Putting noise to work …

Noise Measurement and SEFD Estimation Using TotalPower and Murmur

Mario Armando Natali, I0NAA / KD2RQO

mario.natali@gmail.com

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Putting noise to work

Signal, noise, SNR … speaking the same language

In radio communication, *signal and noise* are fundamental concepts that determine whether information can be successfully transmitted and received.

SNR (Signal to Noise Ratio) tells you how strong the signal is compared to the noise and is defined as the ratio of the average power of the desired signal to the average power of the noise, measured at the same point in the system and within the same bandwidth.

We often state that the signal is “below the noise”…

…. Is this correct ?….. **Oooooh well …. not exactly !**

We should say that the signal is below the noise only on short time scales and over wide bandwidths.
By controlling the bandwidth and applying coherent (or folded) integration, the effective noise power is reduced, allowing reliable signal detection.

Putting noise to work

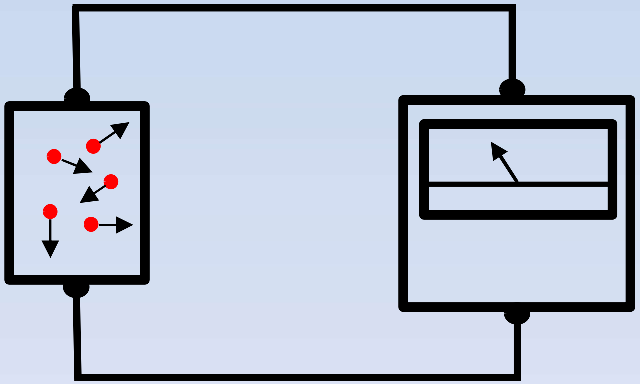
Noise in communication systems

The NOISE is any unwanted signals, random or deterministic, which interfere with the signal of interest and degrades its characteristics.

Noise

- **Internal noise**
  - **Quantization noise**
  - **Intermodulation noise**
  - **Phase noise**
  - ***Thermal noise***
- **External noise**
  - **Artificial noise (man made)**
  - **Environmental noise**
  - **Cosmic noise**

The *thermal noise* is due to the thermal agitation of the electrons which, at a temperature T> 0 K, have a chaotic (Brownian) motion.



The thermal noise voltage has zero mean with Gaussian amplitude distribution.

The effective value is

$$v_{rms} = \sqrt{4kTBR}$$

k = Boltzmann constant (1.38 ·10–23 J/K)
T = Temperature in Kelvin
B = Bandwidth (Hz)
R = Resitance (Ohm)

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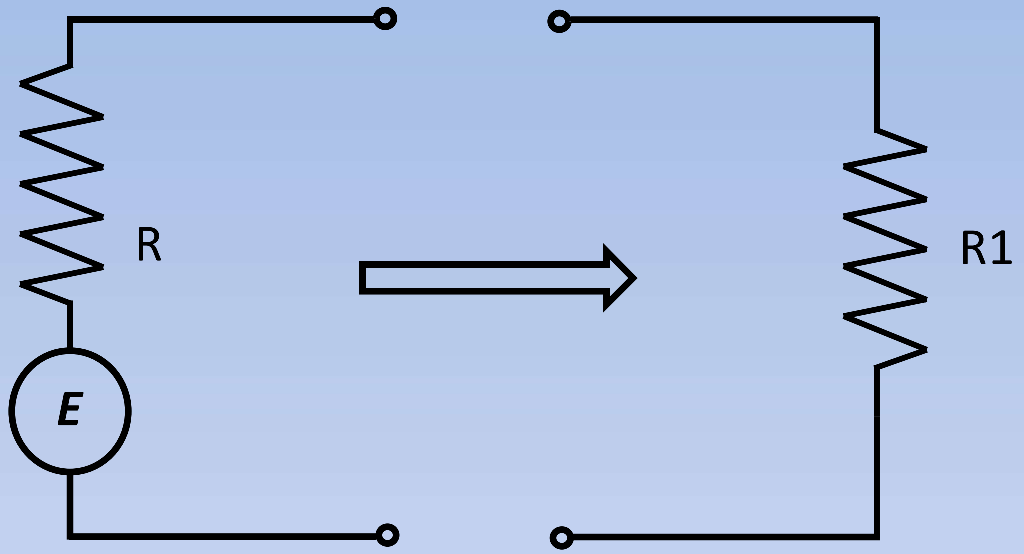
Noise in communication systems

$$v_{rms}=\sqrt{4kTBR}$$



Equivalent circuit of a real resistor R:

generator *E with value v* in series with an *ideal resistor R*

The condition for maximum power transfer occurs when R = R1 (matched load)

In matched conditions, we obtain maximum power transfer from the source to the load

$$I=\frac{v_{rms}}{R+R1} \Longrightarrow P=\frac{v_{rms}^{2}}{4R}=kTB$$

(*) The voltage @ R1 is $\frac{v_{rms}}{2}$

A direct proportionality can therefore be observed between P (noise power) and T (temperature)

To quantify noise, we can therefore use the so-called *equivalent noise temperature T* (*expressed in Kelvin*)

If we want to evaluate the performance (i.e. the sensitivity) of a receiving system, we must rely on a source of reference noise and compare the measured values (Y-factor method) :

$$Y = \frac{P_{hot}}{P_{cold}}$$

P_{hot} = Noise power pointing antenna to the source
P_{cold} = Noise power pointing the antenna to reference source

Focusing on a specific receiving system and using the "equivalent temperature" concept the above equation can be expressed in terms of temperature and represented in dB (Y-factor method) :

$$Y = 10\ log_{10}\left(\frac{T_{sys} + T_{ant}}{T_{sys} + T_{ref}}\right)$$

Y = measured power ratio in dB
Tsys = receiver/system noise temperature
Tant = antenna temperature when pointing to the source
Tref = reference ("cold sky") temperature

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Noise in communication systems

As T_{ref} is much smaller compared to T_{sys} we can write :

$$Y = 10\ log_{10}\left(1 + \frac{T_{ant}}{T_{sys}}\right)$$

Since we also know that (*)

$$T_{ant} = F\frac{A_e}{2\,K_b} = F\frac{A_e}{2760}$$

where $A_e = G\frac{\lambda^2}{4\Pi} = k\,\frac{\pi\,D^2}{\lambda}$

(*) J.D.Kraus, radio Astronomy , 2° edition, Cygnus-Quasar Books, 1986, chapter 6

A_e = Dish effective area
k = Dish efficiency (usually between 0.5 and 0.7)
G = Antenna Gain
D = Dish Diameter
K_b = Boltzman constant 1.380662 $10^{-23}\ J/K$
F = Flux of the source in Jy

If the flux density F of a source is known, the antenna efficiency is specified, and the system temperature T_{sys} is known, the Y-factor can be calculated by measuring the antenna temperature T_{ant} . Naturally, the stronger the radio source, the easier and more accurate the measurement becomes.
For this reason, the Sun is typically the preferred source.

