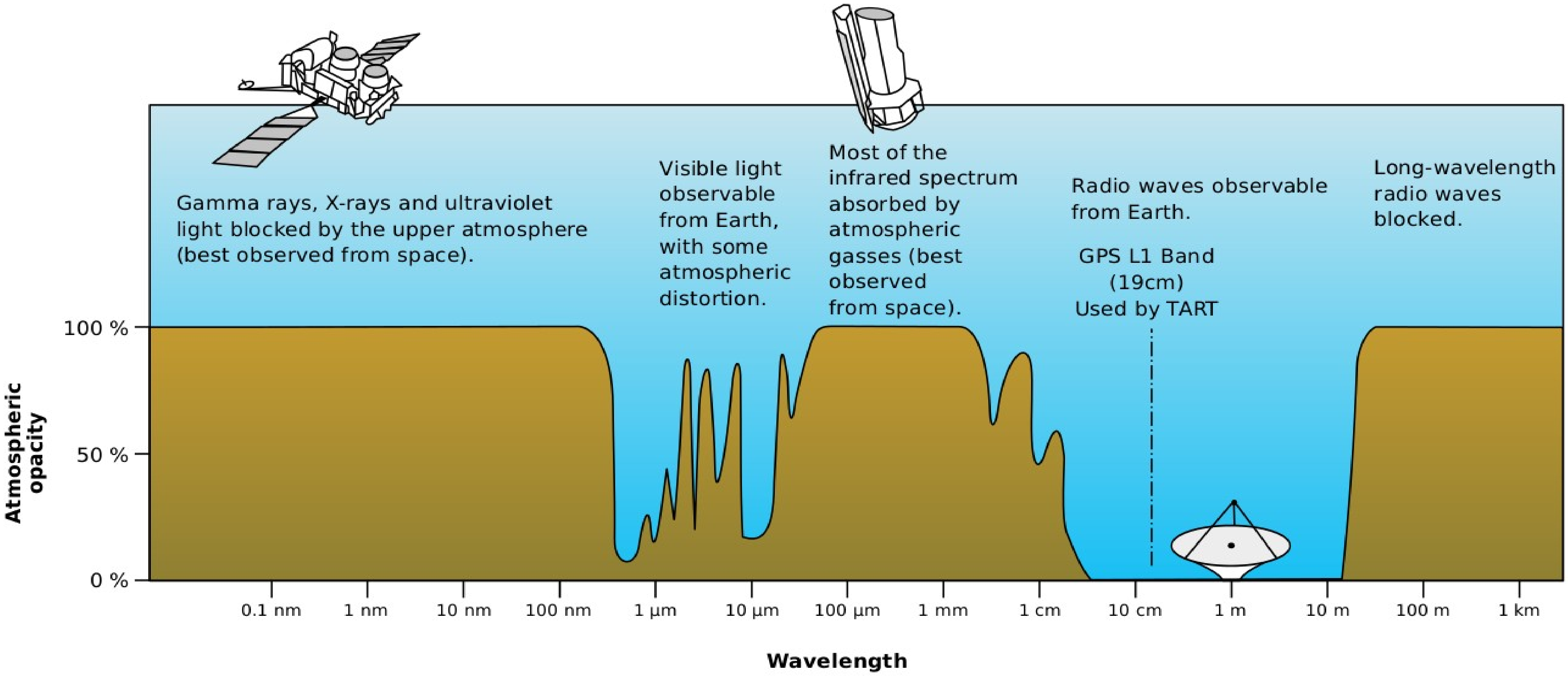
A Scaled Down version of The Long Wavelength Array (SD LWA)?
IT = SDLWA

Phase 2 : Spread **IT**

LFRi's for (West) Central Africa: A two-phased approach

Phase 1 : Proof-of-concept

The **T**ransient **A**rray **R**adio **T**elescope (TART)
- A Radio Interferometer operarting in the GPS L1 Band (centered at ~ 1575 MHz)



(Image courtesy of NASA)

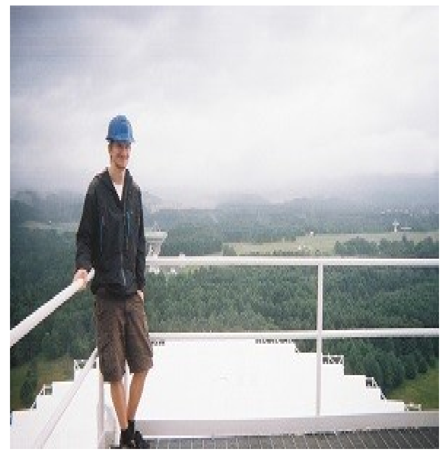
LFRi's for (West) Central Africa: A two-phased approach

Phase 1 - Proof-of-concept : The **T**ransient **A**rray **R**adio **T**elescope (TART)

The Team

SKA Research Chair
Oleg Smirnov
Rhodes Univ (South Africa)

Tim Molteno
Otago Univ (New Zealand)



Maximilian Scheel
Otago Univ (New Zealand)

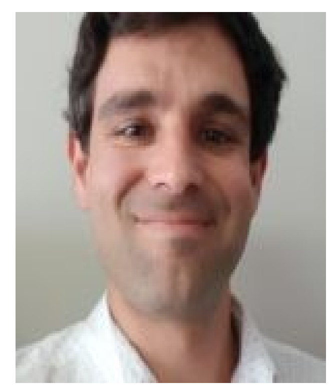
Marcelin Atemkeng
Rhodes Univ (South Africa)

Stanley Kuja
Rhodes Univ (South Africa)

Phill Brown
Otago Univ (New Zealand)

Sonia Ghosh
Rhodes Univ (South Africa)

Rikus Human
Stellenbosch Univ (South Africa)

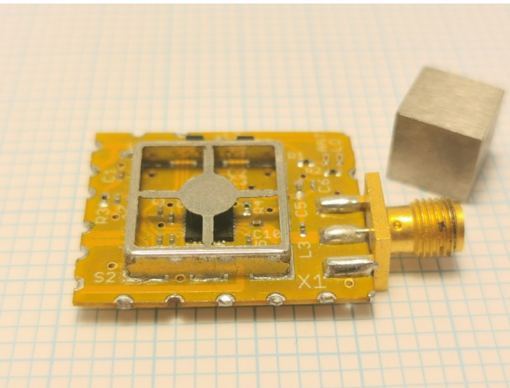


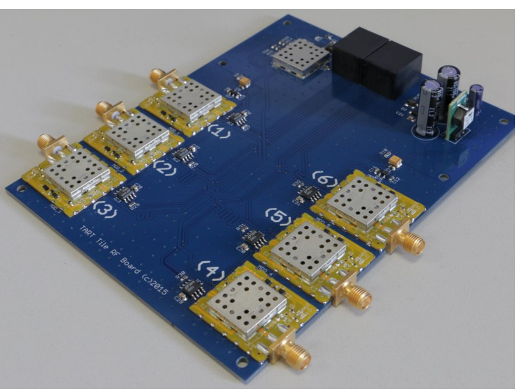
Danie Ludick
Stellenbosch Univ (South Africa)

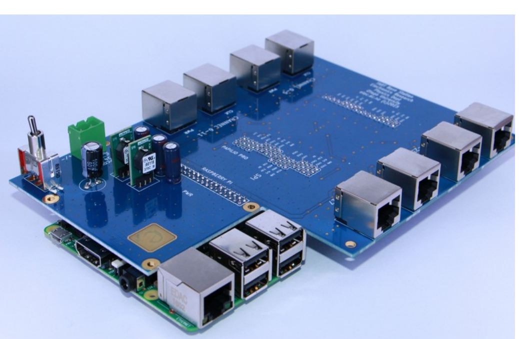
Patrice Okouma
Rhodes Univ (South Africa)

LFRi’s for (West) Central Africa: A two-phased approach

The **T**ransient **A**rray **R**adio **T**elescope (TART)
- A Radio Interferometer operarting in the GPS L1 Band (centered at ~ 1575 MHz)







mage courtesy of Wikipedia)

