A Radio Source Tracker :
Autonomous Attitude Knowledge and Recovery on a Radio Interferometric Swarm

Erwan Rouillé B. Cecconi, B. Segret

SmallSat 2022

LESIA l'Observatoire de Paris | PSL
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

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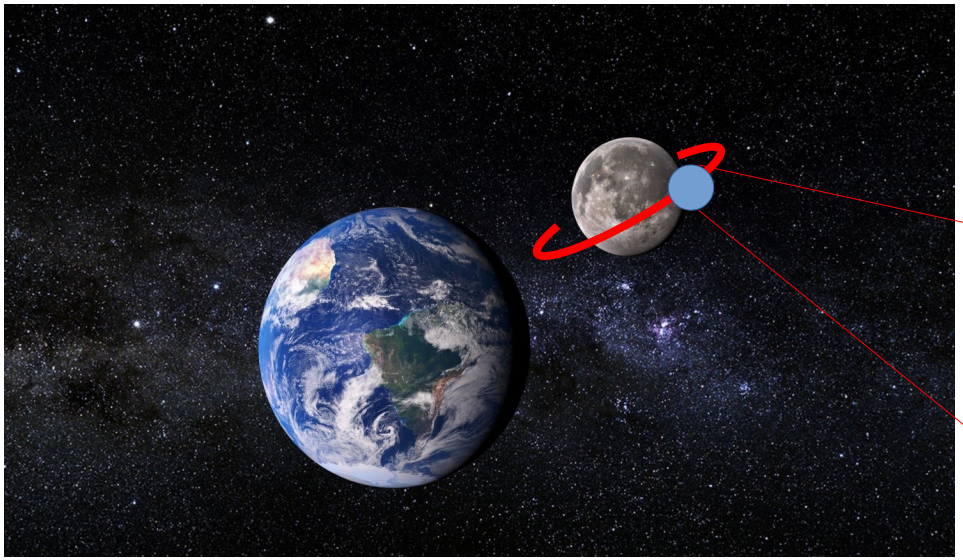
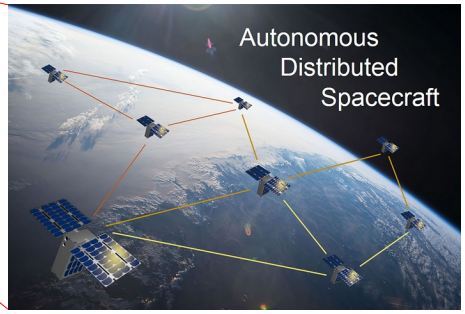
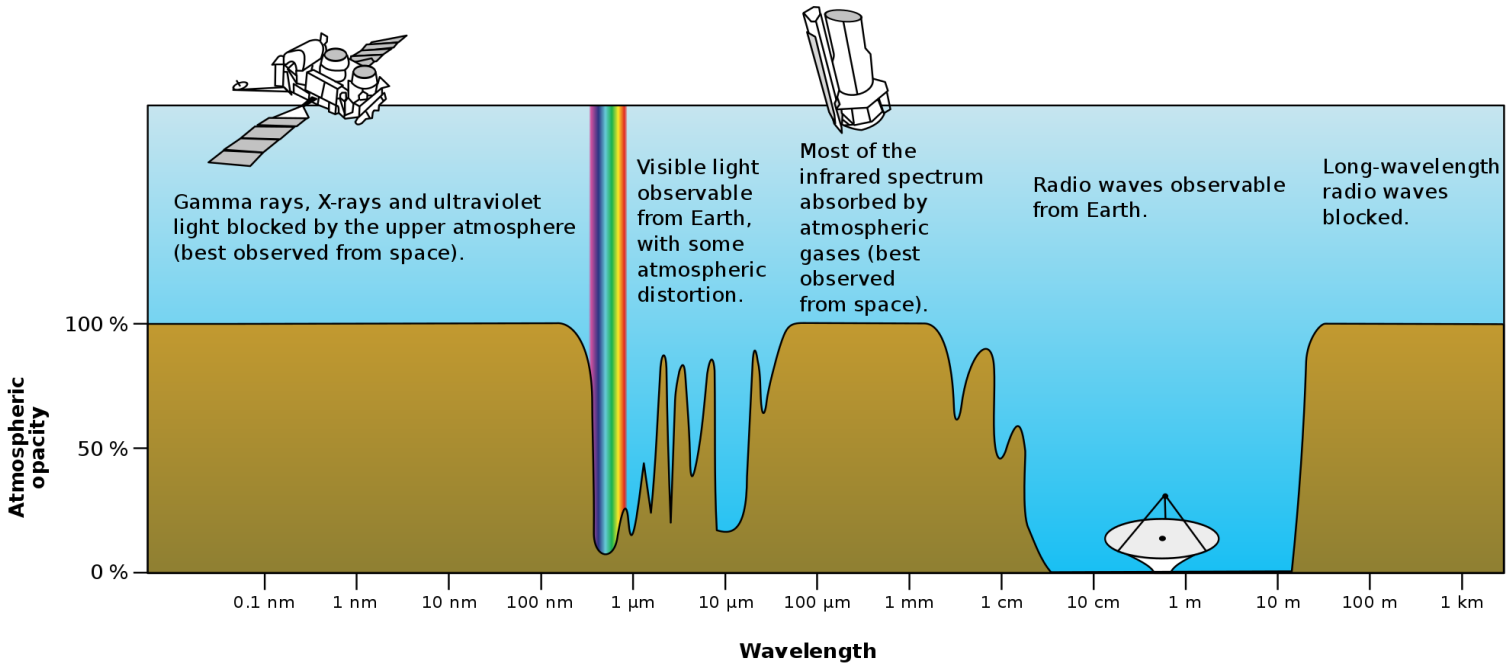
Our “NOIRE” project

- Astrophysical observations
- Swarm of 50 C/S
- Scale: 100 km
- Orbiting the Moon