➢ ***How to measure equivalent antenna temperature ?***

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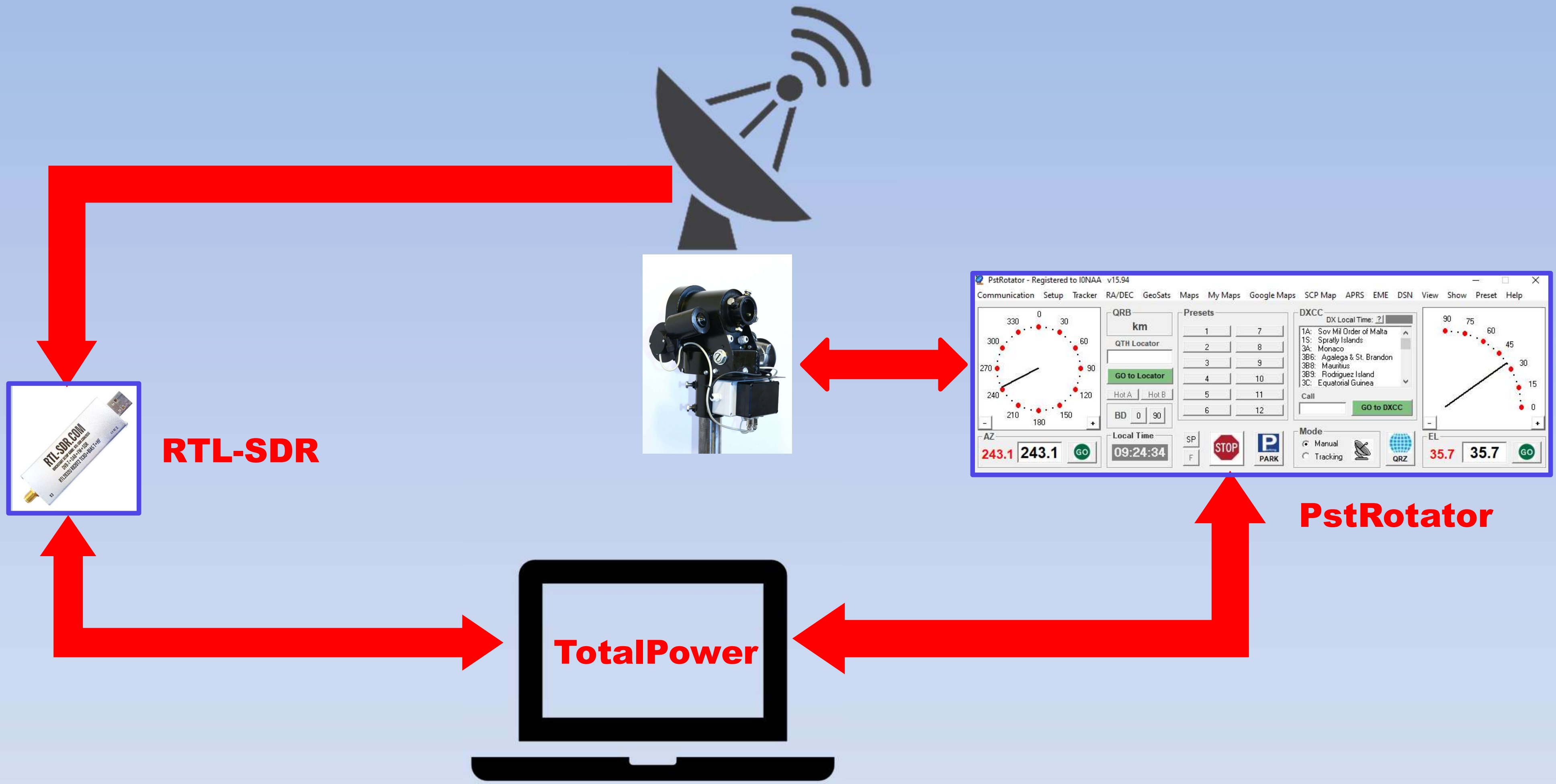
TotalPower : a cheap solution to measure noise



- ✓ **The interface with PstRotator (https://www.pstrotator.com/), implemented using the UDP protocol, provides control over virtually all commercially available antenna rotators.**
- ✓ **TotalPower is available for free download from my website: https://i0naa.altervista.org/**

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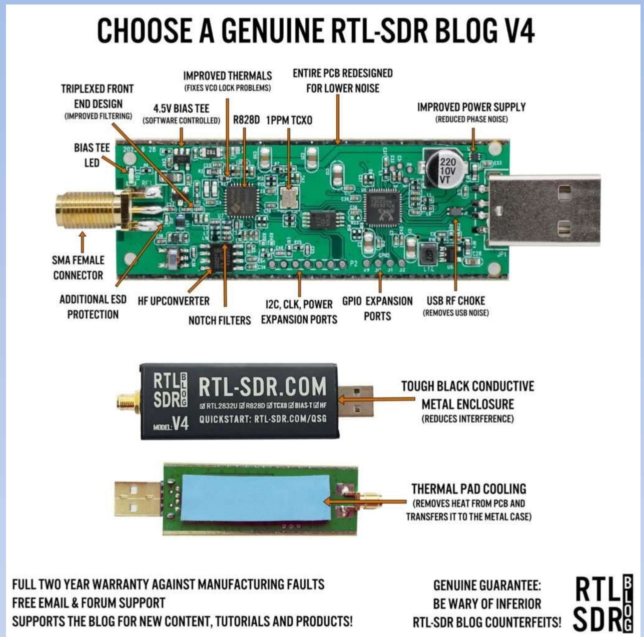
TotalPower : a cheap solution to measure noise



- ✓ **The RTL-SDR samples the incoming signal data and stores it in a 65,536-byte buffer containing a sequence of I/Q samples, which are then made available to the application for further processing.**

- ➢ **Frequency range : ≈ 24 – 1766 MHz**
- ➢ **ADC : 8 bit (7+1)**
- ➢ **Sampling up to 3.2MSPS -> 3.2 Mhz of BW**

The main limitations associated with this low-cost dongle are :

- ➢ ***Performance instability caused by thermal drift.***
- ➢ **Intermodulation.**
- ➢ **Aliasing.**
- ➢ **Overload.**

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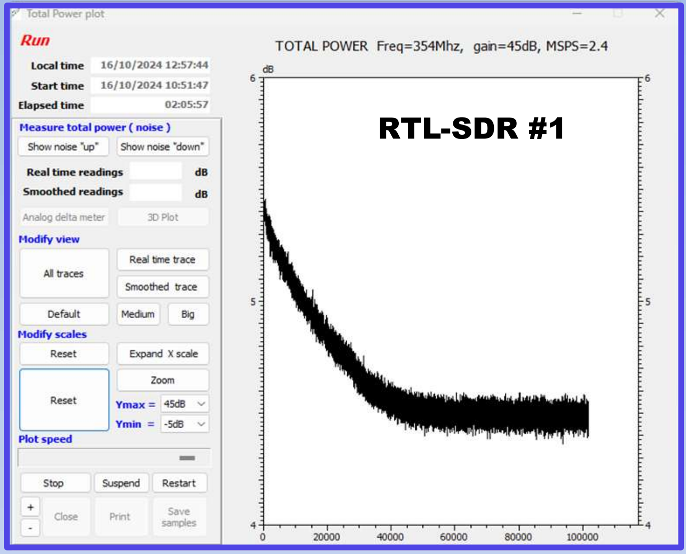
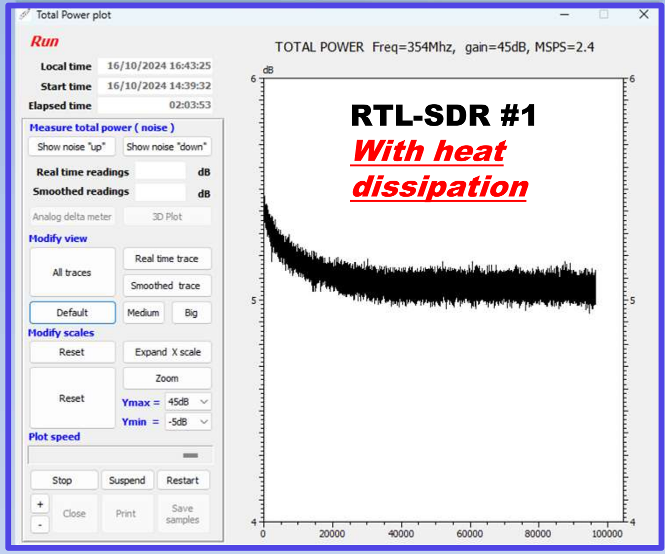
TotalPower : Thermal stabilization