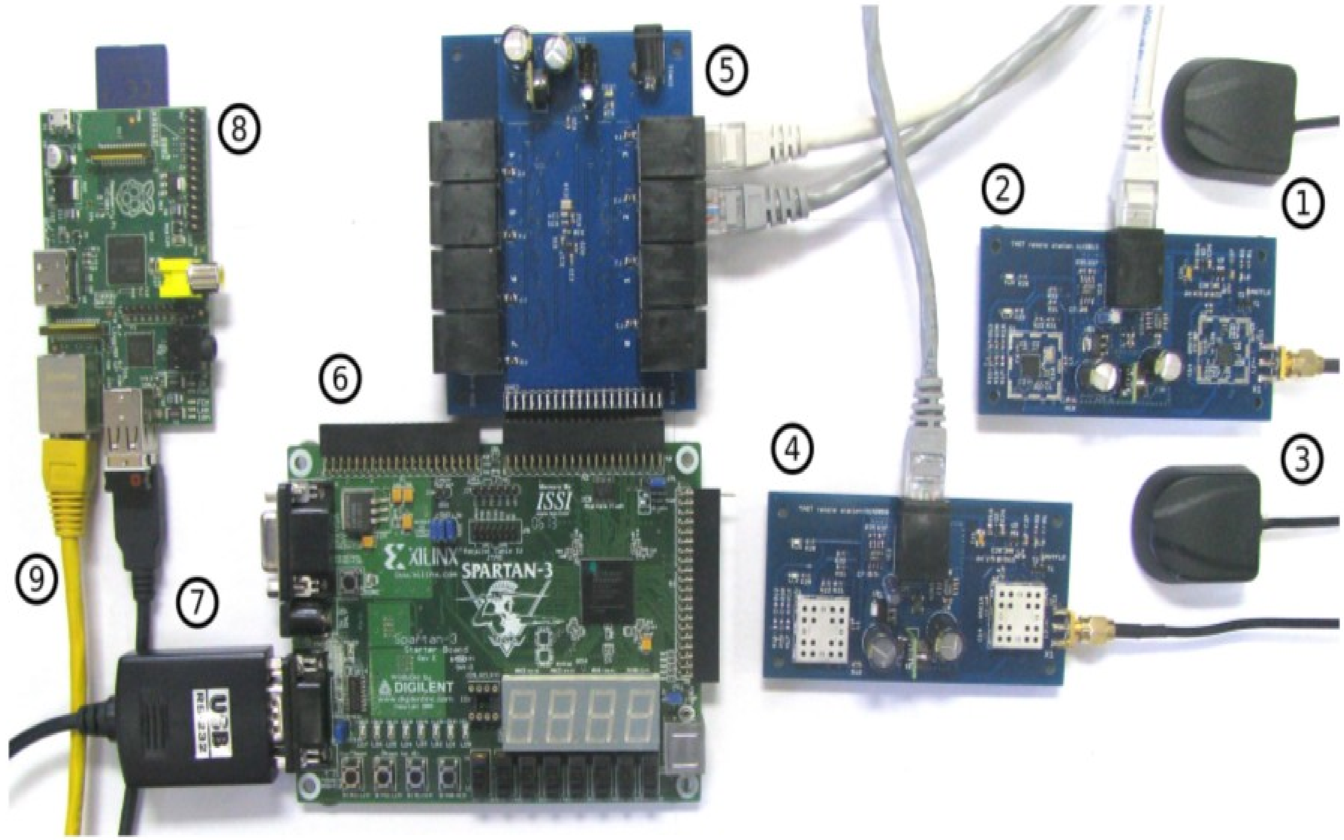


Figure 1.4: The Transient Array Radio Telescope shown with two of eight channels installed. Signals from active GPS patch antennas (1 and 3) are digitised by radio modules (2 and 4). The signal is sent to the base station via CAT-6 cables. The base station comprises the base station board (5), a Spartan 3 FPGA development board (6), a RS-232 to USB converter (7), and a Raspberry Pi computer (8). The Pi is connected to a network via Ethernet cable (9). Note that one of the radio modules (2) is shown with RF shielding removed for clarity.

Source: C. Shaw Msc thesis

LFRi's for (West) Central Africa: A two-phased approach

The **T**ransient **A**rray **R**adio **T**elescope (TART)
- A Radio Interferometer operarting in the GPS L1 Band (centered at ~ 1575 MHz)

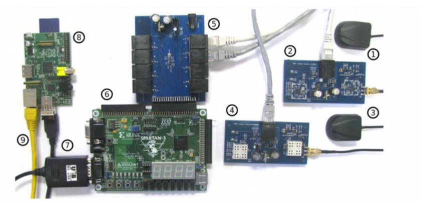


Figure 1.4: The Transient Array Radio Telescope shown with two of eight channels installed. Signals from active GPS patch antennas (1 and 3) are digitised by radio modules (2 and 4). The signal is sent to the base station via CAT-6 cables. The base station comprises the base station board (5), a Spartan 3 FPGA development board (6), a RS-232 to USB converter (7), and a Raspberry Pi computer (8). The Pi is connected to a network via Ethernet cable (9). Note that one of the radio modules (2) is shown with RF shielding removed for clarity.

Source: C. Shaw Msc thesis

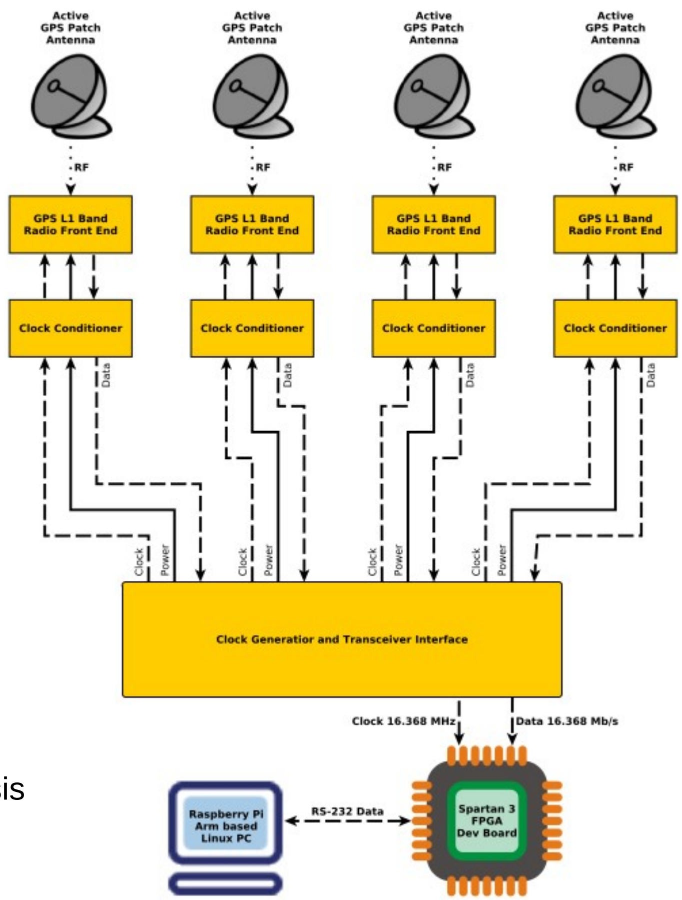
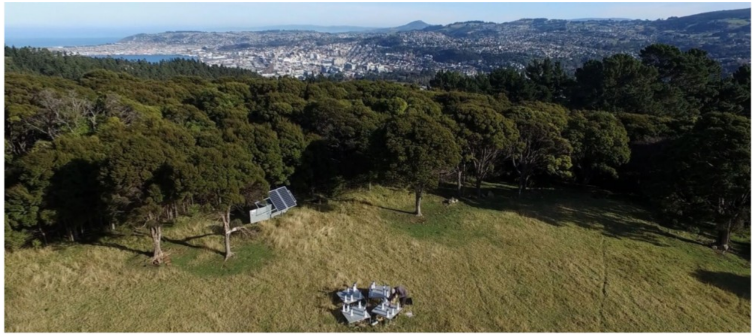


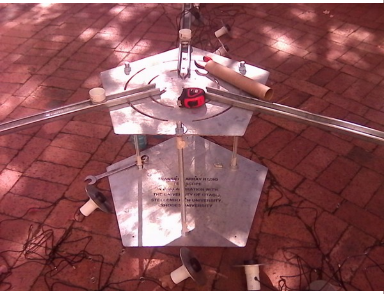
Figure 1.5: The TART consists of up to eight radio modules (4 shown) which are connected to a central base station via Cat-6 cables. Each radio module incorporates a clock conditioner, radio front end, and GPS patch antenna.The base station provides a clock signal (16.368 MHz) and power supply (24 VDC). The incoming data is buffered by the FPGA and transmitted over an RS-232 link to a PC.