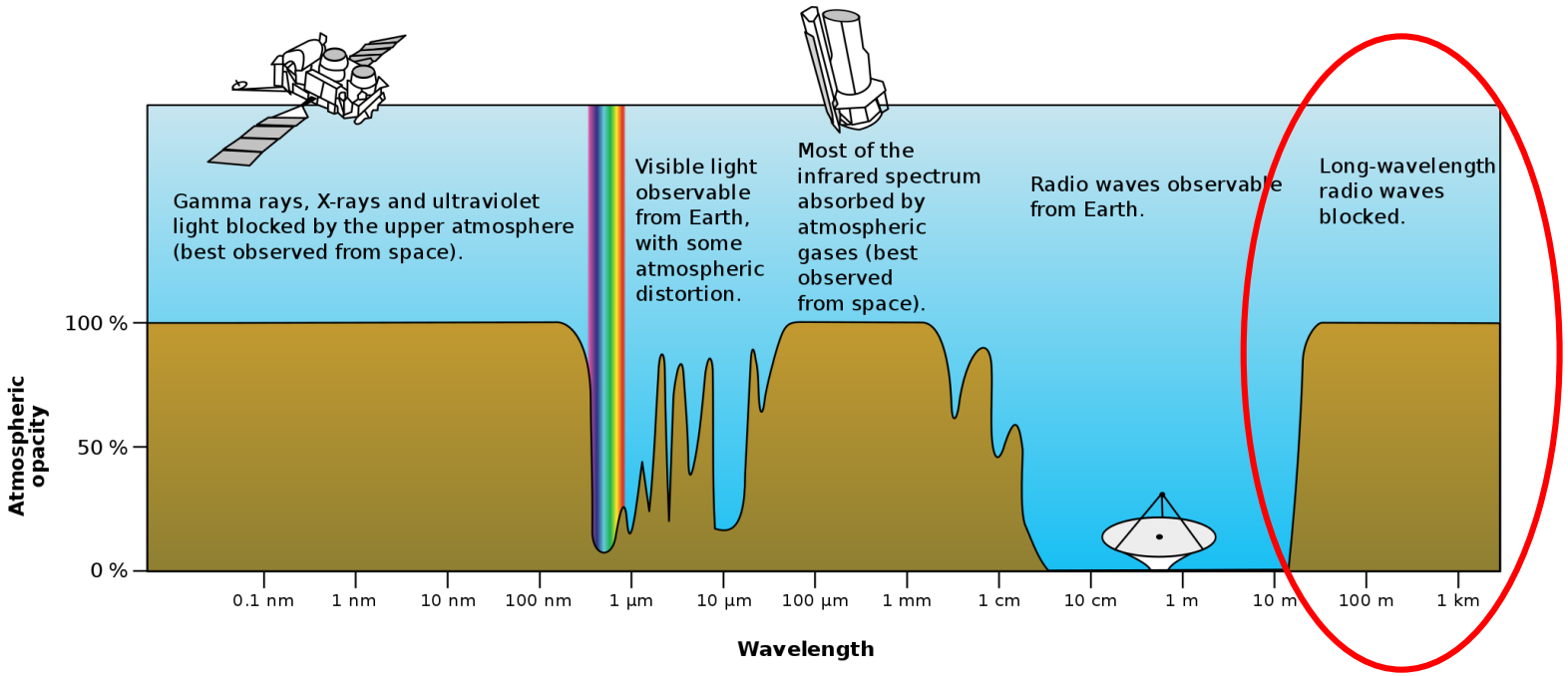




Introduction



Introduction

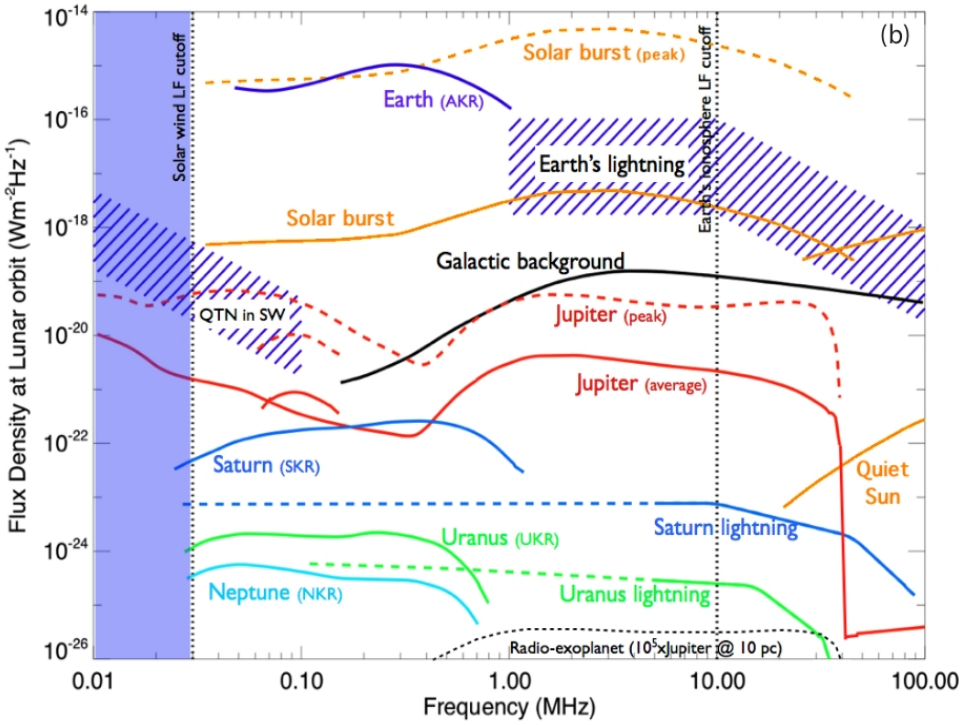


f < 10MHz

Introduction

Science topics :

- Solar physics
- Planetary physics
- Radio sources
- Cosmoslogy



Zarka *et al* 2012

Introduction

Science topics :

- Solar physics
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- Radio Galaxies
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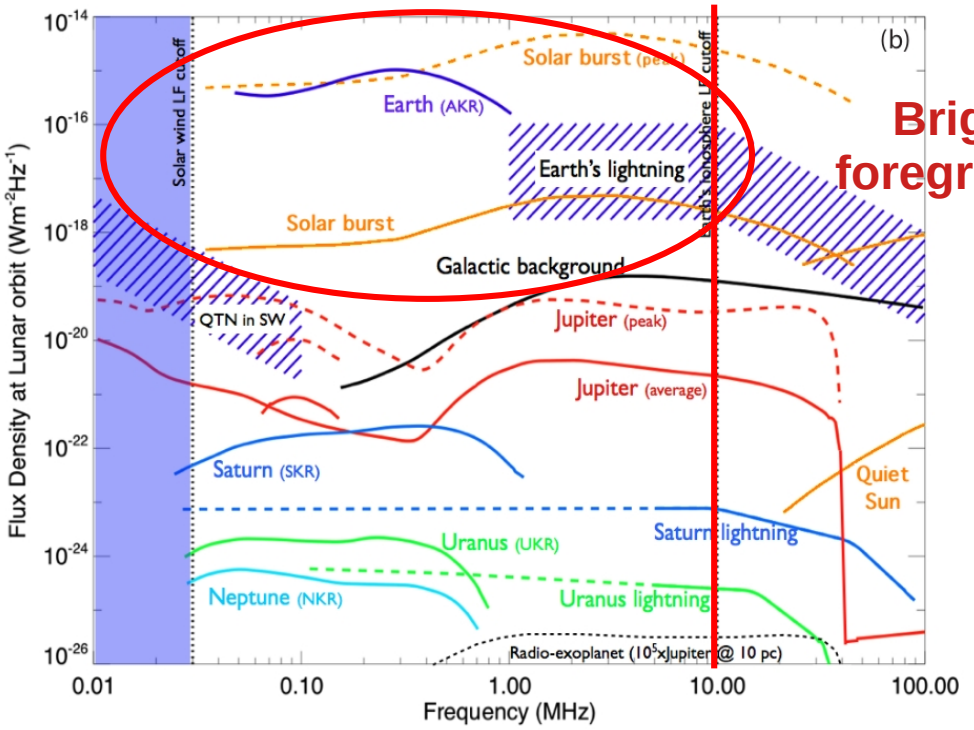
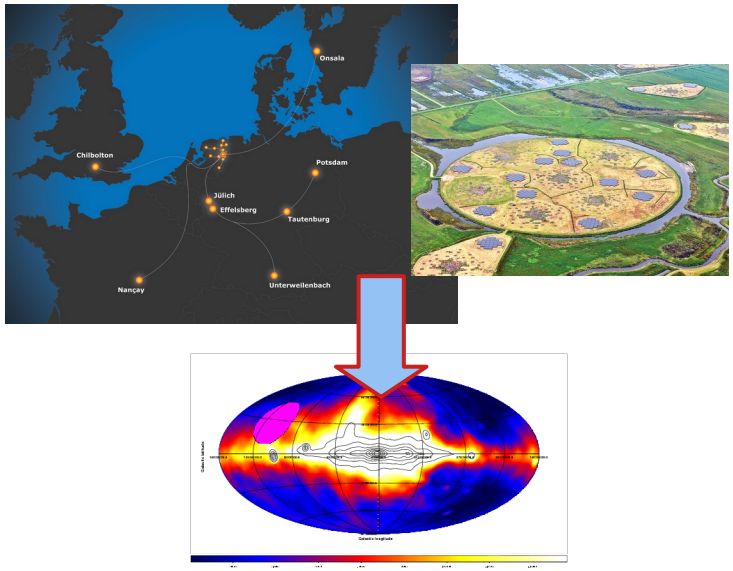


Space Interferometer



Large interferometer:

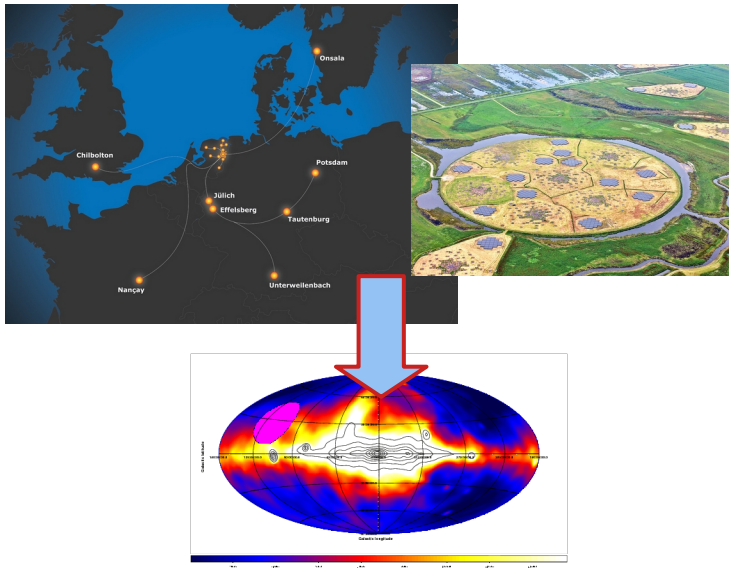
- Generate images

On the ground:

- Lowest frequency ~10MHz

Image credit: ASTRON / Guzmàn *et al* 2009 / nasa.gov / jpl.nasa.gov / Zarka *et al* 2004

Space Interferometer



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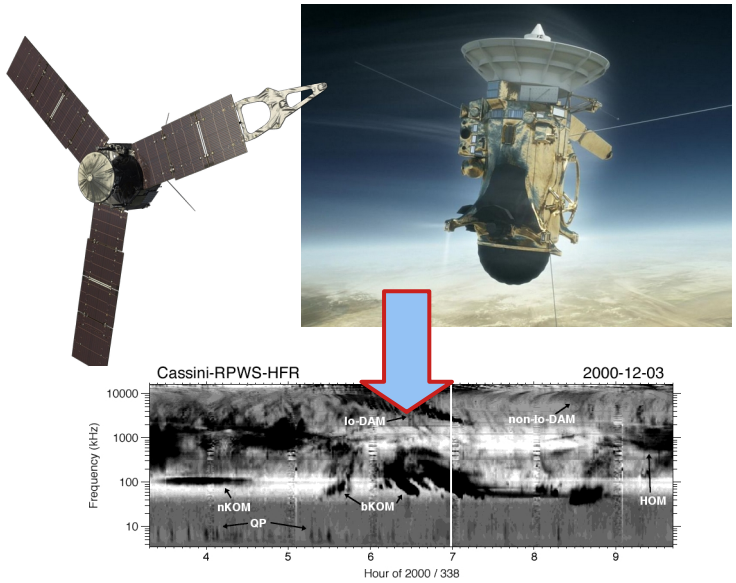


Space probe:

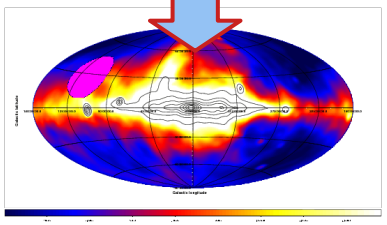
- Low frequency reachable

Single point :

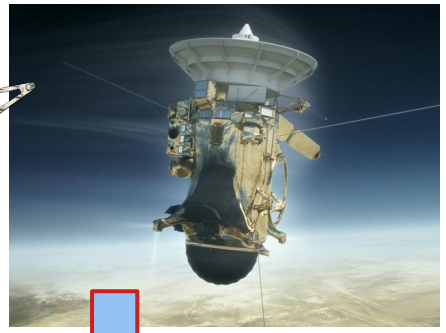
- No direction information

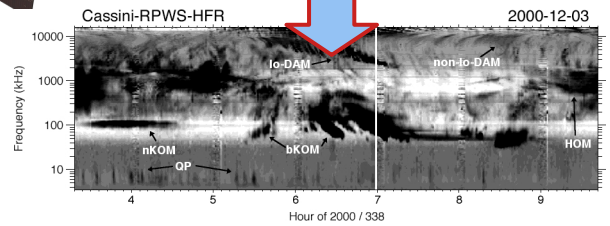
Image credit: ASTRON / Guzmàn *et al* 2009 / nasa.gov / jpl.nasa.gov / Zarka *et al* 2004

Space Interferometer



Space Interferometer





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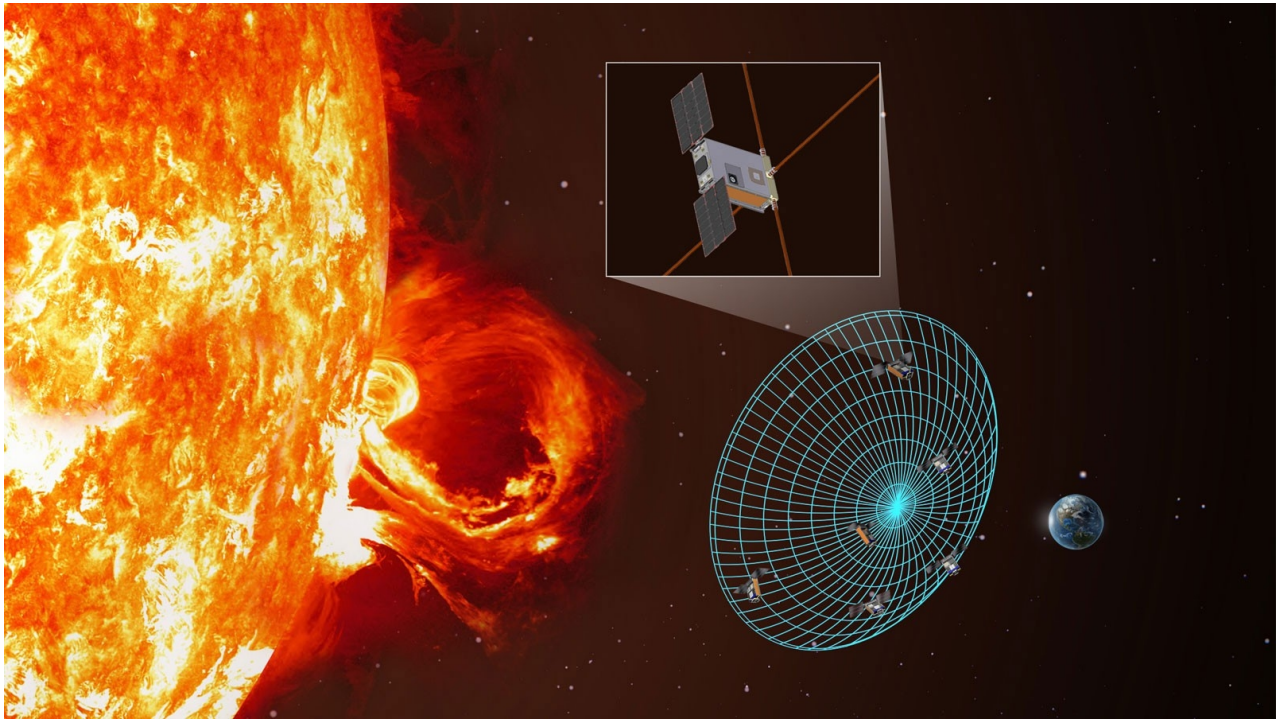
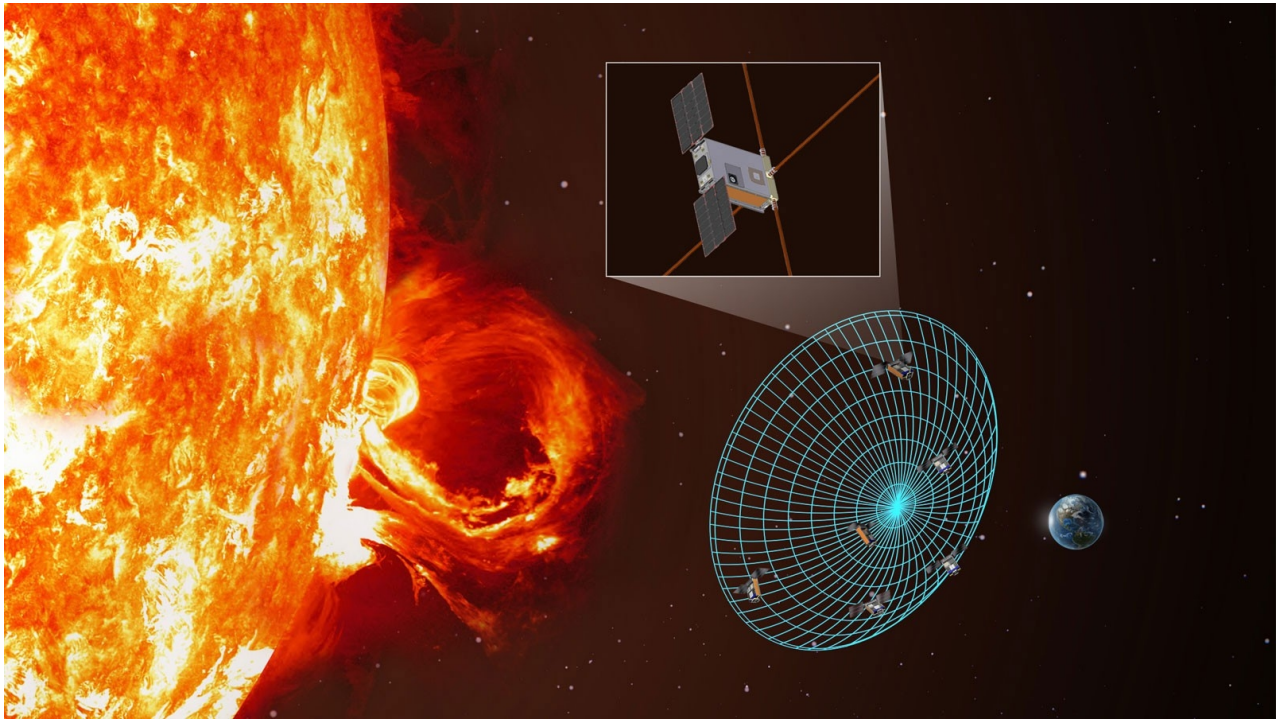
Space Interferometer