2 hours recording without heat dissipation system



2 hours recording with heat dissipation system

Heat dissipation system powered by USB

- ✓ **Tests performed using a commercially available heat dissipation system sourced from the Etsy platform (https://www.etsy.com/) showed that stable operating conditions and consistent receiver performance were achieved after only approximately 20 minutes of warm-up time.**

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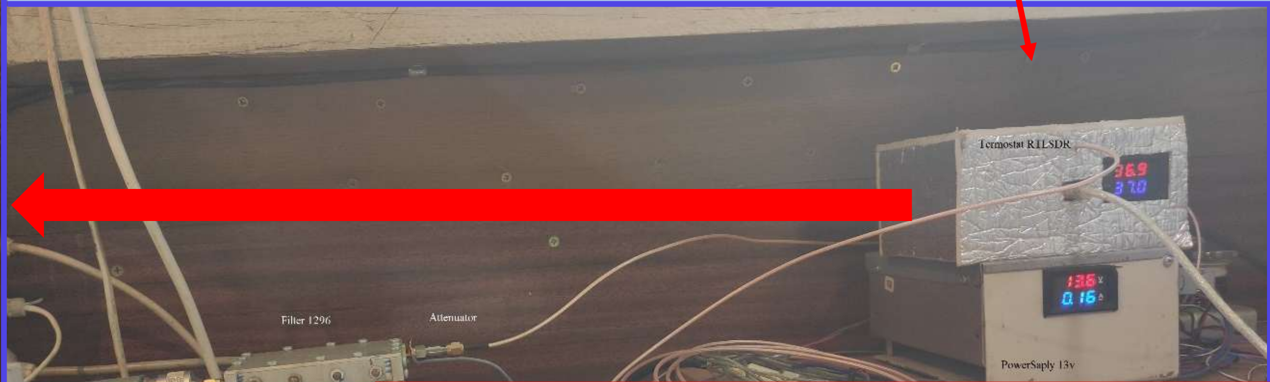
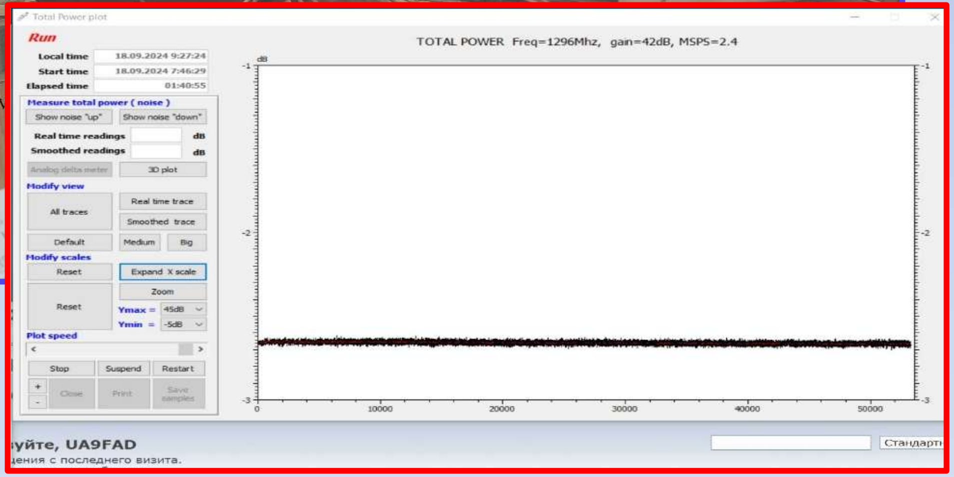
TotalPower : Thermal stabilization

Heating blocks

Thermally insulated enclosure





- ✓ **Excellent results were also achieved by Victor UA9FAD heating the RTL-SDR and stabilizing its operating temperature inside a thermally insulated enclosure using a dedicated temperature controller.**

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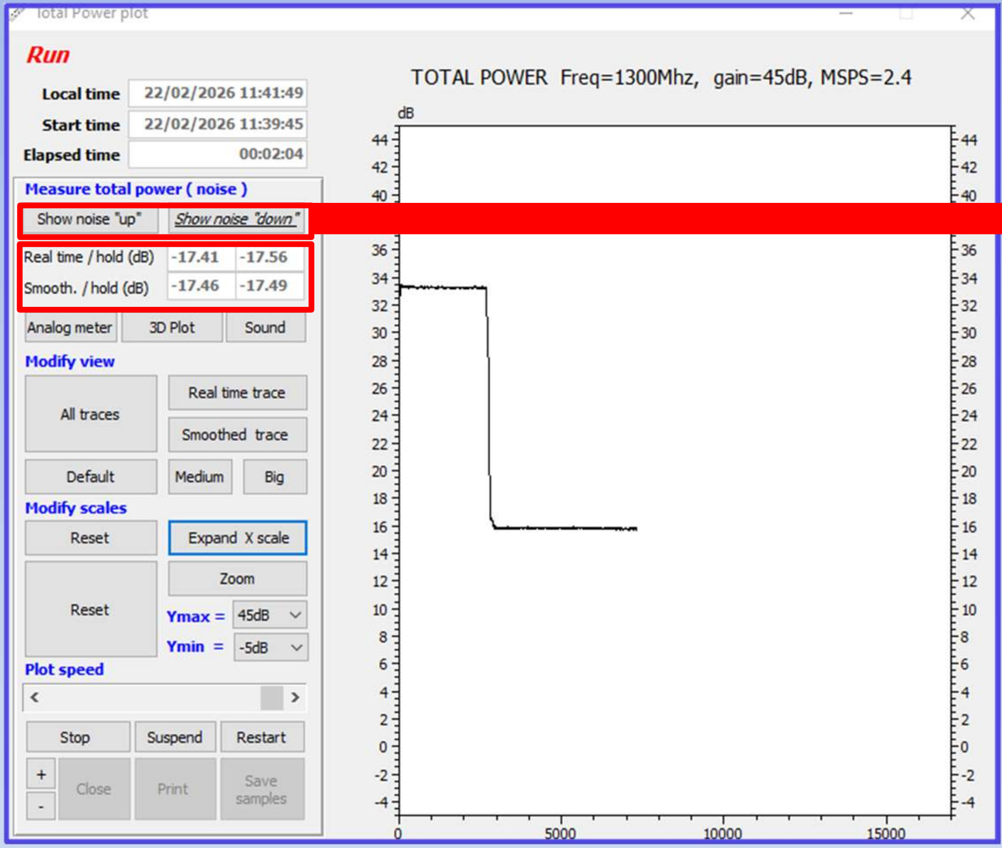
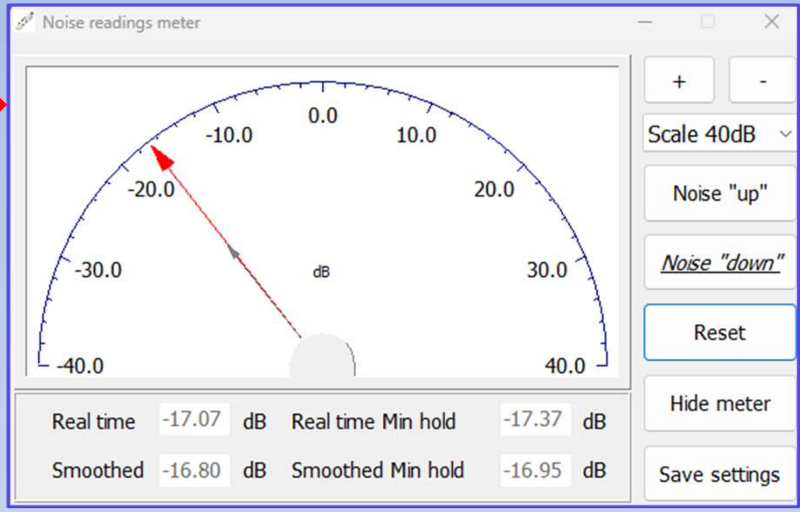
TotalPower : noise measure





TotalPower also displays the measured values with an analog meter.