Image courtesy of Wikipedia



Source: M. Scheel PhD thesis

Scale up TART @ Rhodes Univ

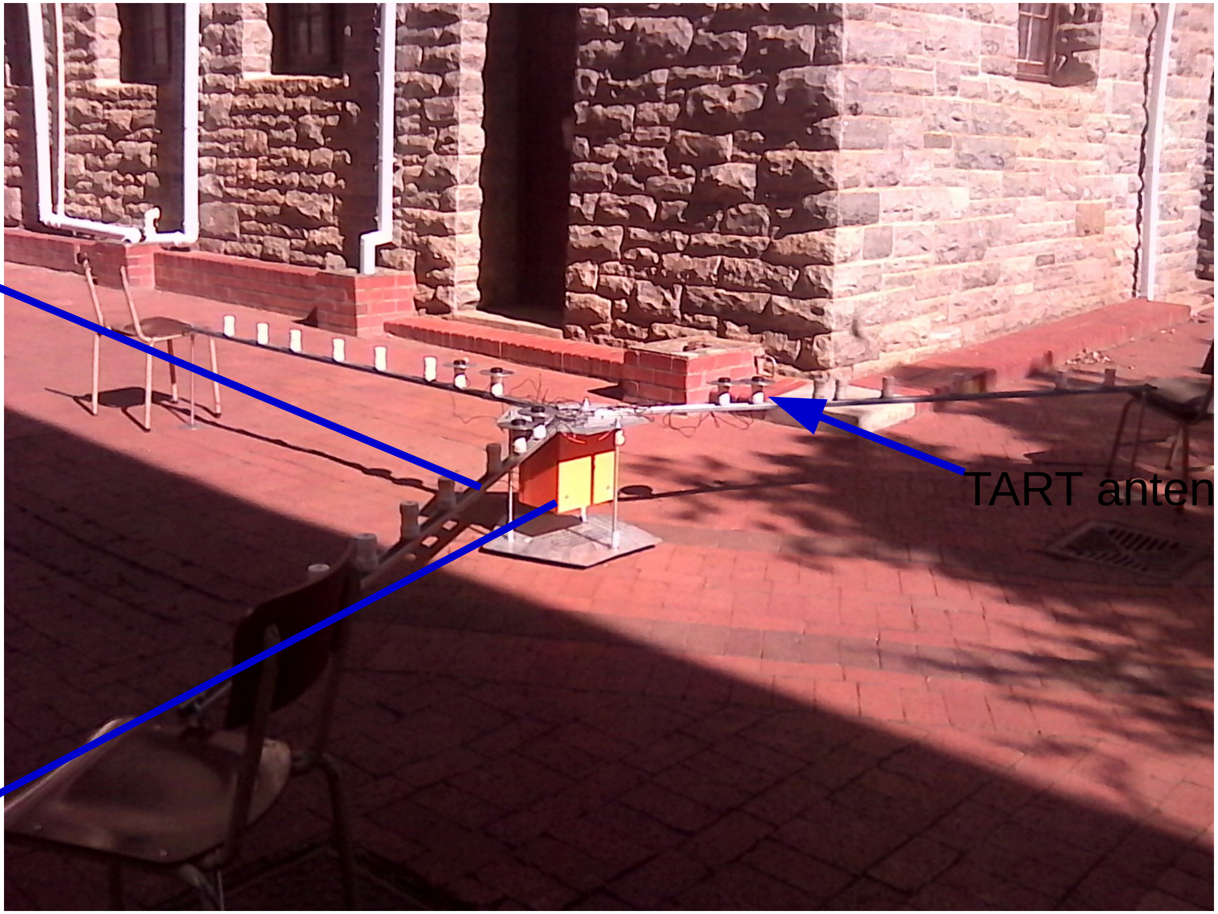





Expenditure on TART?

TART operational cost < Euros 1000/year

TART rails: ~ Euros 500



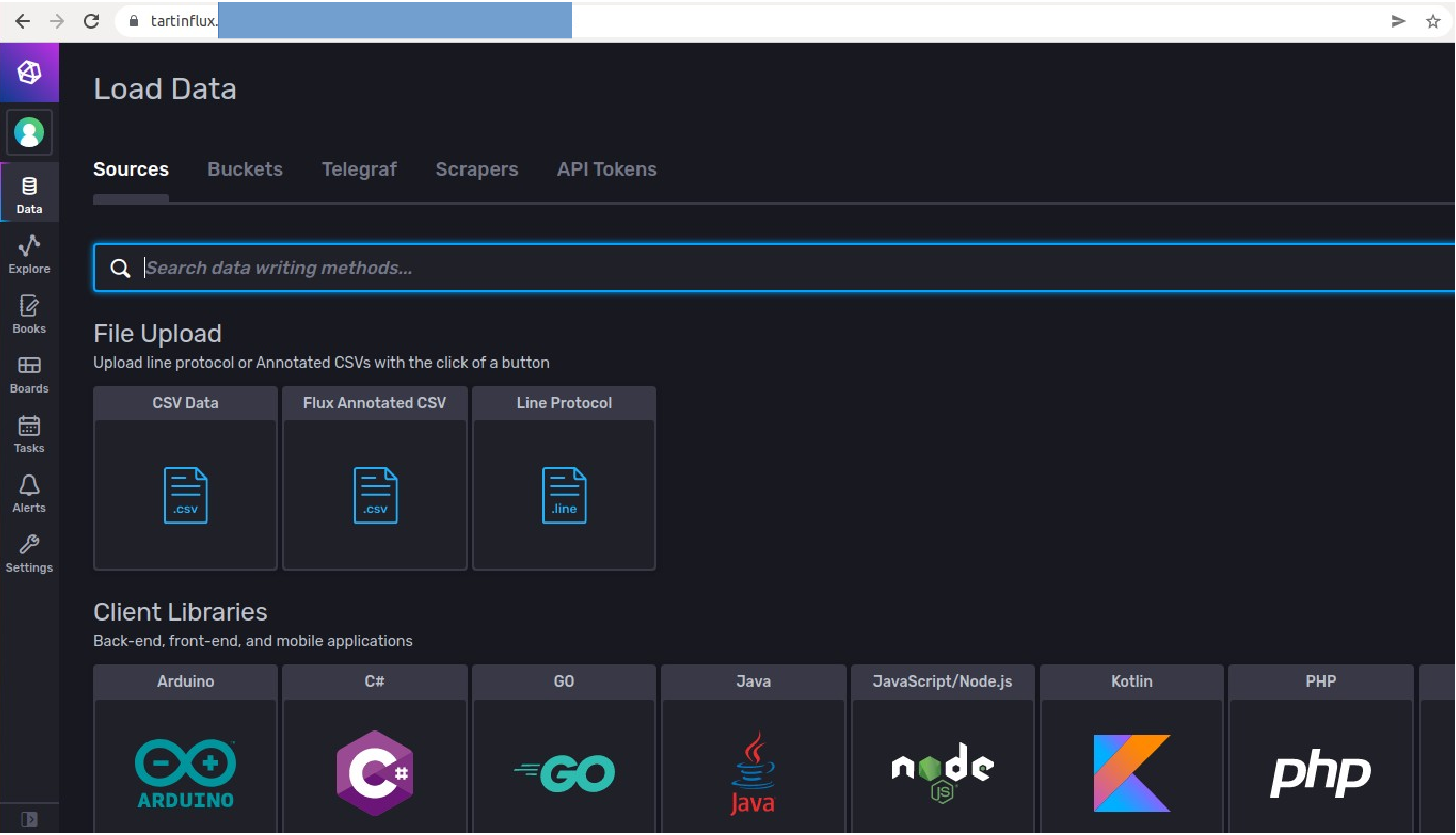
TART antenna: ~ Euros 2/ each

TART back end: ~ Euros 2000

TART power consumption: < 100 Watts

Total Expenditure on TART ~ Euros

Data Back end

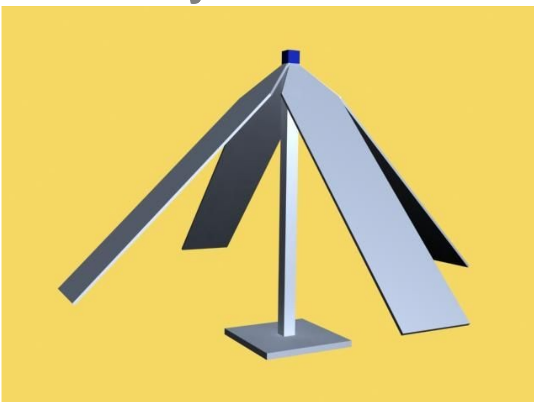


Spread TART to Central Africa With Gabon as a key Testbed

Beyond TART?

Beyond TART : A Scaled Down version of The Long Wavelength Array (SDLWA) ?

Primary Element Model



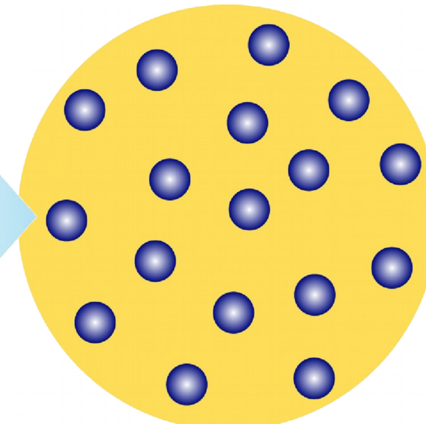
~3 m

~4 m

LWA Station (256 antennas)

100 m

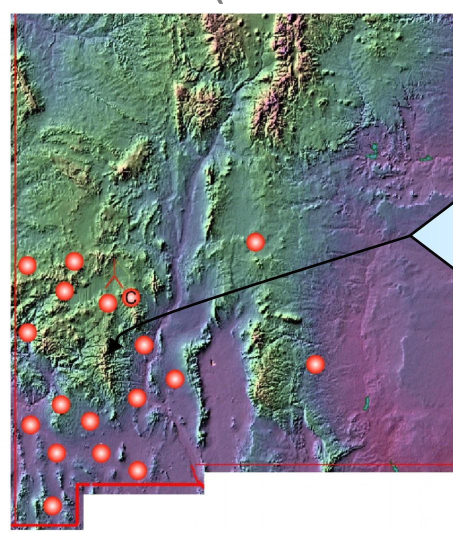
Core Overview



5 km

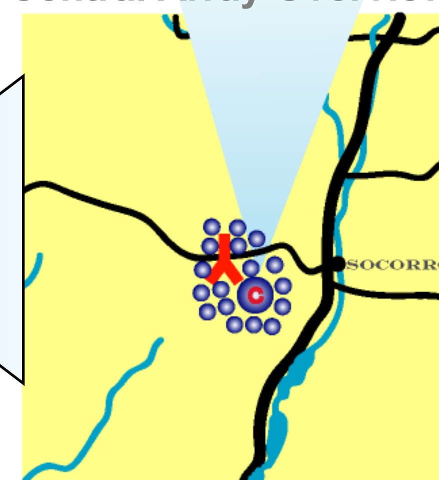
Primary Element for Demonstrator Array

Full LWA (~50 stations)



