NenuFAR sensitivity tools

Philippe Zarka
Observatoire de Paris, CNRS, PSL

and the NenuFAR team
• IDL: Standard for space radio astronomy, t-f measurements → beamforming mode
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• Runs on nancep nodes
• Needs licence tokens

In .bashrc
. /cep/lofar/exelis/idl85/bin/idl_setup.bash
export IDL_STARTUP="/home/philippe.zarka/.idlconf"

In .flexlmrc
*** the relevant license information ***

In .idlconf
!path= expand_path(‘+/cep/lofar/nenufar’)+'/:'+!path

• Alternative = GDL: compatibility issues

• Tools on /cep/lofar/nenufar/pro/general → accessible to all nancep users

• All following text & IDL commands in /databf2/nenufar/workshop/SensitivityTools.txt
nenufar_calc

- Computes the main characteristics of NenuFAR: sensitivity, resolution ...

nenufar_calc, nMAcore (scalar), nMArem (scalar), freq (scalar or vector, MHz)

nenufar_calc,/help

CALL
nenufar_calc, nMAcore,nMArem, freq, l, a1,aMA,aNen, thMA,FoV,thNen, Tsky,Tlna, SefdMA,SefdNen, SminTh,SminConf, $
  elev=elev, azim=azim, dmax=dmax, df=df, dt=dt, decoh=decoh, /lofar, /plot, /quiet

INPUTS
nMAcore = number of Mini-Arrays in core
nMArem  = number of remote Mini-Arrays
freq    = frequency (MHz) [scalar or vector]

KEYWORDS
  elev   = elevation (°) [default=90]
  azim   = azimuth (°) [default=0]
  dmax   = max distance of remote MA (m) [default=400 or 3000]
  df     = bandwidth (MHz) [default=1]
  dt     = integration time (sec) [default=1]
  decoh  = decoherence factor (1 if perfectly coherent, up to ~4 if uncalibrated) [default=1]
  /lofar => confusion according to Cohen 2004 & vanHaarlem et al. 2013 [default = Condon 2002]
  /plot  => display Mini-Arrays effective area
  /quiet => does not print any output
  /help  => extensive help
  /hlp   => summary help

OUTPUTS [same size as freq]
l        = wavelength (m)
a1       = Aeff 1 antenna (m^2)
aMA      = Exact Aeff Mini-Array 19 antennas separated by 5.5 m with overlap (m^2)
aNen     = Aeff of Nenufar (core+remote MA) (m^2)
thMA     = 1D FoV of MA (°)
FoV      = 2D FoV of MA (^°)
thNen    = Angular resolution of Nenufar (core+remote MA) (arcmin)
Tsky     = Sky temperature (K)
Tlna     = System (preamp) temperature (K)
SefdMA   = SEFD of 1 MA (Jy)
SefdNen  = SEFD of Nenufar (core+remote MA) (Jy)
SminTh   = Thermal noise (Jy)
SminConf = Confusion noise (Jy)
nenufar_calc

I = \lambda [m] = \frac{300}{freq} [MHz]

a1 (antenna) = \frac{\lambda^2}{3}

aMA computed by array_area.pro, with overlap, at zenith, or via nenufar_gain at (elev,azim)

nMA = nMAcore + nMArem

aNen = aMA \times nMA

thMA = \frac{\lambda}{25m}

FoV = \pi \times \frac{thMA^2}{4}

thNen = \frac{\lambda}{dmax} [arcmin]
nenufar_calc

\[ T_{\text{sky}} = 60 \times \lambda^{2.55} \]
\[ T_{\text{lna}} \rightarrow \text{tabulated} \]
\[ \text{Sefd}_{\text{MA}} = 2K \left( T_{\text{sky}} + T_{\text{lna}} \right) / a_{\text{MA}} \]
\[ \text{Sefd}_{\text{Nenu}} = 2K \left( T_{\text{sky}} + T_{\text{lna}} \right) / a_{\text{Nenu}} \]
\[ \text{Smin}_\text{Th} = \text{Sefd}_{\text{Nenu}} \times \text{decoh} / \sqrt{2 \times df[\text{Hz}] \times dt[\text{s}]} \]

\[ \text{Smin}_\text{Conf} = 0.2 \times \text{freq}[\text{GHz}]^{-0.7} \times \text{th}_{\text{Nenu}}[\text{arcmin}]^2 \] [Condon 2002]
\[ \text{Smin}_\text{Conf} = 29. \times \left( \text{freq}[\text{MHz}] / 74 \right)^{-0.7} \times \text{th}_{\text{Nenu}}[\text{arcsec}]^{1.54} \] [Cohen 2004, van Haarlem et al. 2013]
\[ T_{\text{sky}} = 60 \times \lambda^{2.55} \]