Above plot shows Sun noise measurement using the Y-factor method by first pointing the antenna toward the Sun and then establishing the cold-sky reference by off-pointing the antenna by approximately 15° (~5× HPBW) while *maintaining the same elevation angle*.

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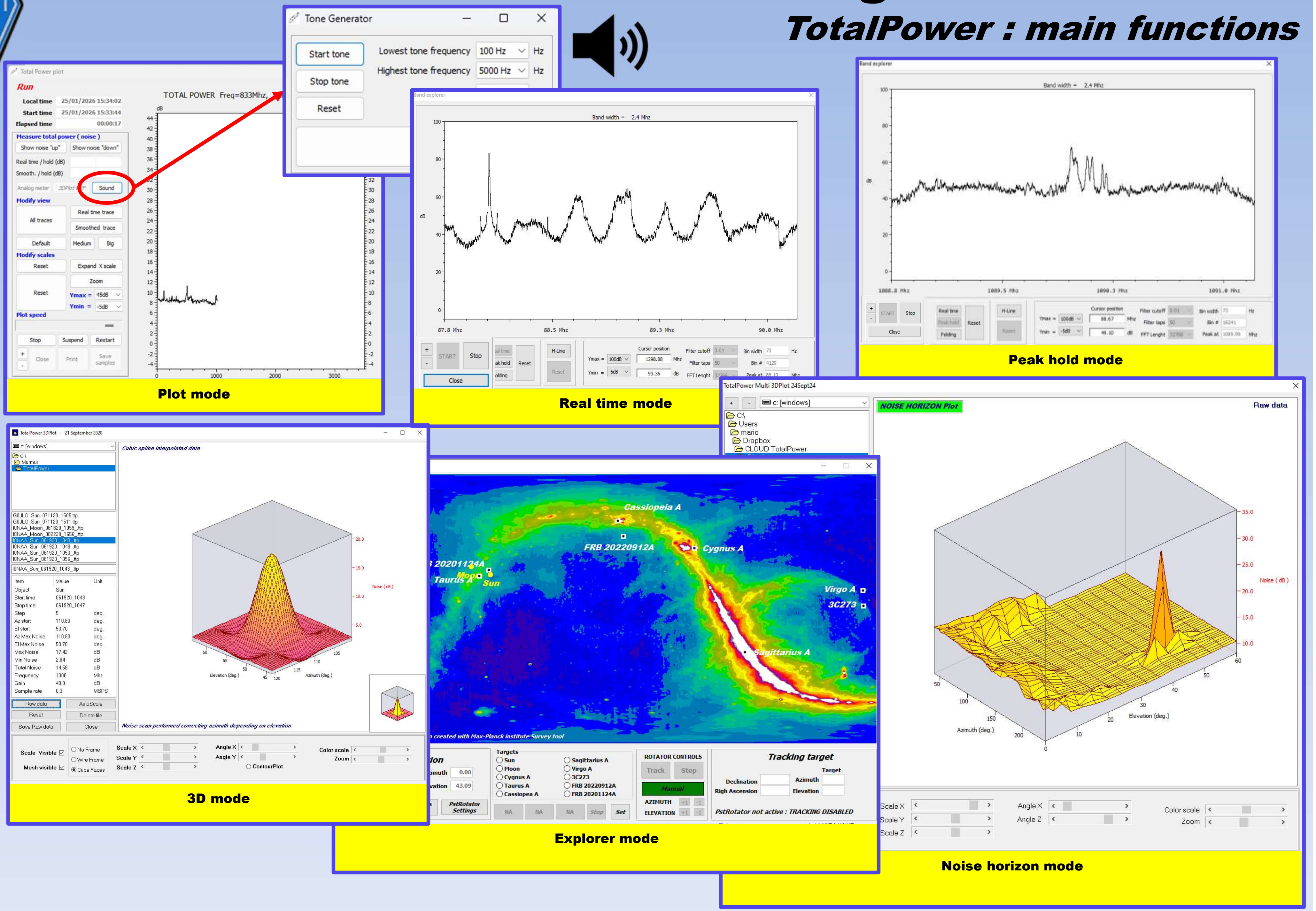
TotalPower : main functions



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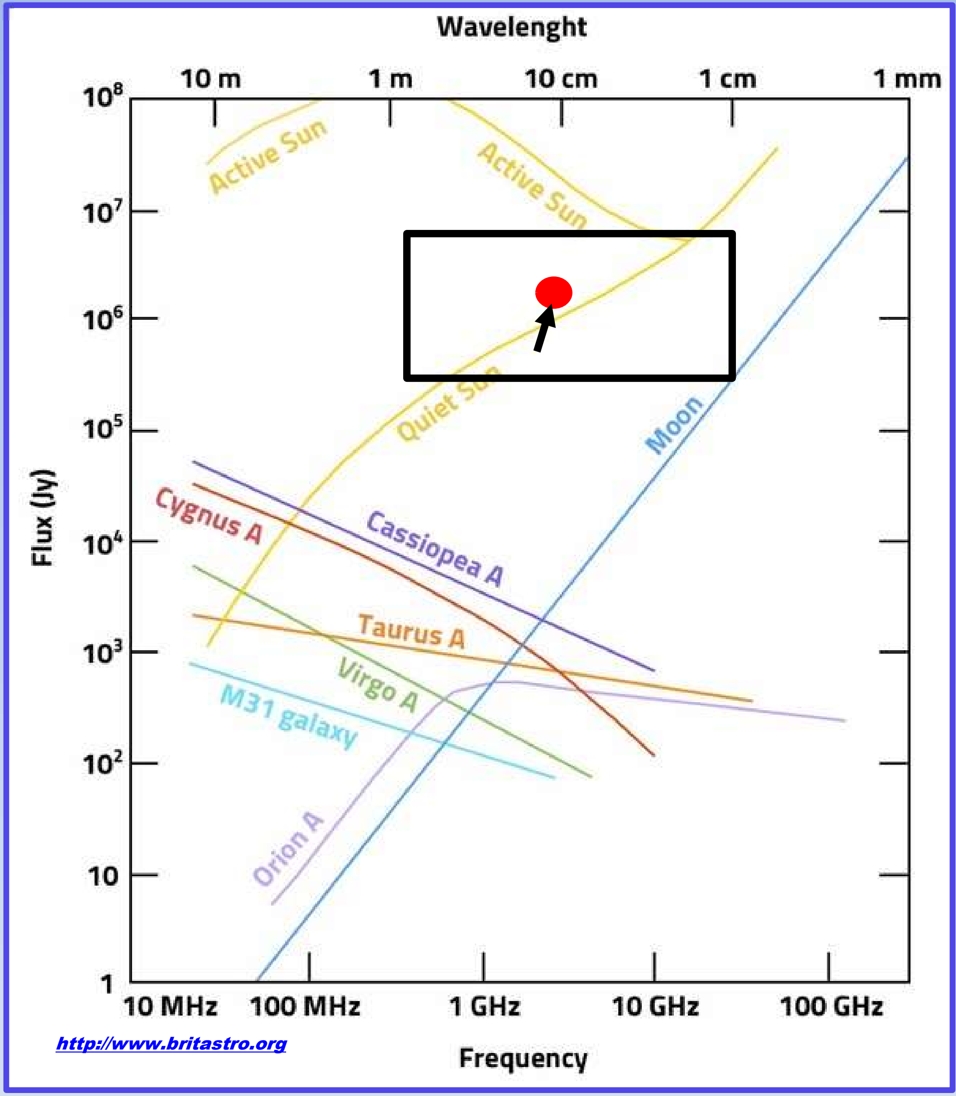
Sun noise