400 km

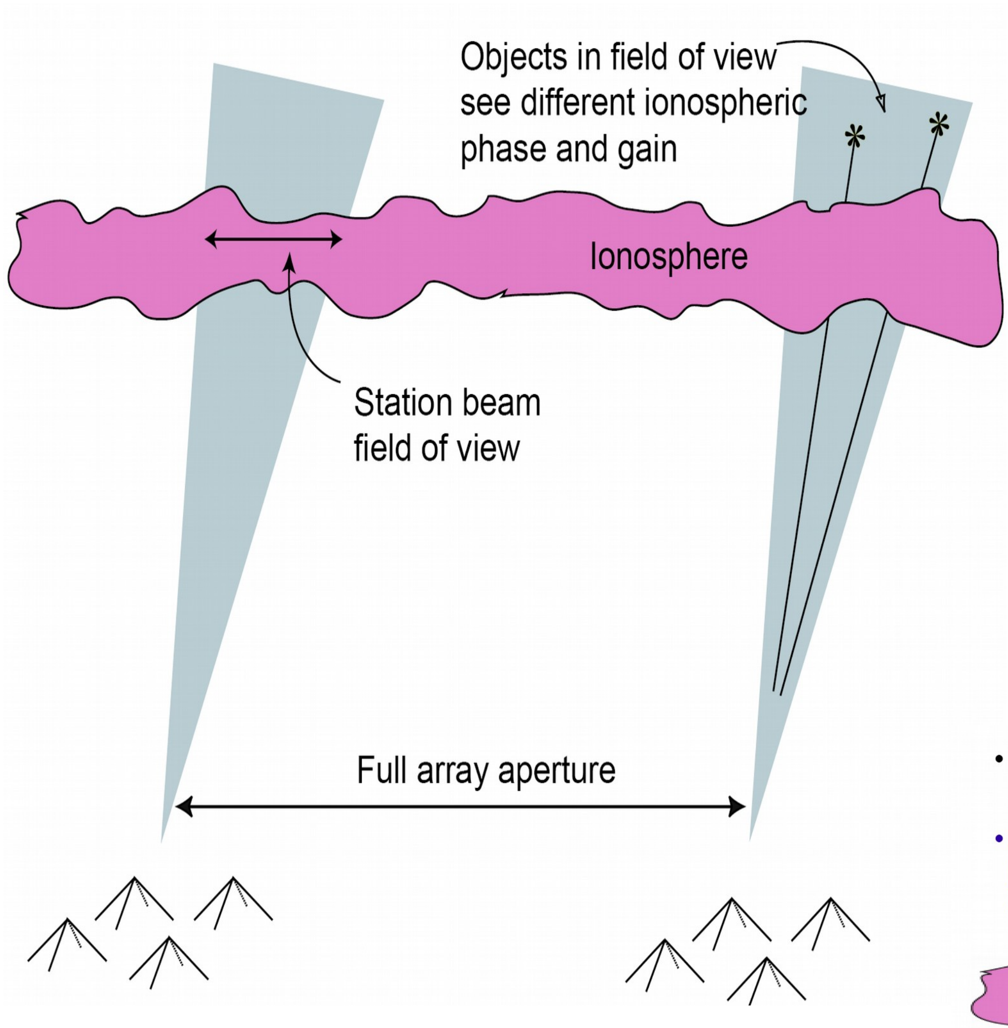
Central Array Overview



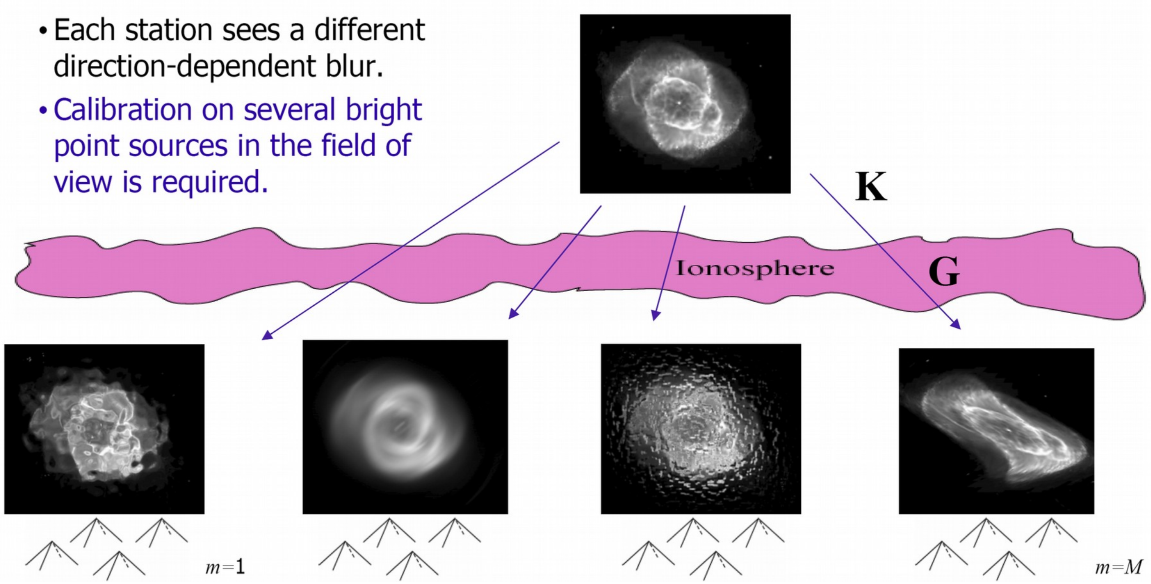
50 km

Images courtesy of C. Watts (LWA collaboration)

Ionosphere Through a SDLWA



Scaled Down means
Only the Ionosphere
As initial science driver

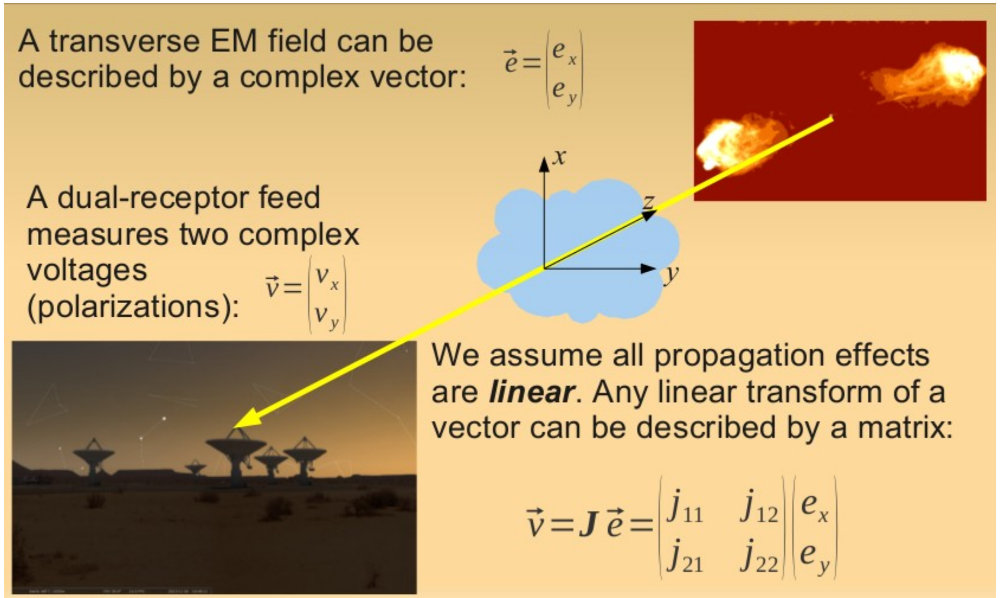


Images courtesy of C. Watts (LWA collaboration)

Ionosphere Through a RI

A transverse EM field can be described by a complex vector: $\vec{e}=\begin{pmatrix} e_x \\ e_y \end{pmatrix}$

A dual-receptor feed measures two complex voltages (polarizations): $\vec{v}=\begin{pmatrix} v_x \\ v_y \end{pmatrix}$



We assume all propagation effects are ***linear***. Any linear transform of a vector can be described by a matrix:

$$\vec{v}=\boldsymbol{J}\vec{e}=\begin{pmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{pmatrix}\begin{pmatrix} e_x \\ e_y \end{pmatrix}$$

Images courtesy of O. Smirnov (SKA South Africa)

Correlation

$$\vec{v}_p=\boldsymbol{J}_p\vec{e}$$

$$\vec{e}$$

$$\vec{v}_q=\boldsymbol{J}_q\vec{e}$$

$v_{xx}=\langle v_{px}v_{qx}^*\rangle$

$v_{yy}=\langle v_{py}v_{qy}^*\rangle$

$v_{xy}=\langle v_{px}v_{qy}^*\rangle$

$v_{yx}=\langle v_{py}v_{qx}^*\rangle$

The same signal reaches antennas ***p*** and ***q*** along two different paths. We then *correlate* the two sets of complex voltages.