\( T_{\text{lna}} \rightarrow \) tabulated

\[ \text{SefdMA} = 2K \frac{(T_{\text{sky}} + T_{\text{lna}})}{a_{\text{MA}}} \]

\[ \text{SefdNen} = 2K \frac{(T_{\text{sky}} + T_{\text{lna}})}{a_{\text{Nen}}} \]

\[ S_{\text{minTh}} = \text{SefdNen} \times \text{decoh} / \sqrt{2 \times df[\text{Hz}] \times dt[\text{s}]} \]

\[ S_{\text{minConf}} = 0.2 \times \text{freq}[\text{GHz}]^{-0.7} \times \text{thNen}[\text{arcmin}]^{2} \]  
[Condon 2002]

\[ S_{\text{minConf}} = 29. \times (\text{freq}[\text{MHz}] / 74)^{-0.7} \times \text{thNen}[\text{arcsec}]^{1.54} \]  
[Cohen 2004, van Haarlem et al. 2013]

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\text{nenufar\_calc,56,0,25.}

\begin{align*}
\text{Freq(MHz)} &= 25.0 & \text{Wavelength(m)} &= 12.0 & \text{nMAcore + remote} &= 56 + 0 \\
\text{dmax(m)} &= 400 & \text{df(MHz),dt(s)} &= 1.0, 1.000 & \text{decoh} &= 1.0 \\
\text{Aeff dipole,MA,NenuFAR(m^2)} &= 48.0, 597.0, 33433. \\
\text{Theta MA(°),FoV MA(°^2)} &= 27.5, 594. \\
\text{Theta NenuFAR(°)} &= 1.72 \\
\text{Tsky,Tlna(K)} &= 33889., 2094. & \text{SEFD MA,NenuFAR(Jy)} &= 166351., 2971. \\
\text{SminThermal,Confusion(Jy)} &= 2.100, 28.136
\end{align*}

\text{nenufar\_calc,56,0,25./plot} \Rightarrow \text{overlap}
nenufar_calc, 56, 0, 25., elev=30. ⇒ lower aMA & aNen, higher SminThermal (same SminConf)

Freq(MHz) = 25.0, Wavelength(m) = 12.0, nMAcore + remote = 56 + 0
Elev, Azim(°) = 30, 0, dmax(m) = 400, df(MHz), dt(s) = 1.0, 1.000, decoh = 1.0
Aeff dipole, MA, NenuFAR(m^2) = 48.0, 260.6, 14596.
Theta MA(°), FoV MA(°^2) = 27.5, 594.  Theta NenuFAR(°) = 1.72
Tsky, Tlna(K) = 33889., 2094.  SEFD MA, NenuFAR(Jy) = 381036., 6804.
SminThermal, Confusion(Jy) = 4.811, 28.136
nenufar_calc

nenufar_calc,56,0,25.,elev=30./plot ⇒ cf. plots from nenufar_gain
freq=findgen(38)*2+10 ⇒ ramp 10-84 MHz by 2 MHz step

nenufar_calc,56,0,freq ⇒ impractical display

nenufar_calc,56,0,freq./plot ⇒ + many plots

nenufar_calc,56,0,freq, l, a1,aMA,aNen, thMA,FoV,thNen, Tsky,Tlna, SefdMA,SefdNen, SminTh,SminConf, /quiet

window,0,xs=1000,ys=900
!p.multi=[0,2,2]
plot,freq,aNen,/xsty,/ynoz,xtit='Frequency (MHz)',ytit='NenuFAR Aeff (mU2!N)',tit='56 core MA',charsize=2.
plot_io,freq,SefdNen,/xsty,xtit='Frequency (MHz)',ytit='NenuFAR SEFD (Jy)',tit='56 core MA',charsize=2.
plot_io,freq,SminTh,/xsty,xtit='Frequency (MHz)',ytit='Thermal Noise (Jy)',tit='56 core MA',charsize=2.
plot_io,freq,SminConf,/xsty,xtit='Frequency (MHz)',ytit='Confusion Noise (Jy)',tit='56 core MA',charsize=2.
same with decoh=2.

/lofar => higher confusion

vary dmax, df, dt :

```
nenufar_calc, 80, 4, 50, dmax=1500, df=20, dt=3600
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```
Freq(MHz)= 50.0     Wavelength(m)=  6.0     nMAcore + remote= 80 + 4
           dmax(m)=  1500     df(MHz),dt(s)= 20.0,  3600.000     decoh= 1.0
Aeff dipole,MA,NenuFAR(m^2)=  12.0,  228.0,  19152.
Theta MA(°),FoV MA(°^2)=  13.8,    149.     Theta NenuFAR(arcmin)= 13.75
Tsky,Tlna(K)=    5787.,     488.     SEFD MA,NenuFAR(Jy)=    75964.,      904.
SminThermal,Confusion(Jy)=    0.002,    0.308
```