1 Jy = 10^{-26} Wm^{-2} Hz^{-1}



Flux density data for major cosmicradio sources

Due to the significant temporal variability of solar radio emissions, accurate prediction require almost real-time evaluation of the solar flux density interpolating observational data acquired from NOAA solar flux monitoring observatories operating at multiple reference frequencies.

➢ ***How to predict expected noise?***

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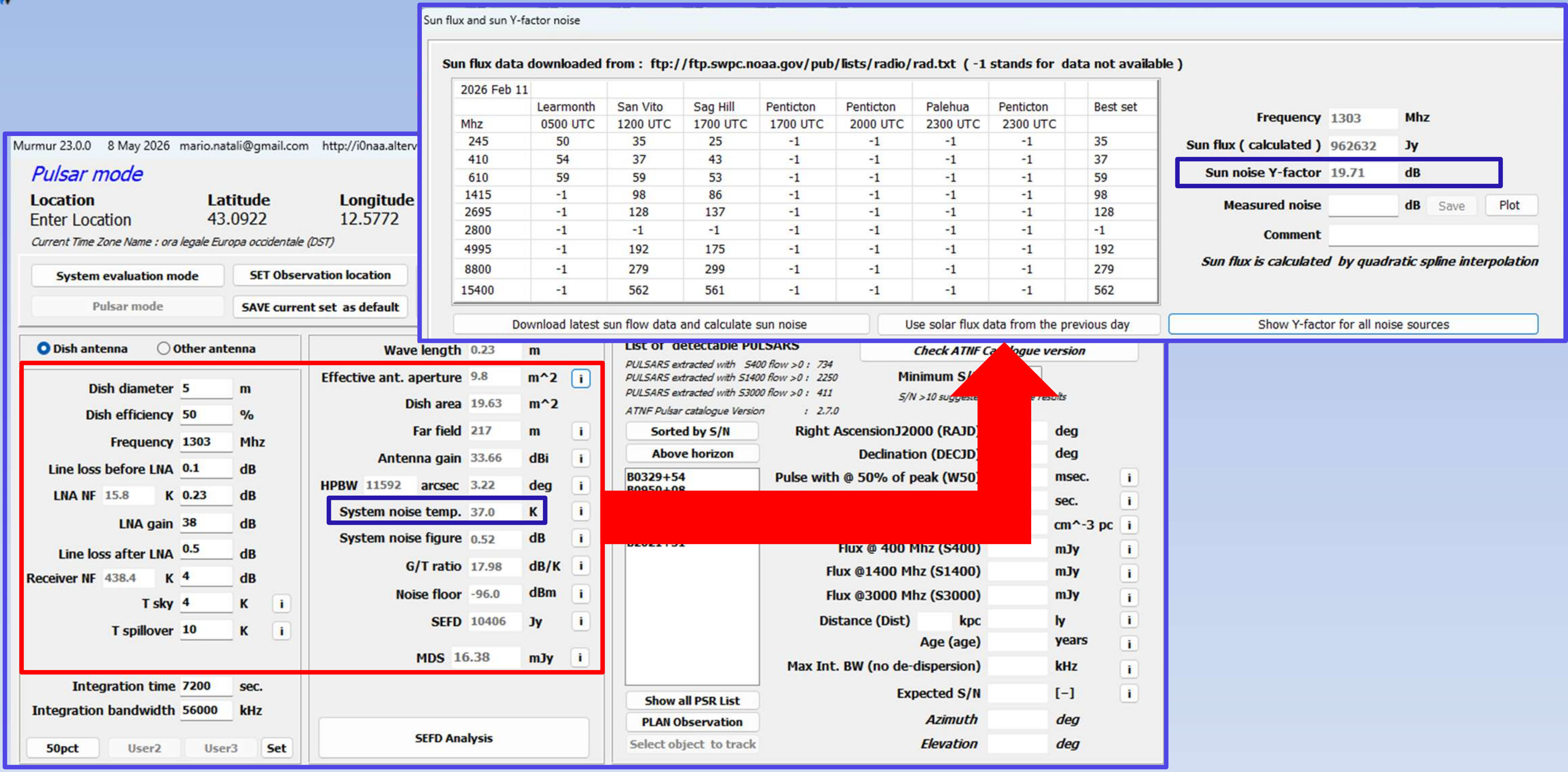
Murmur : the prediction program



2026 Feb 11 Mhz	Learmonth 0500 UTC	San Vito 1200 UTC	Sag Hill 1700 UTC	Penticton 1700 UTC	Penticton 2000 UTC	Palehua 2300 UTC	Penticton 2300 UTC	Best set
245	50	35	25	-1	-1	-1	-1	35
410	54	37	43	-1	-1	-1	-1	37
610	59	59	53	-1	-1	-1	-1	59
1415	-1	98	86	-1	-1	-1	-1	98
2695	-1	128	137	-1	-1	-1	-1	128
2800	-1	-1	-1	-1	-1	-1	-1	-1
4995	-1	192	175	-1	-1	-1	-1	192
8800	-1	279	299	-1	-1	-1	-1	279
15400	-1	562	561	-1	-1	-1	-1	562

The predicted solar Y-factor is calculated by taking into account the receiving system parameters together with a spline interpolation of the latest solar flux measurements downloaded from the NOAA solar observatories FTP server.

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Murmur : the prediction program

Sun flux and sun Y-factor noise

Sun flux data downloaded from : ftp://ftp.swpc.noaa.gov/pub/lists/radio/rad.txt (-1 stands for data not available)

2026 Feb 11								
	Learmonth	San Vito	Sag Hill	Penticton	Penticton	Palehua	Penticton	Best set
Mhz	0500 UTC	1200 UTC	1700 UTC	1700 UTC	2000 UTC	2300 UTC	2300 UTC	
245	50	35	25	-1	-1	-1	-1	35
410	54	37	43	-1	-1	-1	-1	37
610	59	59	53	-1	-1	-1	-1	59
1415	-1	98	86	-1	-1	-1	-1	98
2695	-1	128	137	-1	-1	-1	-1	128
2800	-1	-1	-1	-1	-1	-1	-1	-1
4995	-1	192	175	-1	-1	-1	-1	192
8800	-1	279	299	-1	-1	-1	-1	279
15400	-1	562	561	-1	-1	-1	-1	562

Frequency 1303 **Mhz**
Sun flux (calculated) 962632 **Jy**
Sun noise Y-factor 19.71 **dB**
Measured noise **dB** Save Plot
Comment

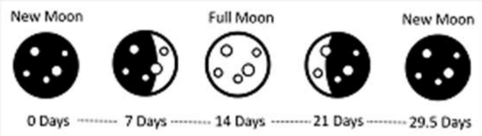
Sun flux is calculated by quadratic spline interpolation

Download latest sun flow data and calculate sun noise | Use solar flux data from the previous day | Show Y-factor for all noise sources

Y-Factor noise

	Cassiopeia A	Cygnus A	Taurus A	Sagittarius A	Virgo A	3C273	Moon
Flux (Jy)	1947	1748	912	520	223	42	726
Noise Y-Factor (dB)	0.75	0.67	0.37	0.21	0.09	0.02	0.29

Moon distance (Km) 403747.7
Moon age (days) 21.34
Moon estimated surface temperature (K) 242



Close

Murmur also calculates the expected Y-factor noise of he major cosmic radio sources.