The 2×2 Visibility Matrix

An interferometer *correlates* the vectors $\vec{v}_p, \vec{v}_q$:

$$v_{xx}=\langle v_{px}v_{qx}^*\rangle, v_{xy}=\langle v_{px}v_{qy}^*\rangle, v_{yx}=\langle v_{py}v_{qx}^*\rangle, v_{yy}=\langle v_{py}v_{qy}^*\rangle$$

Let us write this as a matrix product:

$$\boldsymbol{V}_{pq}=2\langle\vec{v}_p\vec{v}_q^\dagger\rangle=2\left\langle\begin{pmatrix} v_{px} \\ v_{py} \end{pmatrix}(v_{qx}^* \; v_{qy}^*)\right\rangle=2\begin{pmatrix} v_{xx} & v_{xy} \\ v_{yx} & v_{yy} \end{pmatrix}$$

($\langle\rangle$: time/freq averaging; $\dagger$: conjugate-and-transpose)

$\boldsymbol{V}_{pq}$ is also called the *visibility matrix.*

Antennas p,q measure $\vec{v}_p=\boldsymbol{J}_p\vec{e}$, $\vec{v}_q=\boldsymbol{J}_q\vec{e}$. Therefore:

$$\boldsymbol{V}_{pq}=2\langle(\boldsymbol{J}_p\vec{e})(\boldsymbol{J}_q\vec{e})^\dagger\rangle=2\langle\boldsymbol{J}_p(\vec{e}\vec{e}^\dagger)\boldsymbol{J}_q^\dagger\rangle=\boldsymbol{J}_p 2\langle\vec{e}\vec{e}^\dagger\rangle\boldsymbol{J}_q^\dagger$$

(making use of $(\boldsymbol{AB})^\dagger=\boldsymbol{B}^\dagger\boldsymbol{A}^\dagger$, and assuming $\boldsymbol{J}_p$ is constant over $\langle\rangle$)

The inner quantity is called the *coherency* or *brightness*, and (by definition of the Stokes parameters) is actually:

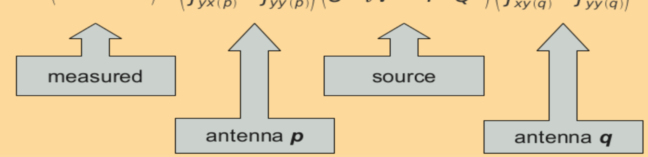
$$\boldsymbol{B}=2\langle\vec{e}\vec{e}^\dagger\rangle\equiv\begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}$$

$(I\equiv\langle|e_x|^2\rangle+\langle|e_y|^2\rangle=\langle e_x e_x^*\rangle+\langle e_y e_y^*\rangle,\quad Q\equiv\langle|e_x|^2\rangle-\langle|e_y|^2\rangle=\langle e_x e_x^*\rangle-\langle e_y e_y^*\rangle,$ etc.)

- The RIME, in its simplest form:

$$\boldsymbol{V}_{pq}=\boldsymbol{J}_p\boldsymbol{B}\boldsymbol{J}_q^\dagger$$

$$\begin{pmatrix} XX & XY \\ YX & YY \end{pmatrix}=\begin{pmatrix} j_{xx(p)} & j_{xy(p)} \\ j_{yx(p)} & j_{yy(p)} \end{pmatrix}\begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}\begin{pmatrix} j_{xx(q)}^* & j_{yx(q)}^* \\ j_{xy(q)}^* & j_{yy(q)}^* \end{pmatrix}$$



Total Expenditure on LWA : Euros ~ 300 000

Images courtesy of G. Taylor (LWA collaboration)

5/4/22, 12:24 AM LWA Order Info

Item	Description	Price	Availability *
LWA-FEE	Front-End Electronics, Active Balun for one crossed-dipole antenna (dual assembly)	US $525.50	2 to 3 weeks ARO
LWA-ANT	Crossed-dipole antenna including mast	US $904.85	2 to 3 weeks ARO
LWA-STK	Ground stake for Item LWA-ANT	US $82.50	2 to 3 weeks ARO
LWA-SYS	Includes 1 each LWA-FEE, LWA-ANT, LWA-STK	US $1500.00	2 to 3 weeks ARO
LWAPC	LWA Power Coupler without quadrature coupler	US $495.00	2 to 4 weeks ARO
LWAPC-Q	LWA Power Coupler with quadrature coupler	US $745.00	2 to 4 weeks ARO
LWATV-RPi	Pre-programmed 8 GB micro-SD memory card with LWA TV GUI	US $15.00	Stock
SHIP	Shipping	Determined at time of shipment	

* ARO: After Receipt of Order and payment and depending on components lead-time and availability