SunRISE :
- Solar burst
- 6 Nanosat
- GEO graveyard
- < 10km

Image credit: jpl.nasa.gov

Space Interferometer



SunRISE :
- Solar burst
- 6 Nanosat
- GEO graveyard
- < 10km

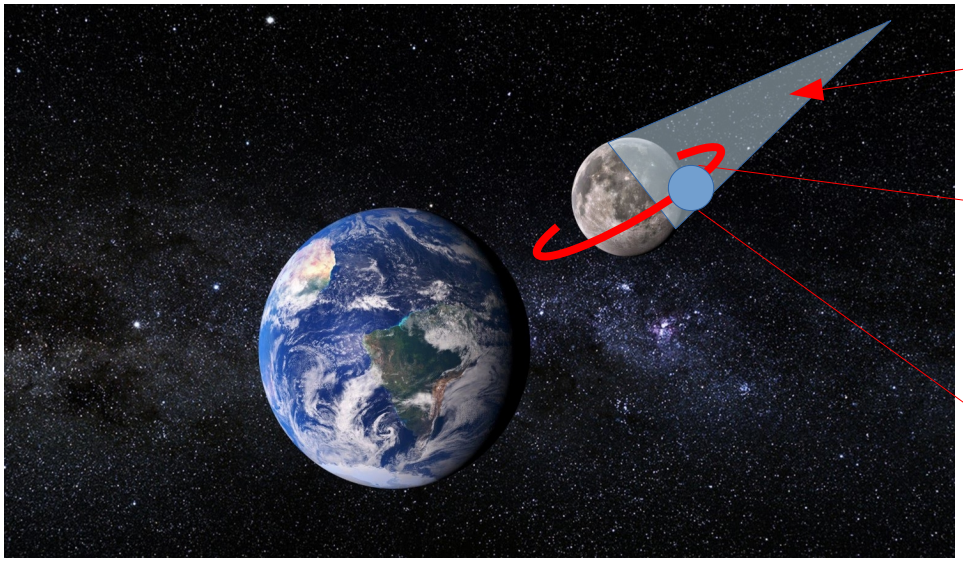
Limited science coverage:
- resolution
- sensibility
- Earth emissions

Image credit: jpl.nasa.gov

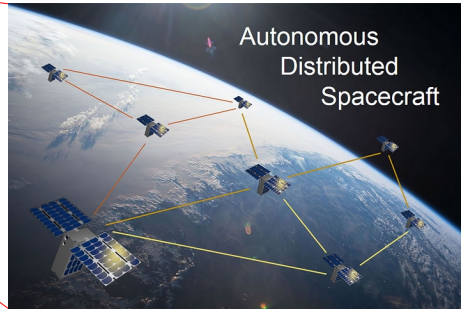
Space Interferometer

- NOIRE project

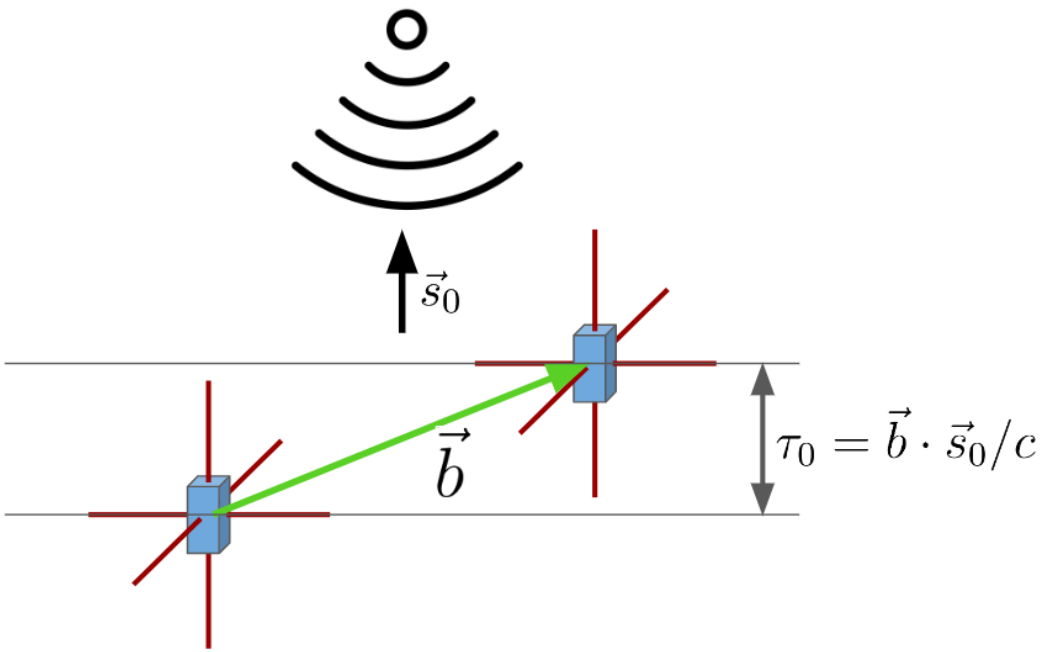
- 50 C/S
- scale: 100 km
- Protected by the Moon