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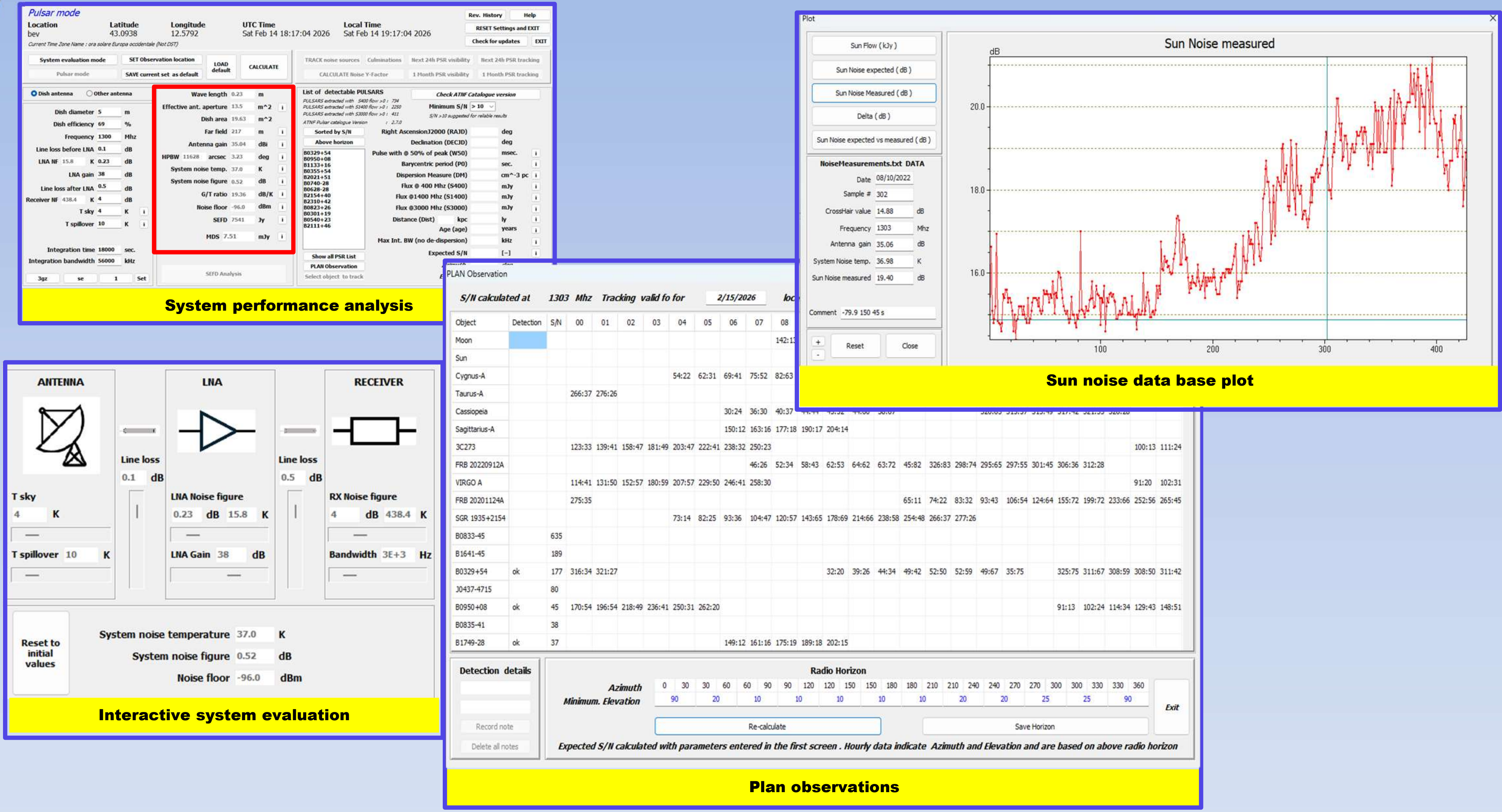
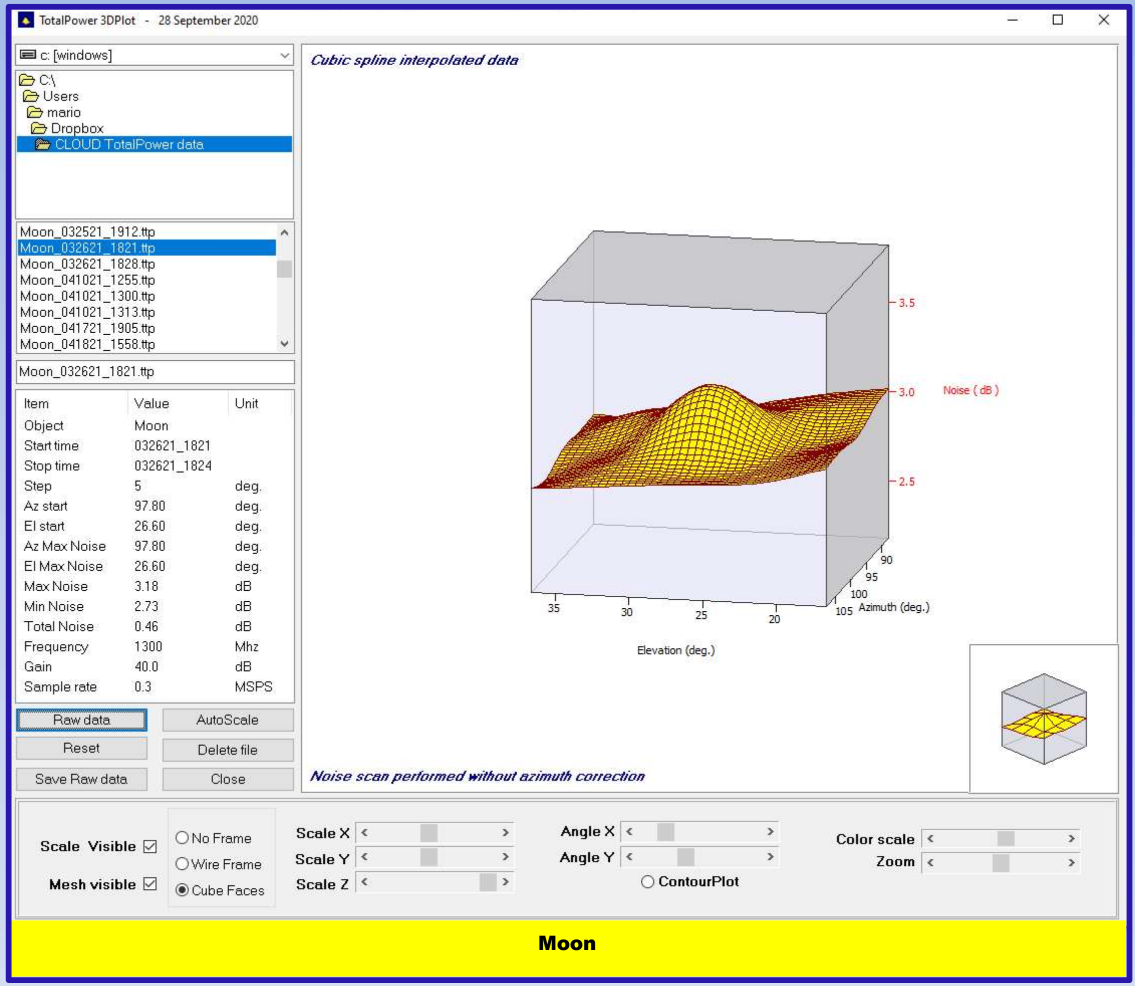
Murmur : main functions