** **Effective 1 January 2022, we will resume shipment of the LWA Antenna to international destinations**

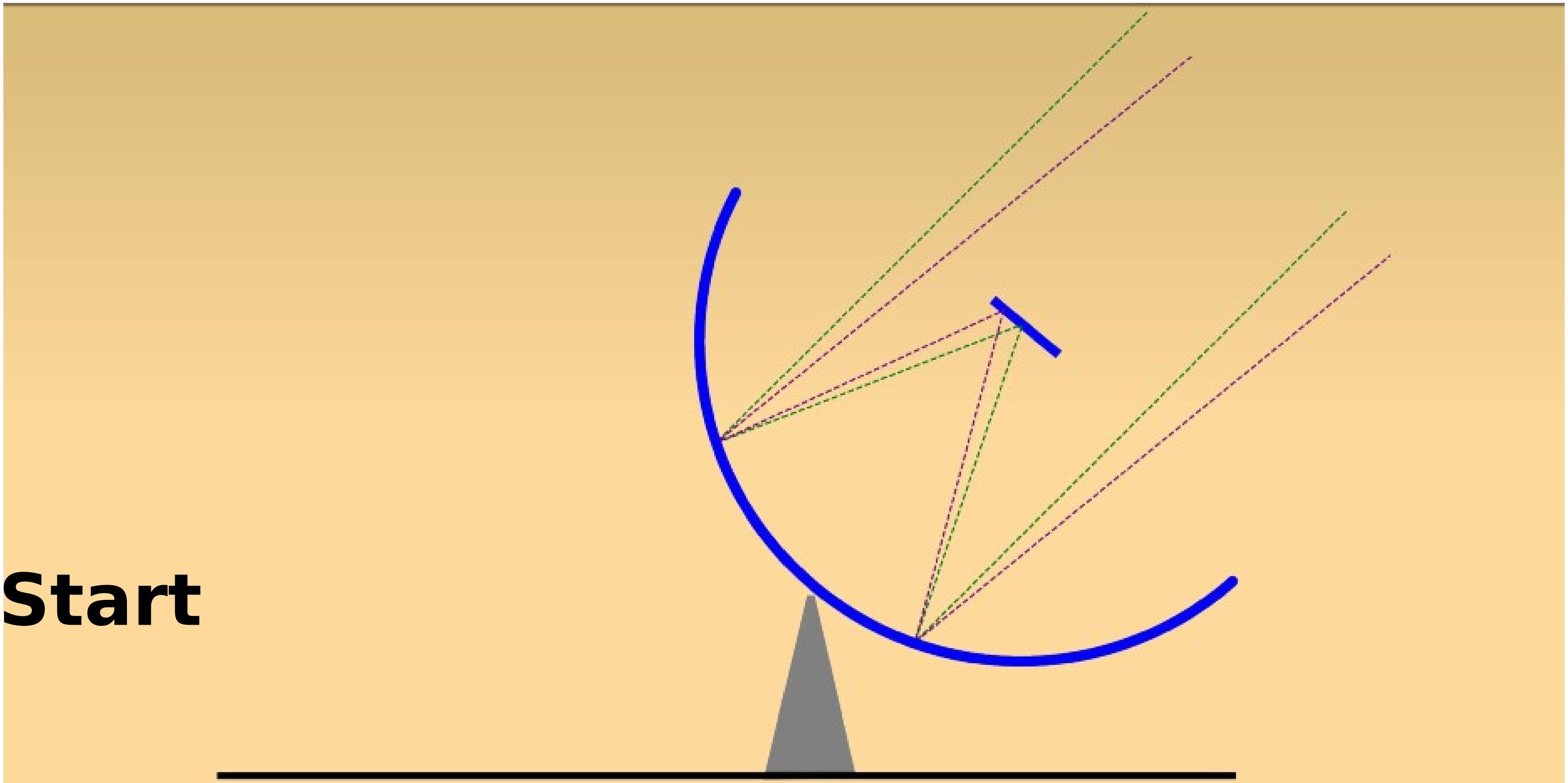
Correlator : ~ Euros 150 000

Antenna : ~ Euros 75 000

Thank you

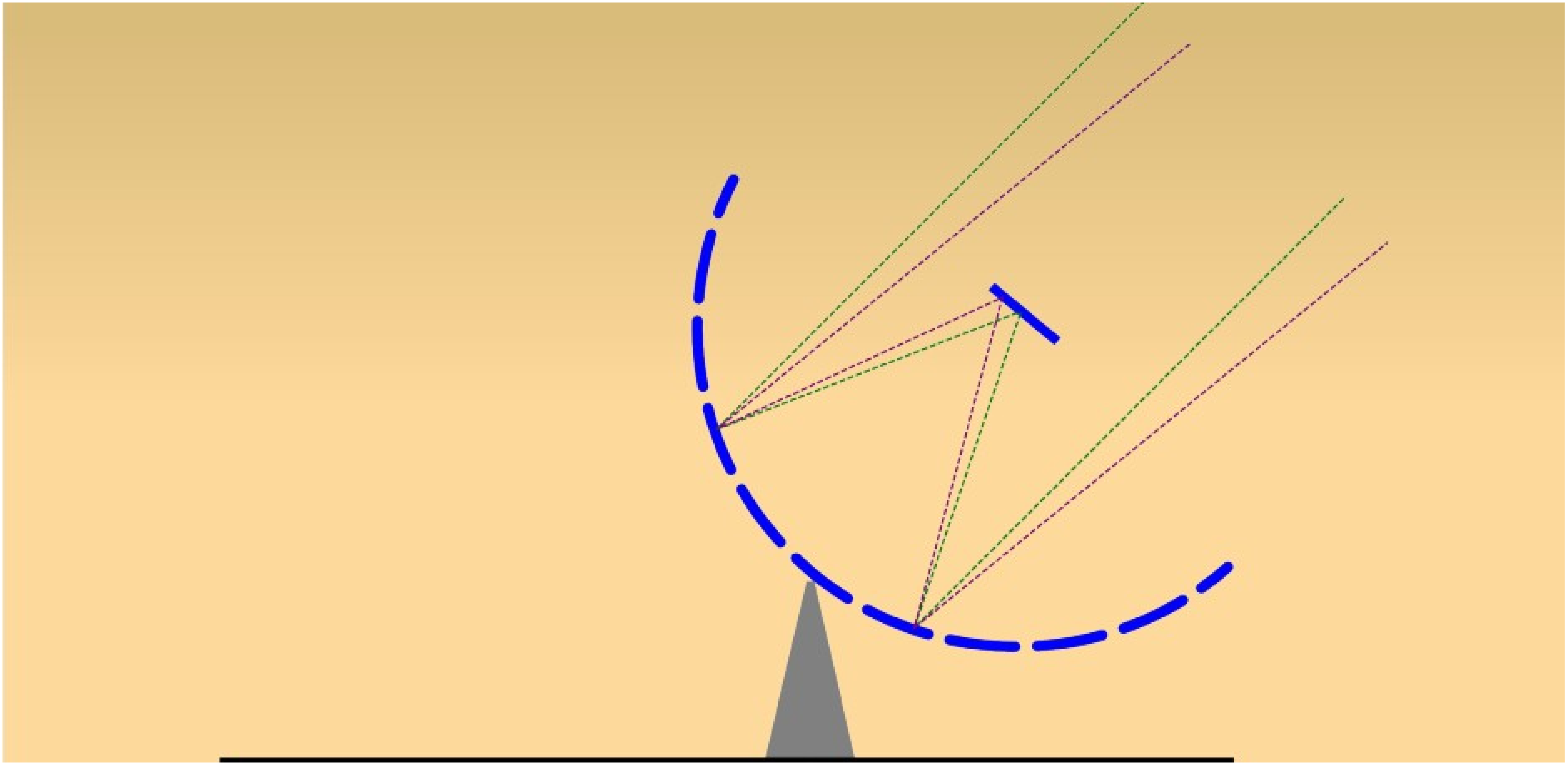
For The Attention

How To Make A Radio-Interferometer 1



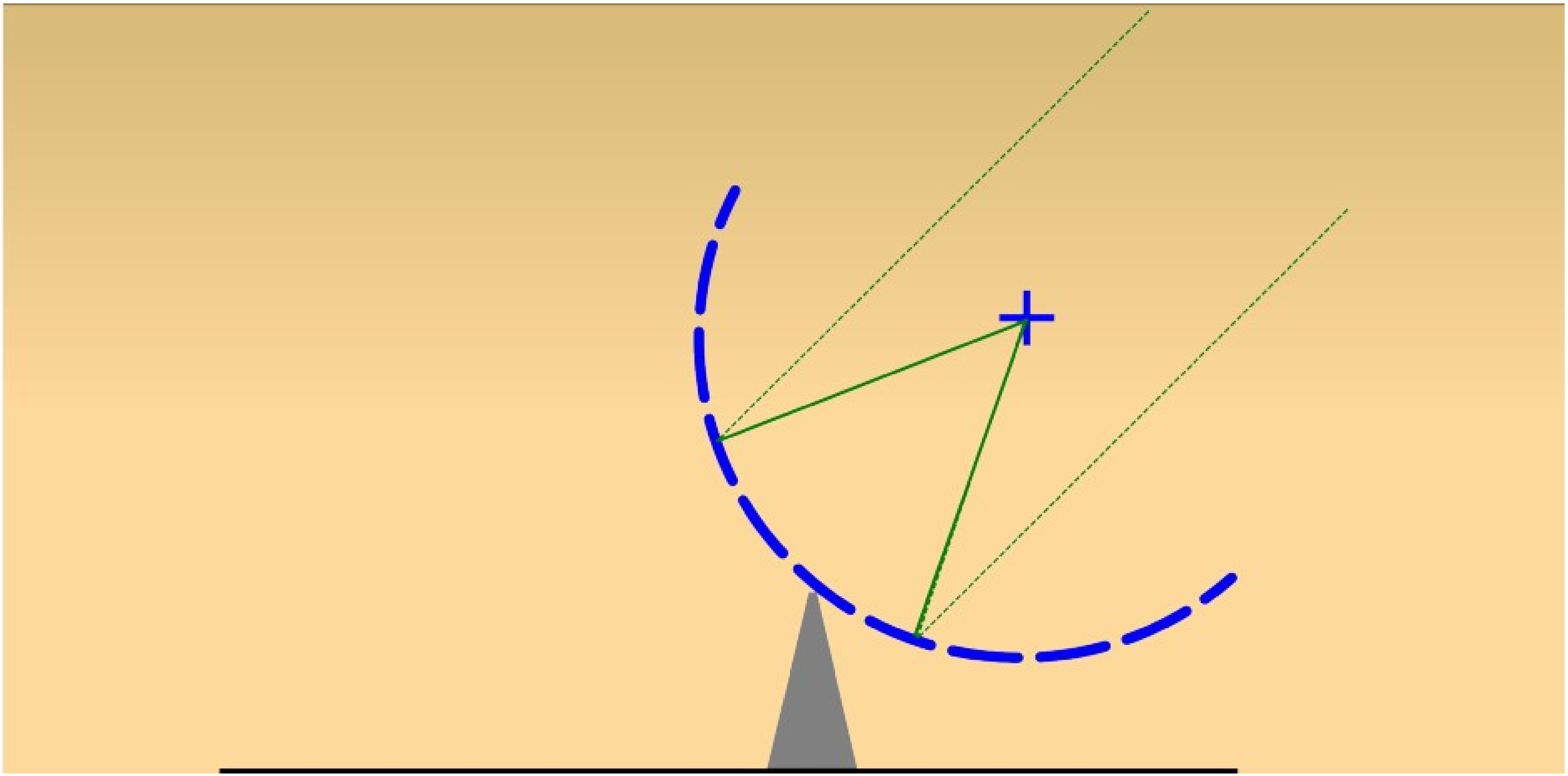
Start with a normal reflector

How To Make A Radio-Interferometer 2



Then break it up into sections ...

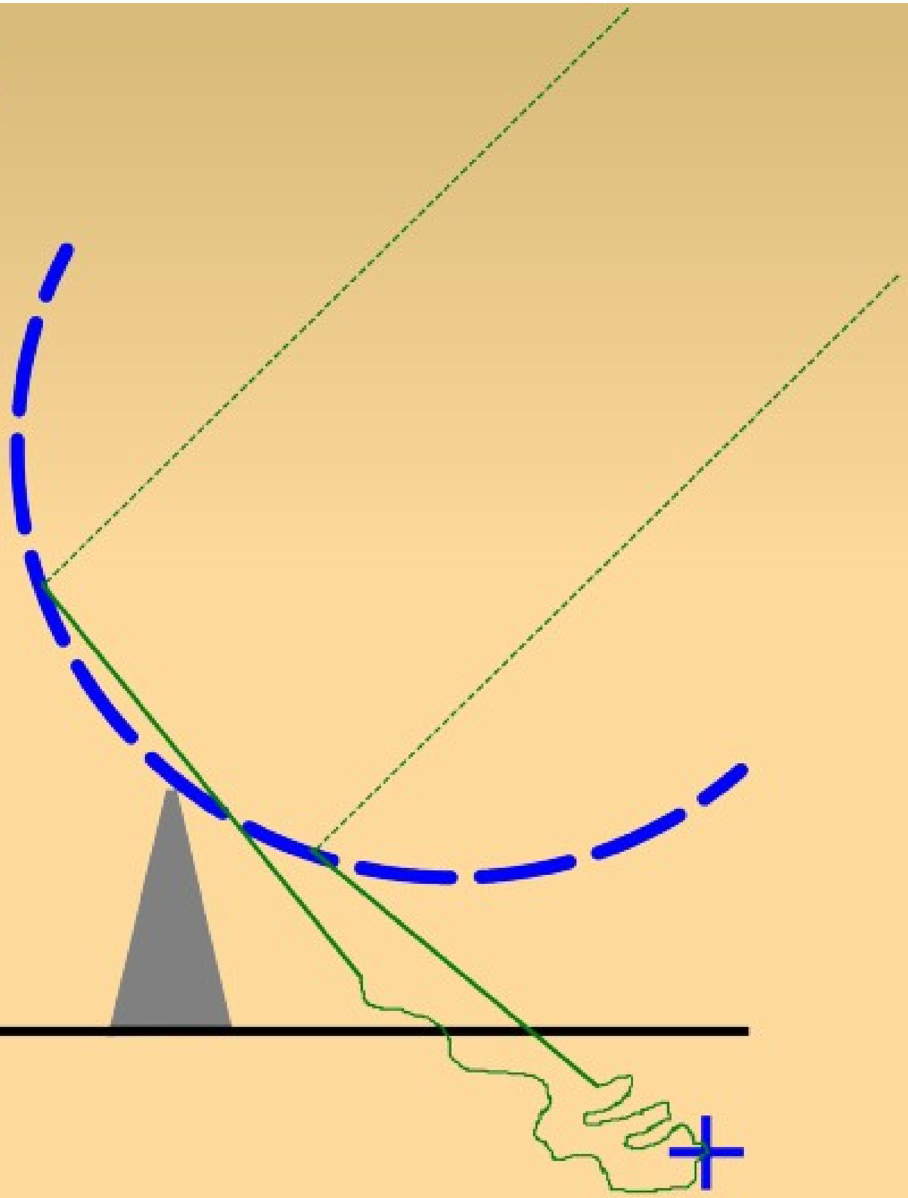
How To Make A Radio-Interferometer 3



Replace the optical paths with electronics ...