Noise free zone



Swarm attitude knowledge

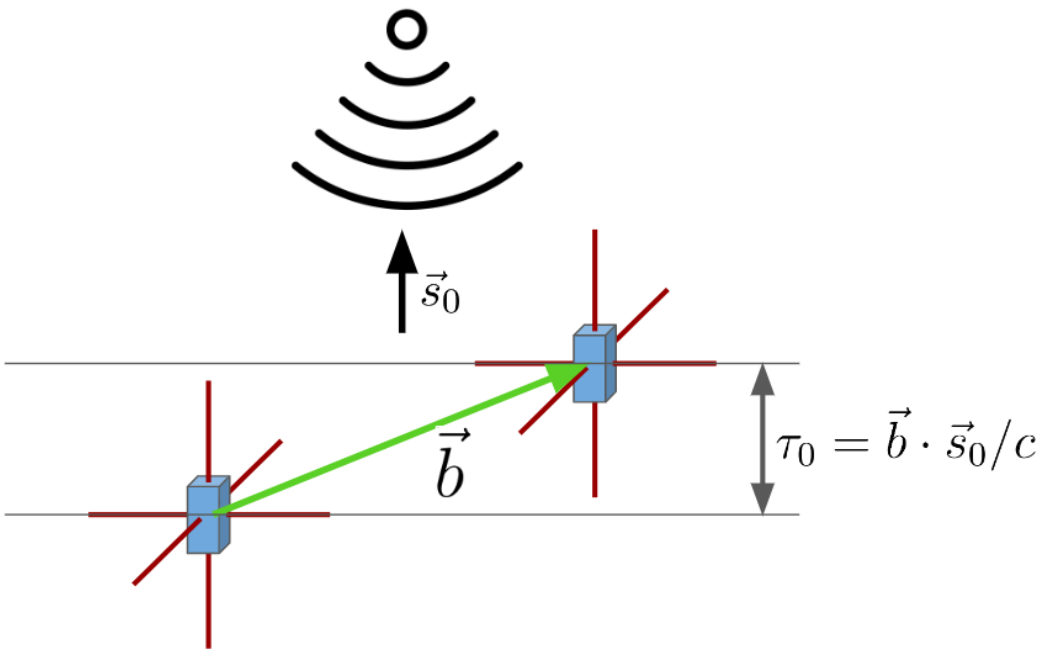


→ Principle: delay compensation

→ Delay = f(b,s)

→ require knowledge of b
= topology

Swarm attitude knowledge



→ Principle: delay compensation

→ Delay = f(b,s)

→ require knowledge of b
= topology

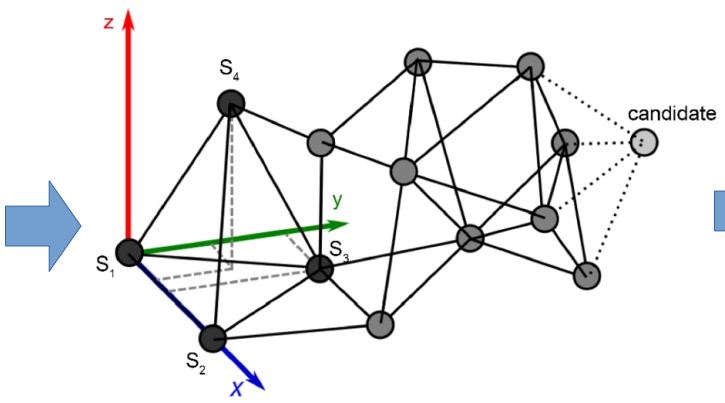
→ No GNSS for lunar orbits

=> Autonomy

Swarm attitude knowledge

Distance measurements
→ Relative topology

→ Position in arbitrary frame

$D_{i,j}$ 

$\vec{X}_{i/Rs}$

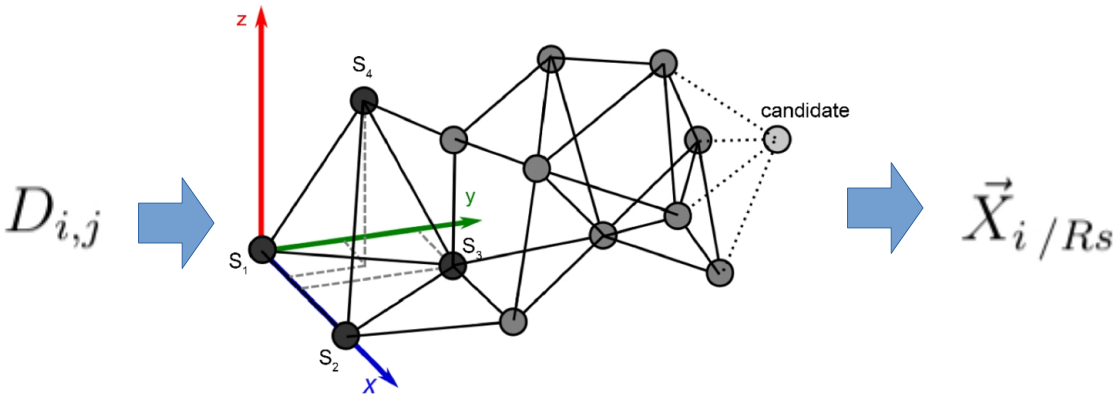
Source : Duisterwinkel et. al. 2018

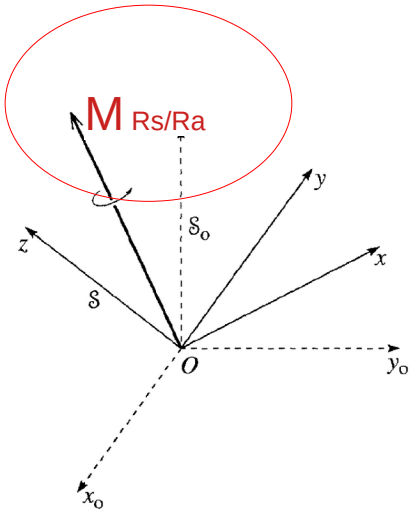
Swarm attitude knowledge

Distance measurements
→ Relative topology

→ Position in arbitrary frame

What is the transform that links this arbitrary frame to the absolute frame ?