- ✓ **Murmur began as a pulsar detectability predictor and has evolved into a full-stack EME performance analyzer, delivering quantitative RX-chain modelling, noise-budget evaluation, and cosmic source noise prediction.**
- ✓ **Murmur is available for free download from my website: https://i0naa.altervista.org/ .**

Putting noise to work

CAVEAT – 3D Plot



- **When measuring very weak radio sources, ground noise must be carefully taken into account. High-resolution 3D plots are an excellent tool for visualizing and understanding its impact on the measurements.**

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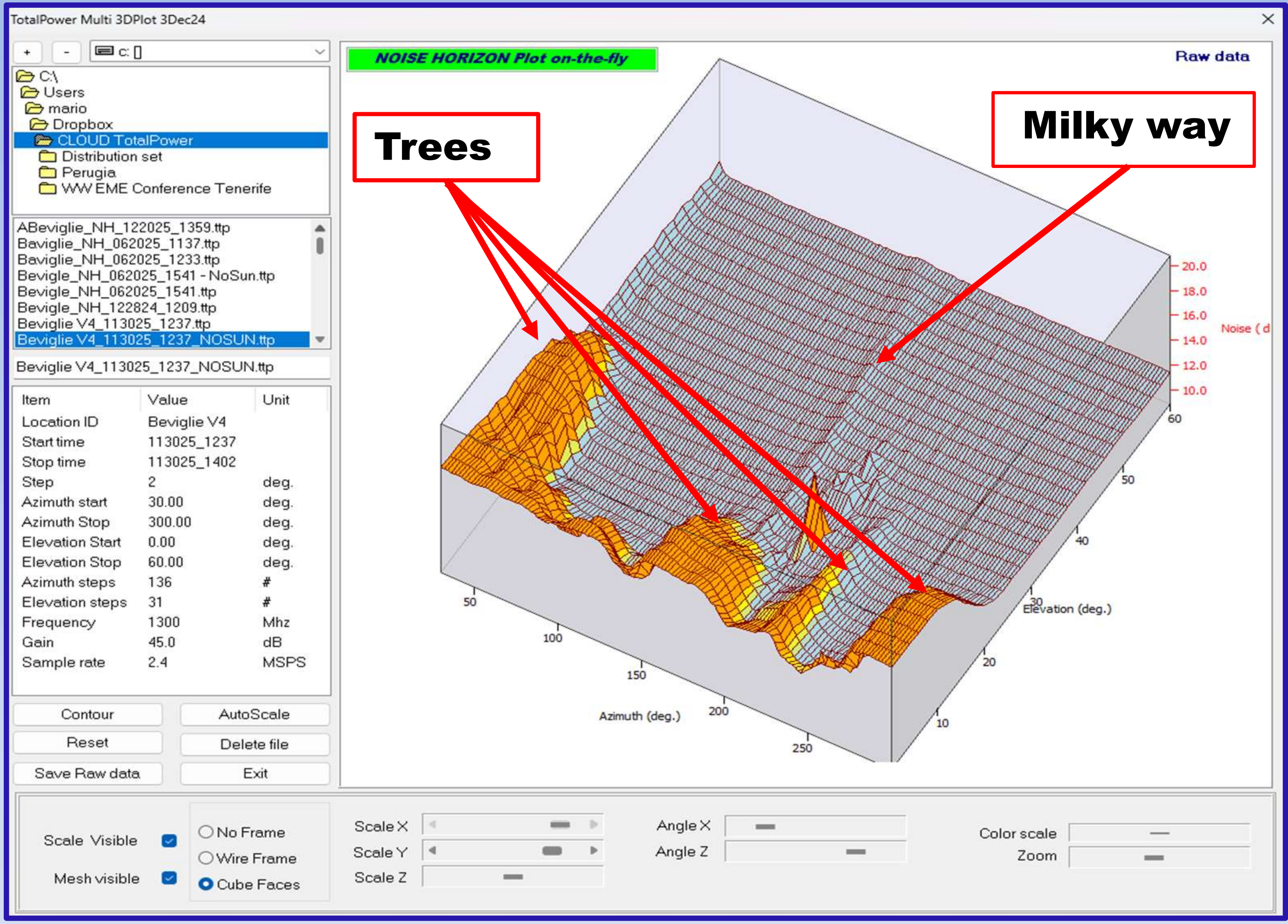
CAVEAT – Noise horizon



- ➢ **A high-resolution noise horizon map helps identify the coldest sky regions for accurate measurements.**
- ➢ **Even the Milky Way, visible in this map, can affect the results.**

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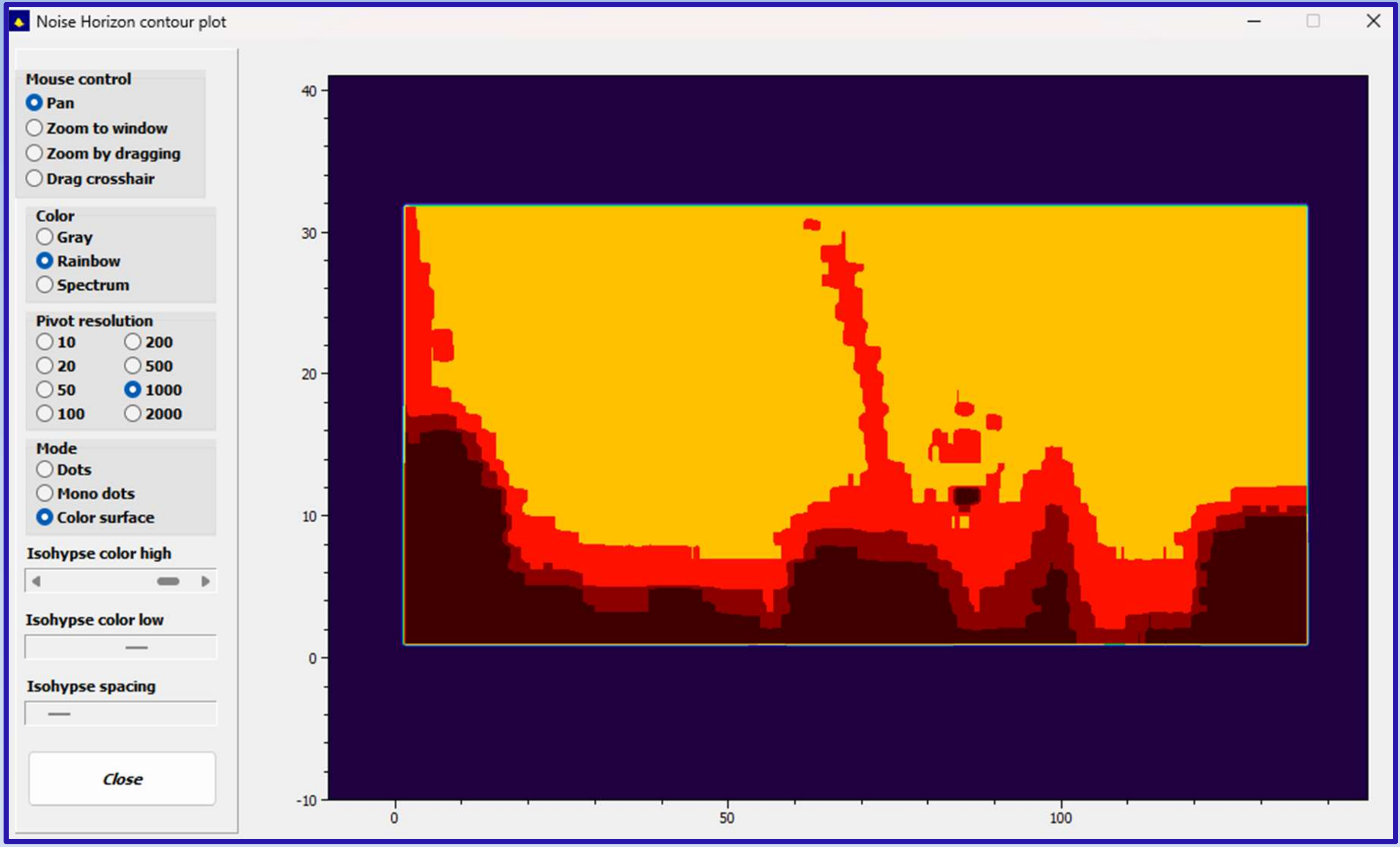
CAVEAT – Noise horizon