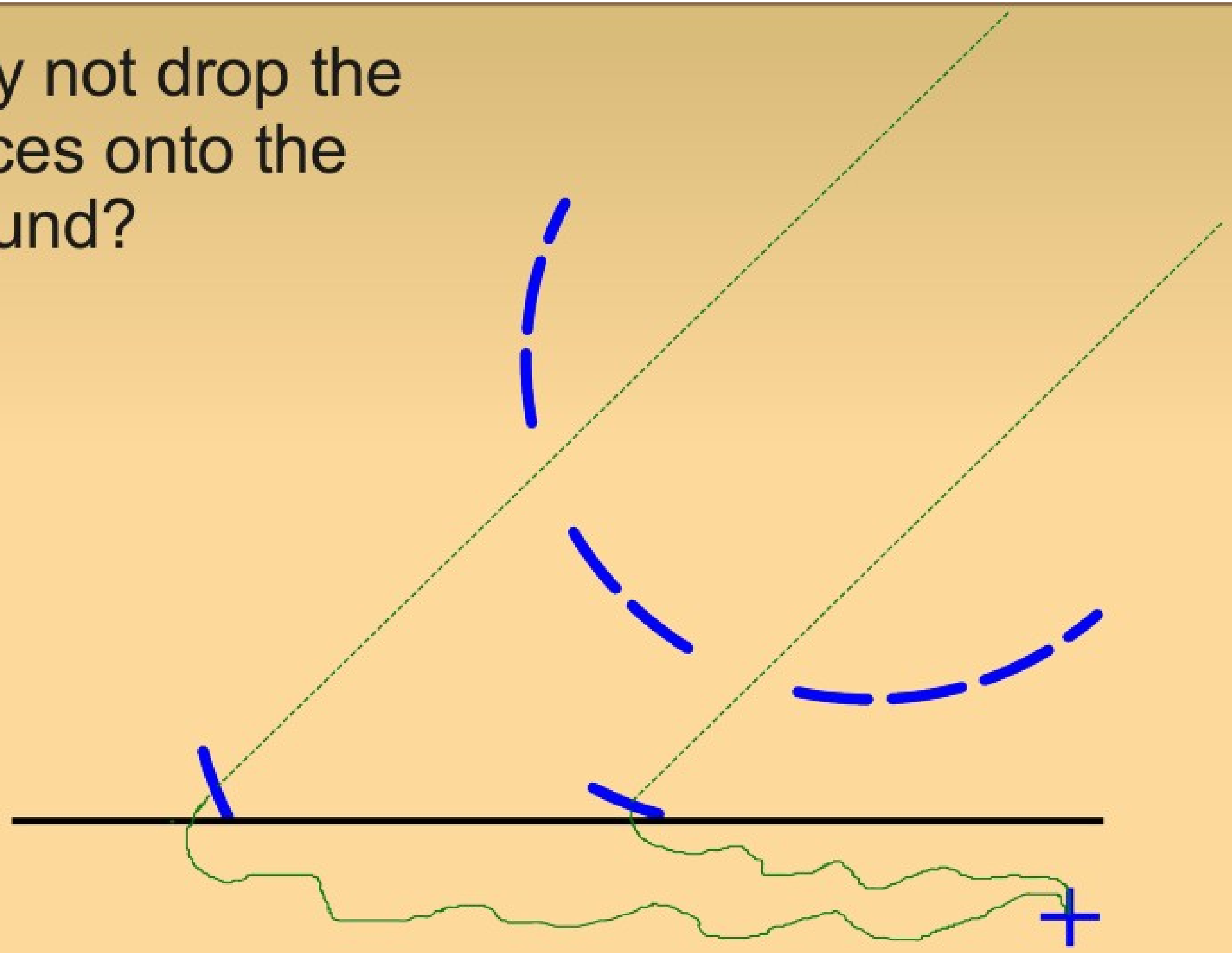
How To Make A Radio-Interferometer 2

- Move the electronics outside the dish
- ...and add cable delays



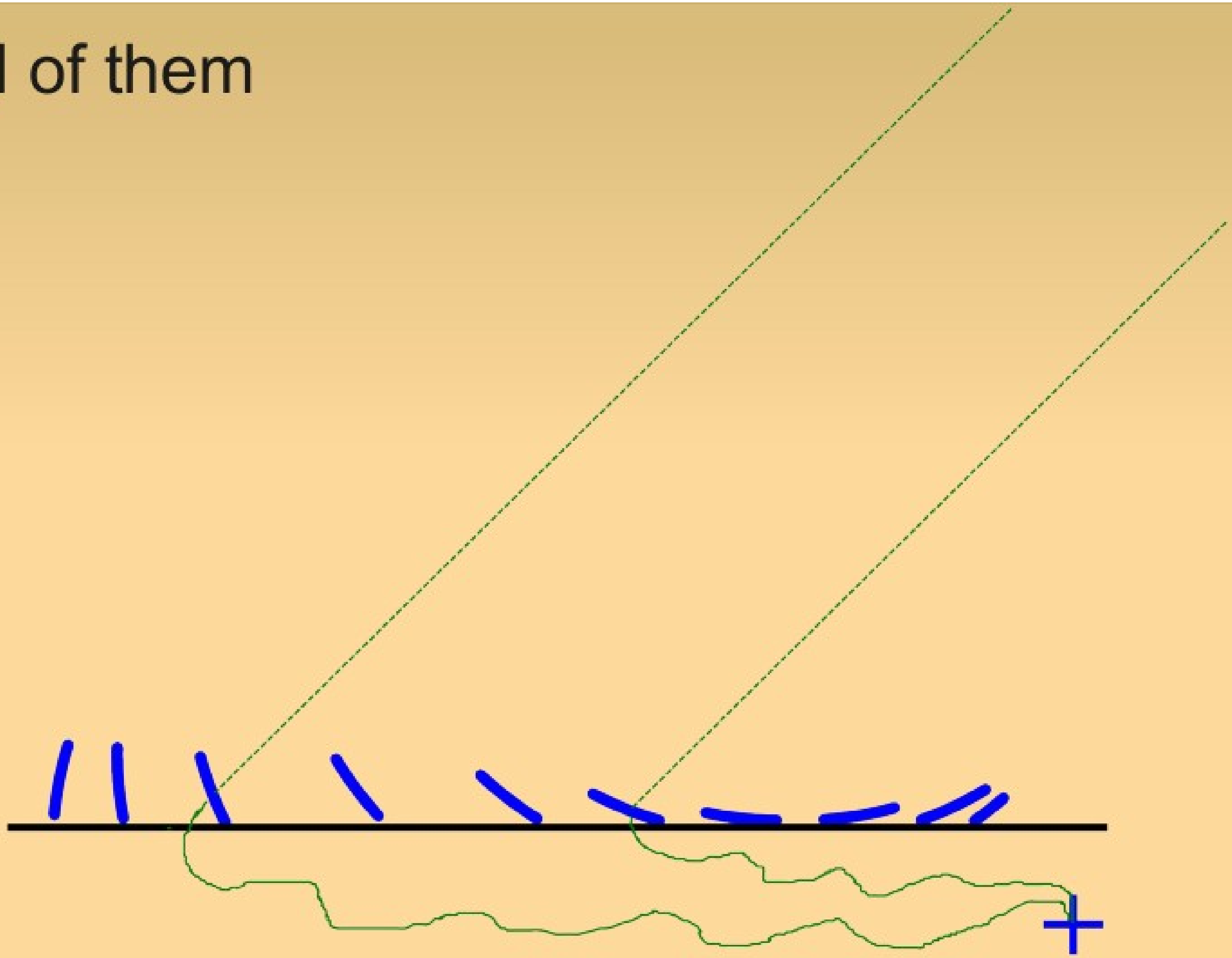
How To Make A Radio-Interferometer 2

- Why not drop the pieces onto the ground?