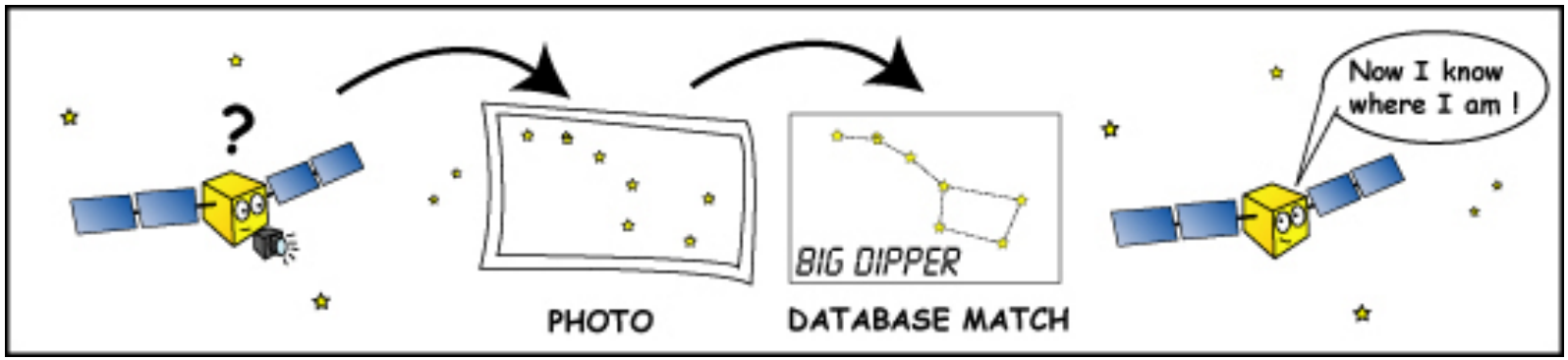




Source : Duisterwinkel et. al. 2018

Radio Source Tracker

Principle: same as a Star-Tracker

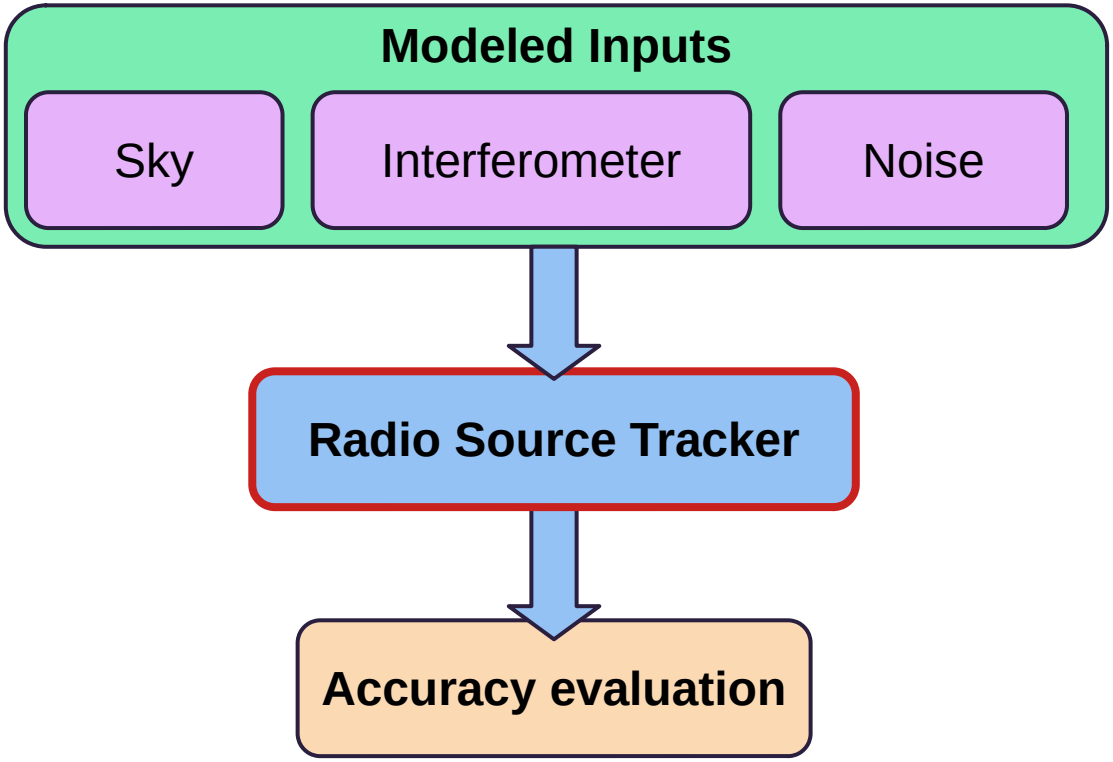


Relative topology → full sky images with arbitrary coordinates

Images are generated using the main payload

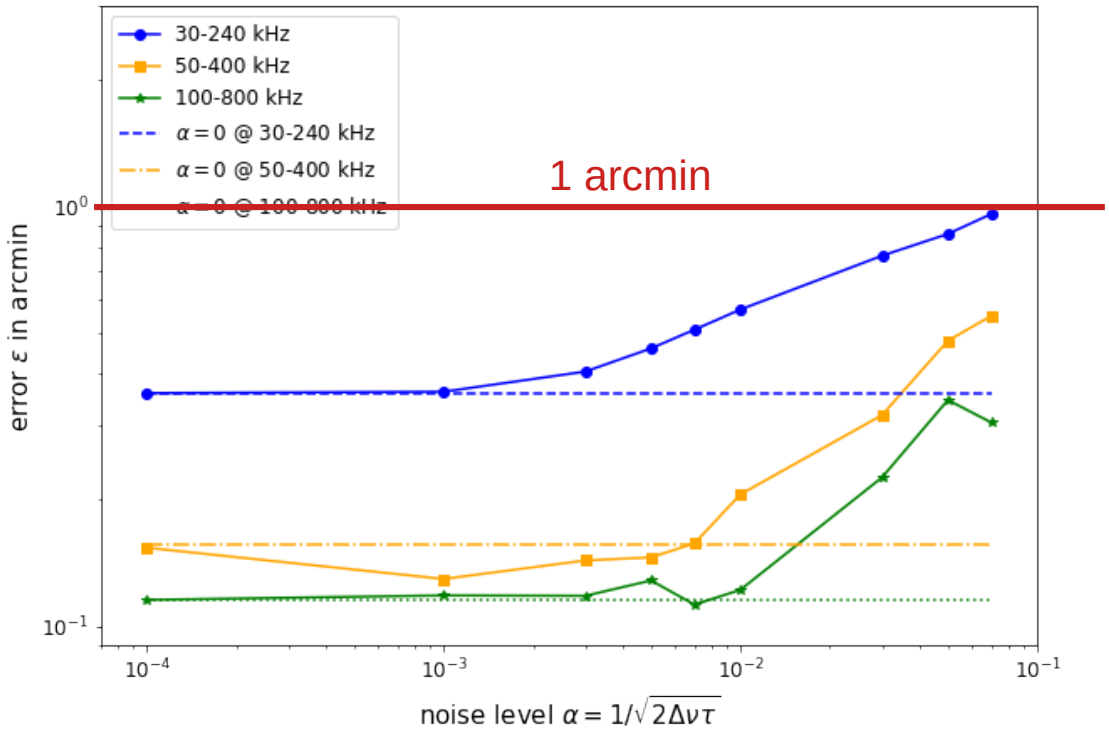
Image credit: jpl.nasa.gov

Radio Source Tracker



Results

- Autonomy: √
- Accuracy < 1arcmin
- Works as long as 3 catalog sources can be detected



Conclusion: LF interferometry faisible

- LF interferometry essential and feasible
  Work in progress
- Noise free zone should be preserved
- Other concept studies and projects (ALO, DSL, ...)

Any question ?

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Backup Slides

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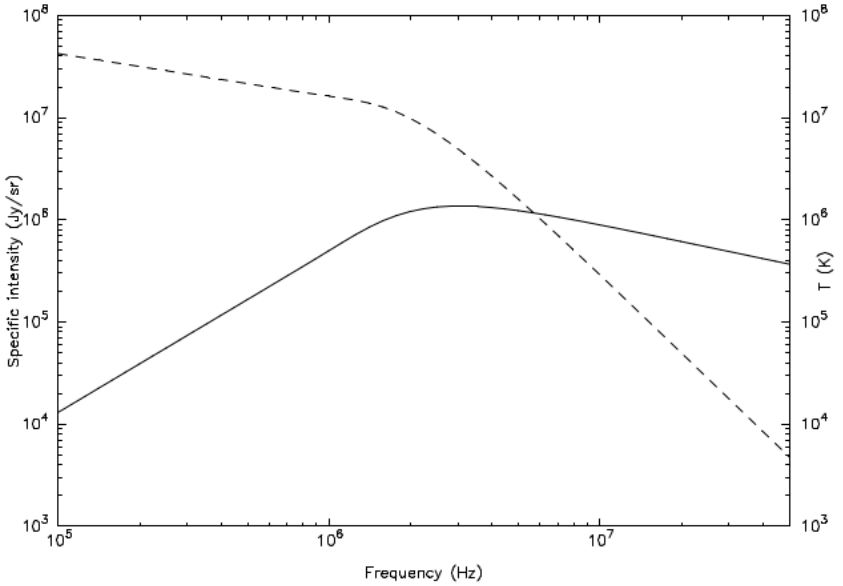
Sky model

Sky brightness supposed to follow the same spectrum as the one of the Galaxy

The input model is based on a skymap at 50MHz (GSM)