etc.
Adding a strong source (e.g. A-team) to NenuFAR's SEFD

```
nenufar_calc,56,0,freq, l, a1,aMA,aNen, thMA,FoV,thNen, Tsky,Tlna, SefdMA,SefdNen, SminTh,SminConf, /quiet

SCasA, freq, Scas

Cas A flux density spectrum (Jy) over frequency ramp freq (MHz) from [de Gasperin et al. 2020 & UTR-2]
```

```
plot_io,freq,Scas,/xsty,yra=[min(SefdNen),max(Scas)],xtit='Frequency (MHz)',ytit='NenuFAR SEFD & Cas A (Jy)',tit='56 core MA',charsize=2.
oplot,freq,SefdNen,line=2
```
\[ \text{Stot} = \text{SefdNen} + \text{Scas} \]
\[ \text{SminTh} = \frac{\text{Stot}}{\sqrt{2 \times 1 \times e^{-6}} 1} \quad \Rightarrow \quad \text{Stot} \times \text{decoh} / \sqrt{2 \times \text{df}\,[\text{Hz}] \times \text{dt}\,[\text{s}]} \]

plot_io, freq, SminTh, /xsty, xtit='Frequency (MHz)', ytit='Thermal Noise (Jy)', tit='56 core MA (SEFD+CAsA)', chsize=2., line=2

oplot, freq, SminTh
**nenufar_gain**

- Theoretical gain of NenuFAR for a pointing at elev, azim, freq

**nenufar_gain, elev(°), azim(°), freq (MHz) (all scalars)**

⇒ core only, up to 56 MA presently tabulated, soon updated to 80, then 96
⇒ takes into account array factor and antenna gains

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Computes the theoretical gain of current NenuFAR configuration for a pointing at elev, azim and frequency freq

**CALL**

`nenufar_gain, elev, azim, freq, ae, g_array, g_NE, g_NW, /accurate,/plot,/quiet`

**INPUTS**

elev, azim = elevation, azimuth (deg.) [scalars]
freq = frequency (MHz) [scalar]

**KEYWORDS**

nMA = nMA => if less than maximum available
/accurate => accurate (<0.1%) and longer calculation of Aeff
/plot => display Mini-Arrays effective area & antennas layout
/quiet => does not print any output
/help => extensive help
/hlp => summary help

**OUTPUTS**

ae = effective area of NenuFAR core [m^2]
g_array = array gain [linear value]
g_NE = array & NE_SW antenna gain [linear value]
g_NW = array & NW_SE antenna gain [linear value]
aMA = effective area of 1 MA [m^2]
nenufar_gain

- Theoretical gain of NenuFAR for a pointing at elev, azim, freq

\[ \text{nenufar\_gain, elev}(^\circ), \text{azim}(^\circ), \text{freq (MHz)} \ (\text{all scalars}) \]

- core only, up to 56 MA presently tabulated, soon updated to 80, then 96
- takes into account array factor and antenna gains

\[ \text{nenufar\_gain, /hlp} \]

\[ \text{nenufar\_gain, [IN] elev, azim, freq, $} \]
\[ \text{[OUT] ae, g\_array, g\_NE, g\_NW, aMA, $} \]
\[ \text{[KEY] nMA=nMA, /accurate, /plot, /quiet} \]
nenufar_gain

Elevation = 90°, Azimuth = 0°, Frequency = 50 MHz

n Mini-Arrays = 56
Ae Array = 12768.0 m^2
Gain Array = 4456.87 = 36.4903 dB
Gain Array * NE_SW = 17459.4 = 42.4203 dB
Gain Array * NW_SE = 17459.4 = 42.4203 dB
Ae 1 MA = 228.000 m^2
nenufar_gain

nenufar_gain, 90, 0, 50, /plot
**Elevation = 30°, Azimuth = 0°, Frequency = 50 MHz**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n Mini-Arrays</td>
<td>56</td>
</tr>
<tr>
<td>Ae Array</td>
<td>8350.02 m²</td>
</tr>
<tr>
<td>Gain Array</td>
<td>2914.71 = 34.6460 dB</td>
</tr>
<tr>
<td>Gain Array * NE_SW</td>
<td>4136.14 = 36.1660 dB</td>
</tr>
<tr>
<td>Gain Array * NW_SE</td>
<td>4136.14 = 36.1660 dB</td>
</tr>
<tr>
<td>Ae 1 MA</td>
<td>149.108 m²</td>
</tr>
</tbody>
</table>
nenufar_gain

nenufar_gain,30,0,50,/plot
Elevation = 30°, Azimuth = 100°, Frequency = 50 MHz
n Mini-Arrays = 30
Ae Array = 4515.93 m²
Gain Array = 1576.36 dB
Gain Array * NE_SW = 2310.23 dB
Gain Array * NW_SE = 2165.98 dB
Ae 1 MA = 150.531 m²
nenufar_gain, 30, 100, 50, nMA=30, /plot