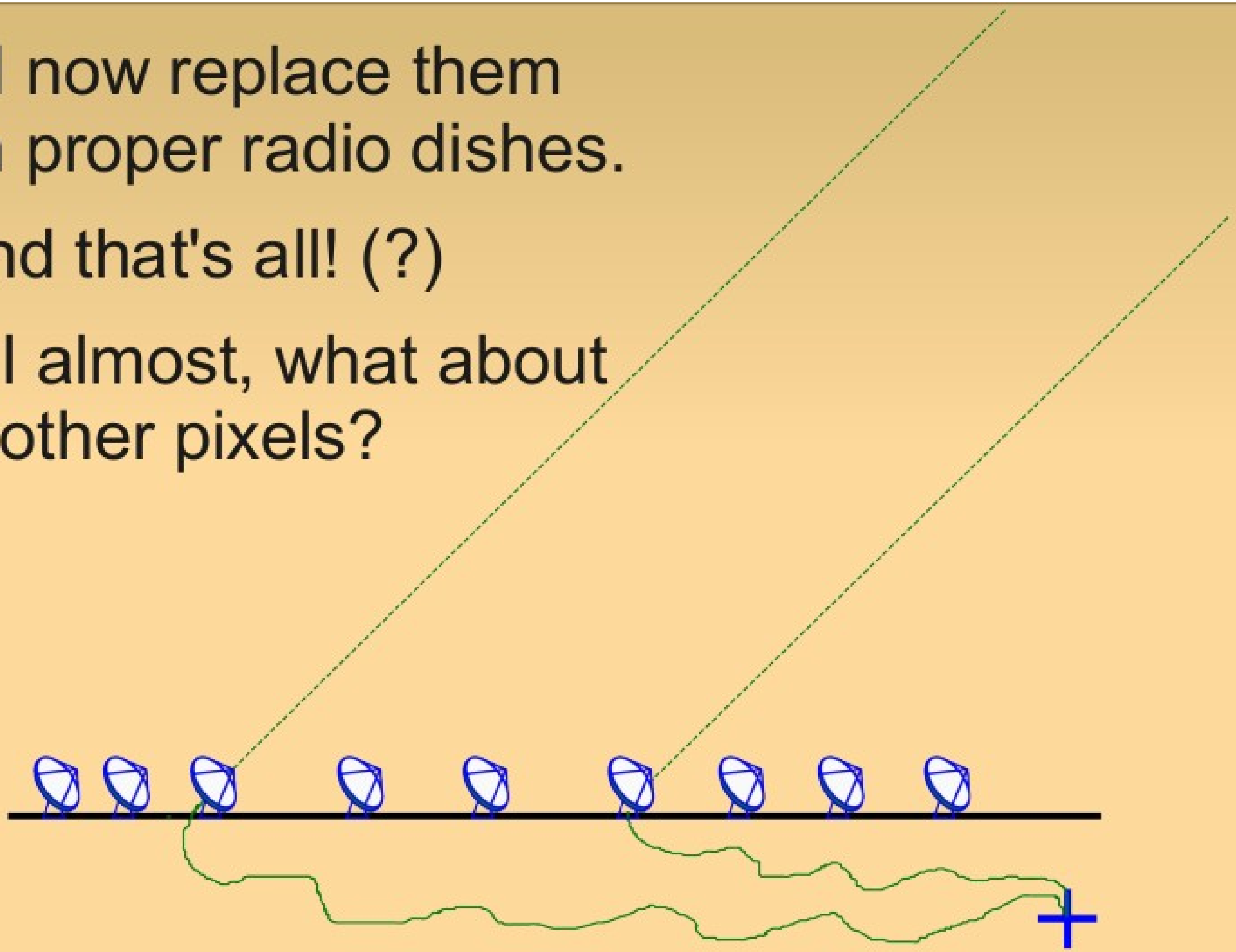
How To Make A Radio-Interferometer 2

- ...all of them

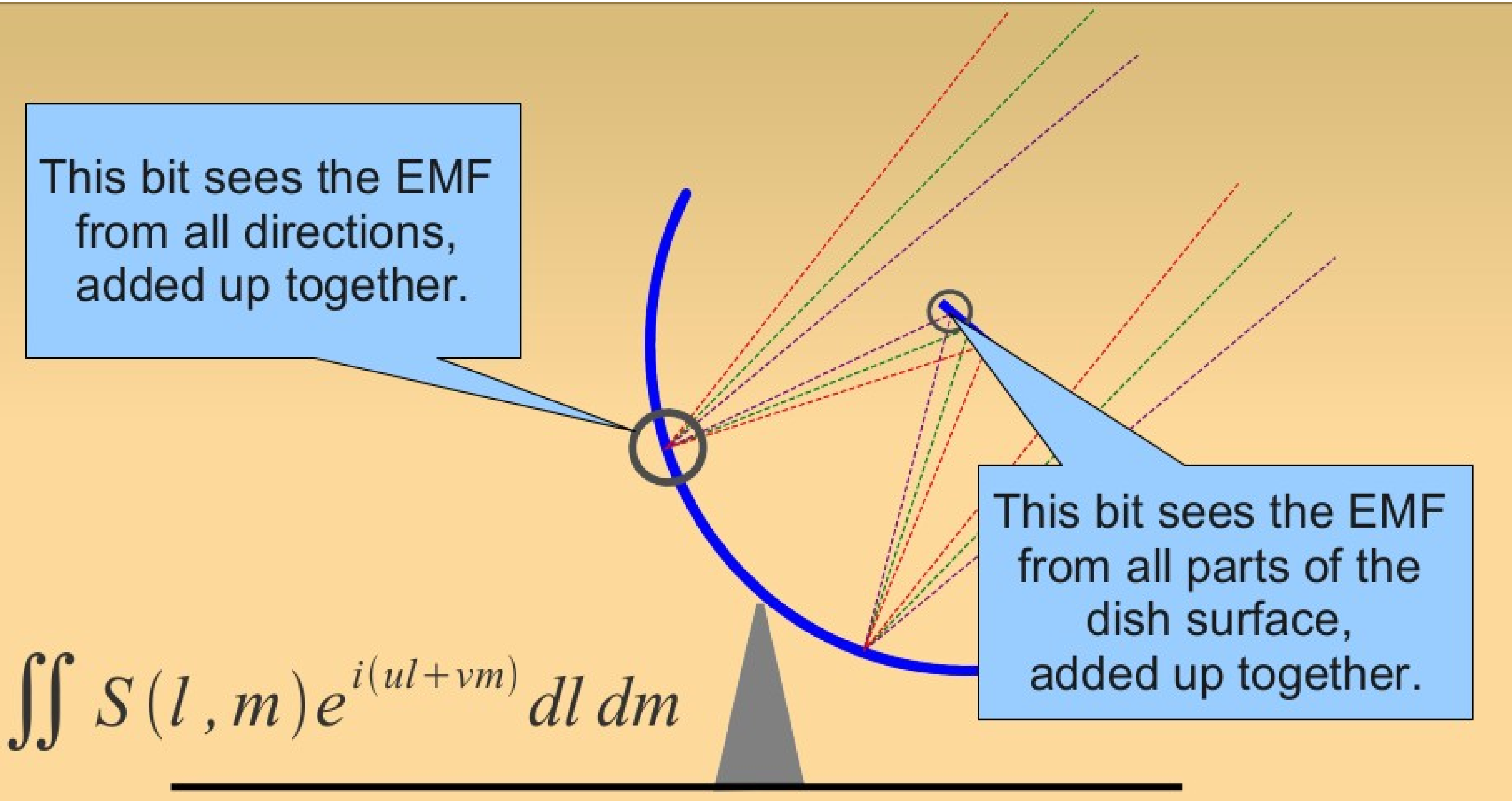


How To Make A Radio-Interferometer 2

- And now replace them with proper radio dishes.
- ...and that's all! (?)
- Well almost, what about the other pixels?

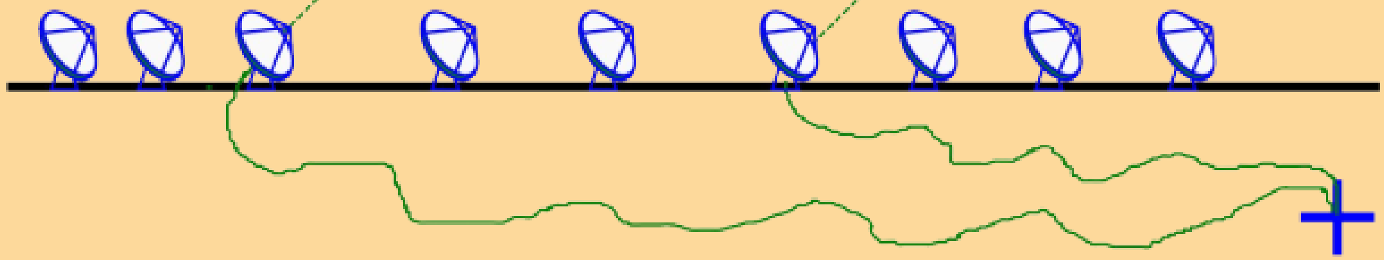


How To Make A Radio-Interferometer 2



How To Make A Radio-Interferometer 2

- An optical imaging system implicitly performs two Fourier transforms:
    1. Aperture EMF distribution = FT of the sky
    2. Focal plane = FT^{-1} of the aperture EMF
- A radio interferometer array measures (1)
    - Then we do the second FT in software
    - Hence, “aperture synthesis” imaging



How To Make A Radio-Interferometer 2

Then break it up into sections ...

Atmospheric Distorsisons?

- Incoming signal is subject to distortions (refraction, delay, amplitude loss)
  - atmospheric and electronic