Point sources are modeled aside



$$T(\nu) = \begin{cases} T_{2\mathrm{MHz}} \left(\frac{\nu}{2\mathrm{MHz}}\right)^{-2.53} & \text{at } \nu > 2MHz \\ T_{2\mathrm{MHz}} \left(\frac{\nu}{2\mathrm{MHz}}\right)^{-0.3} & \text{at } \nu \leq 2MHz \end{cases}$$

Sky model

Point sources (LOFAR catalog)

$$\mathcal{V}_{sp\ (i,j)} = \sum_{s} \|E(s)\|^2 \exp\left(-i_c\ \vec{k}(s) \cdot \vec{b}_{i,j}\right)$$

Continuum (GSM)

$$\mathcal{V}_{c\ (i,j)} = \sum_{\Delta\Omega \in \Omega} \iint_{\Delta\Omega} B(\Omega_k) \exp\left(-i_c\ \vec{k} \cdot \vec{b}_{i,j}\right) d\Omega_k$$
$$= \sum_{\vec{k}} B(k)\ \Delta\Omega\ .\ \exp\left(-i_c\ \vec{k} \cdot \vec{b}_{i,j}\right)$$

Sky model

+ uncorrelated noise

$$\mathcal{V} = \mathcal{V}_{\text{simu}} + \epsilon \qquad \epsilon \hookrightarrow \mathcal{N}(0, \sigma)$$

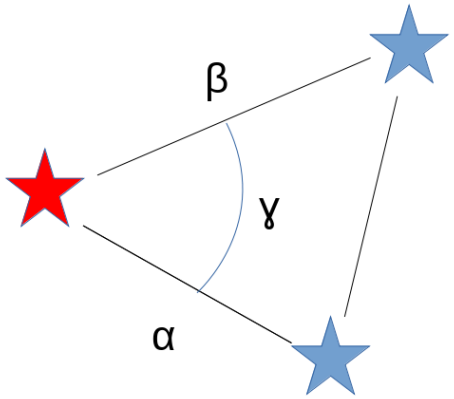
$$\sigma = \frac{S_{\text{sys}}}{\sqrt{2\Delta\nu\tau}} \qquad S_{\text{sys}} = \frac{k_B T_{\text{sys}}}{\eta A_{\text{eff}}} \qquad \eta A_{\text{eff}} = \frac{4\pi}{\lambda^2}$$

Expressed as a « noise level »

$$\sigma = \alpha \cdot \frac{4\pi k_B T_{\text{sys}}}{\lambda^2} \qquad \alpha = \frac{1}{\sqrt{2\Delta\nu\tau}}$$

Pattern Match

Tables of geometrical parameters



Comparison :
Voting system
→ thresholds :

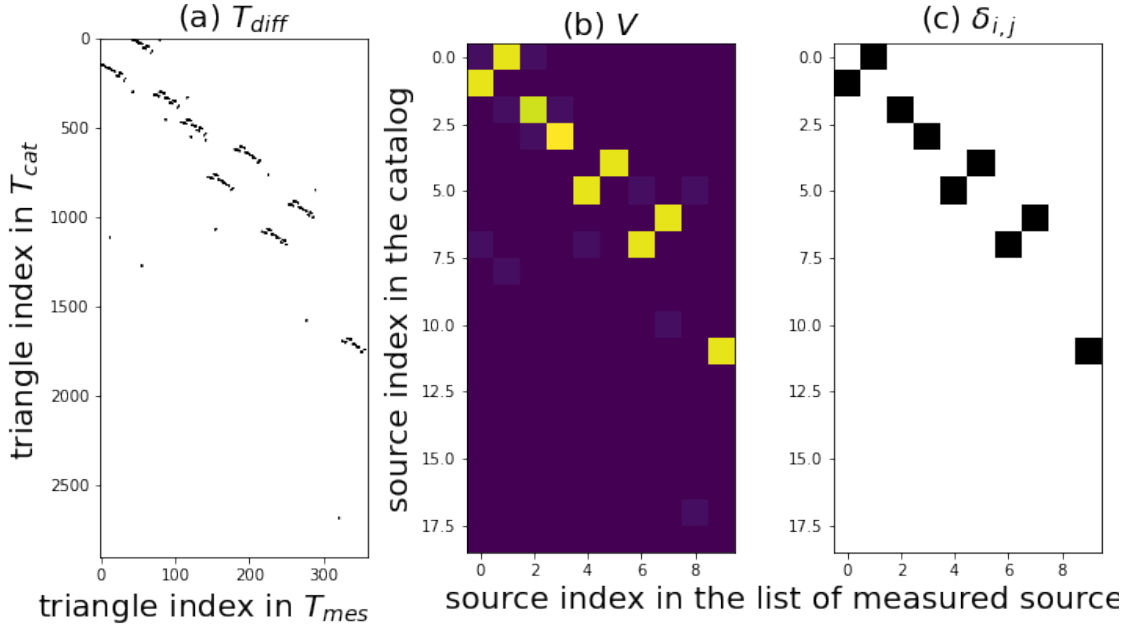
$$\|\alpha_{\text{cat}} - \alpha_{\text{mes}}\| \leq 2\Delta\theta_2$$

$$\|\gamma_{\text{cat}} - \gamma_{\text{mes}}\| \leq 2\Delta\theta_2 \left(\frac{1}{\alpha_{\text{cat}}} + \frac{1}{\beta_{\text{cat}}}\right)$$

Measured sources
??
#2
#1
#3
#4
#6

Catalog
#1
#2
#3
#4
#5
#6
#7
#8
#9

Pattern Match



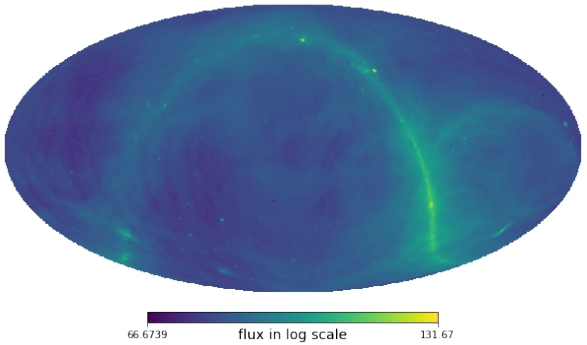
Triangles meeting thresholds

Number of vote per source

Sources index to permut

III] Méthode – Génération d'image

Modèle de ciel



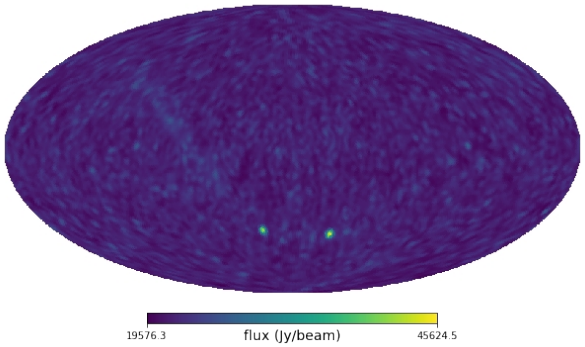
Calcul des visibilités

$$\mathcal{V}_{i,j} = \iint B(\Omega_k) \quad \exp\left(-i_c\, \vec{k} \cdot \vec{b}_{i,j}\right) d\Omega_k$$

Transformé de Fourier Discrète (DFT)

$$I(\theta,\phi) = \Re\left(\frac{1}{N_{bl}} \sum_{(i,j)} \mathcal{V}_{i,j}\ \mathrm{e}^{+i_c \vec{k}(\theta,\phi)\cdot\vec{b}_{i,j}}\right)$$

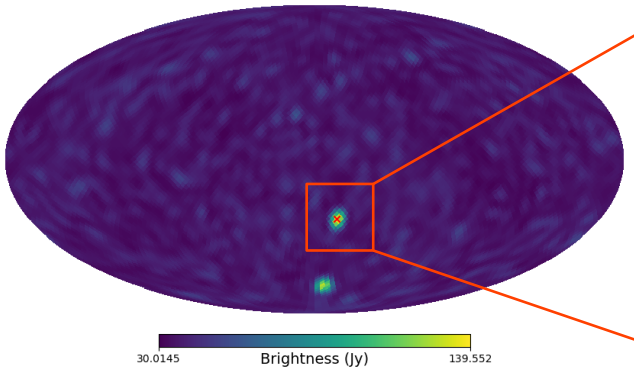
Reconstruction du ciel



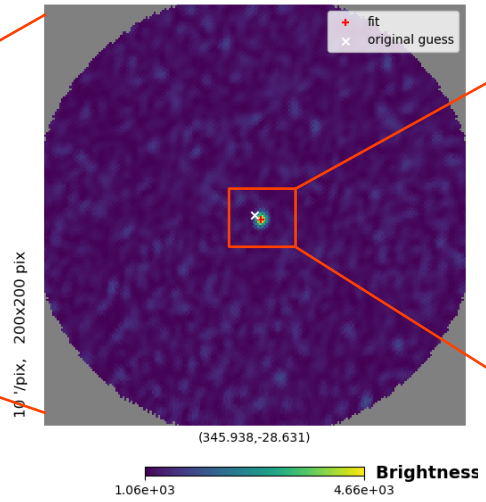
III] Méthode – Trouver une source

Zooms successifs sur le point le plus brillant de l'image précédente

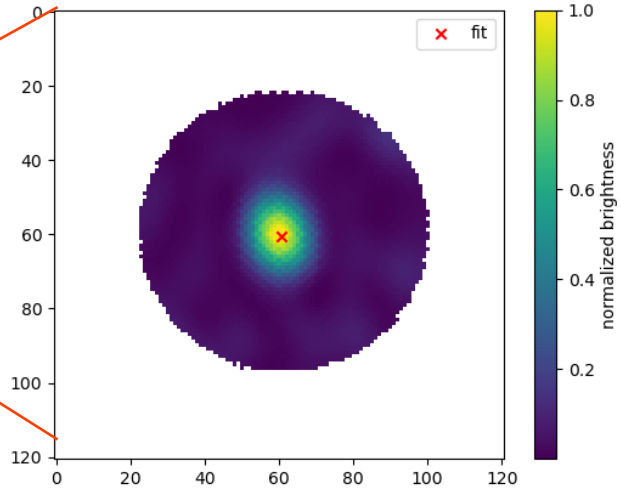
Full sky image at f1



Zoom at f2



2nd zoom at f2

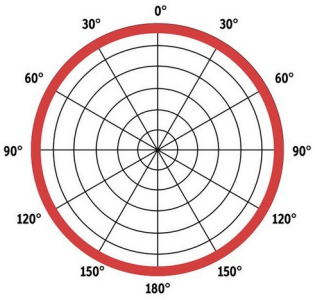


Fit Gaussien

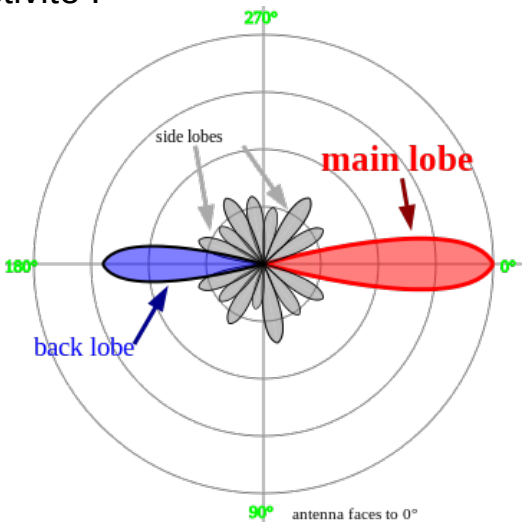
III] Méthode - Peeling

Lobes de réseaux : Une source brillante impacte tout le ciel

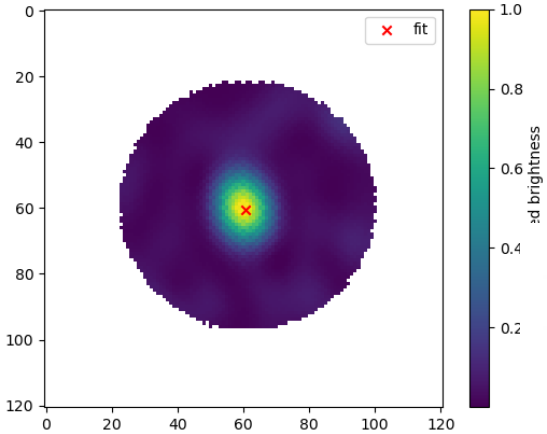
Directivité :



Un nœud



Réseau phasé



Fit Gaussien

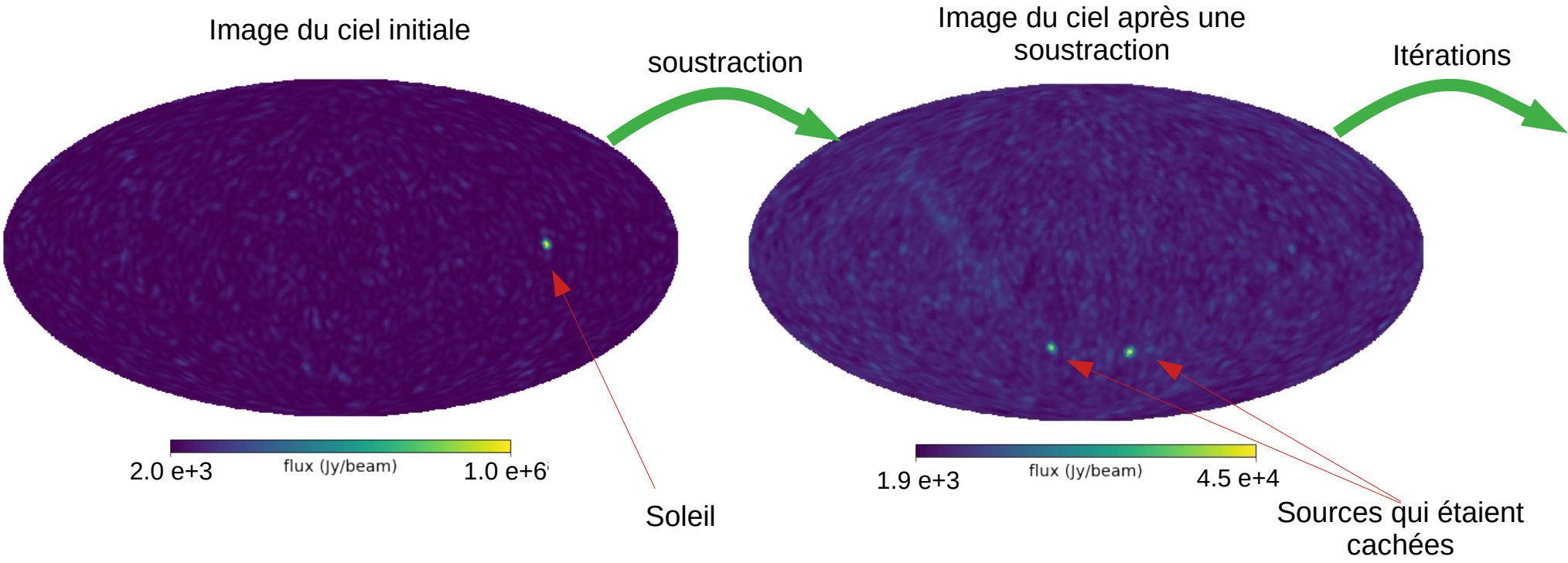
$$(B_s,\ \vec{k}_s)$$

$$\mathcal{V}_{i,j} - = B_s\ exp(i\vec{k}_s \cdot \vec{b}_{i,j})$$

Source : Wikipedia & sweetwater.com

III] Méthode - Peeling

Exemple :



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