- **The dynamic contour map complements the 3D plot by helping visualize and interpret the underlying noise patterns.**

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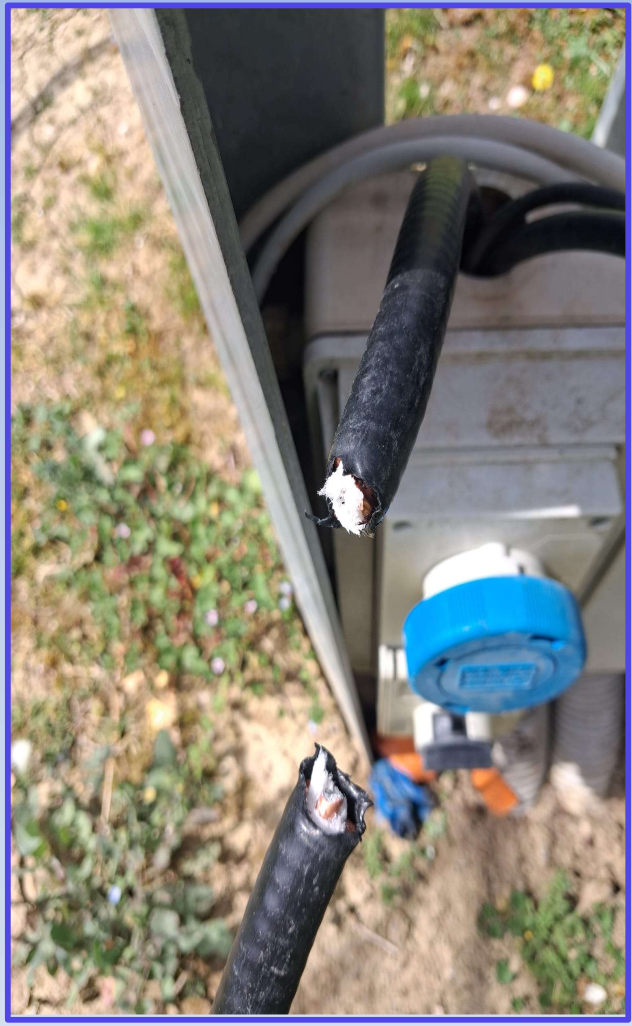
CAVEAT – Noise horizon



- **… anyway, be very careful when setting Azimuth and Elevation limits before generating 3D plots or Noise Horizon maps… 🙁**

Putting noise to work

SEFD : System Equivalent Flux Density

- **We have seen the classical methodology for system optimization.**
- **A large number of parameters must be measured and analyzed in order to properly characterize and define a system.**
- **When comparing different systems, or when monitoring system performance over time, all of these parameters must be continuously tracked.**
- **However, there is a single well-established parameter (very common in radio astronomy) that efficiently combines all of them:**

SEFD (System Equivalent Flux Density)

Putting noise to work

SEFD : System Equivalent Flux Density

System Equivalent Flux Density (SEFD) is the flux density of a hypothetical radio source that produces, at the output of a radio telescope, a signal-to-noise ratio of unity (S/N = 1) for a given system noise temperature, per unit bandwidth and per unit integration time.

$$SEFD = \frac{2kT_{sys}}{A_{eff}}$$

k = Boltzmann constant (1.38 ·10–23 J/K)
T sys = Temperature (in Kelvin)
Aeff = Effective collecting area of the antenna

The SEFD is expressed in jansky (Jy), 1 Jy = 10^{-26} ***W*** m^{-2} ***Hz*** $^{-1}$

- **A lower SEFD corresponds to higher system sensitivity.**
- **SEFD accounts for the combined effects of the antenna, receiver, losses, sky noise, atmospheric contribution, and environment.**
- **Two systems with the same SEFD are equivalent in sensitivity, regardless of their individual design details.**

Putting noise to work

SEFD : System Equivalent Flux Density

Considering the radiometer equation, which defines the sensitivity of a radio telescope as the RMS noise fluctuation of the system :

$$\Delta T_{sys} = \frac{T_{sys}}{\sqrt[2]{t n_p \, \Delta f}}$$

$T_{sys} = T_{rec} + T_{spill} + T_{atm} + T_{sky}$ (in Kelvin)

- T_{rec} = receiver noise temperature
- T_{spill} = spillover contribution from the ground
- T_{atm} = atmosphere emissions (important @ > 5 Ghz)
- T_{sk} = Sky background radiation

t = integration time (sec)

$n_p = 1$ for single polarization observations

Δf = observing bandwidth (Hz)

And considering that to a source with flux density F corresponds an antenna temperature T_A :

$$T_a = T_{sys} \frac{F}{SEFD}$$

(If $F = SEFD$ then $T_A = T_{sys}$)

We can rewrite SNR as :

$$SNR = \frac{T_{sys}\left(\frac{F}{SEFD}\right)}{\frac{T_{sys}}{\sqrt[2]{t n_p \, \Delta f}}} = \frac{F}{SEFD} \sqrt[2]{t n_p \, \Delta f}$$

Knowing the system SEFD and the flux density of a radio source F, it is possible to calculate the required receiver bandwidth and integration time needed to achieve a specified signal-to-noise ratio (S/N).

Putting noise to work

SEFD : Field measurements

We have seen that :

$$T_{ant} = T_{sys}\frac{F}{SEFD} \Rightarrow \frac{T_{ant}}{T_{sys}} = \frac{F}{SEFD}$$

Measuring Pon and Poff we obtain the Y factor of source :

$$Y_{source} = \frac{P_{hot}}{P_{cold}} \Rightarrow P \propto T \Rightarrow Y_{source} = \frac{T_{ant} + T_{off}}{T_{off}} = 1 + \frac{T_{ant}}{T_{off}}$$

$S = flux\ of\ source\ (Jy)$
$T_{hot} = Antenna\ temperature\ when\ pointig\ the\ source (K)$
$T_{cold} = Antenna\ temperature\ when\ pointig\ cold\ sky (K)$

Combining the two equations we have:

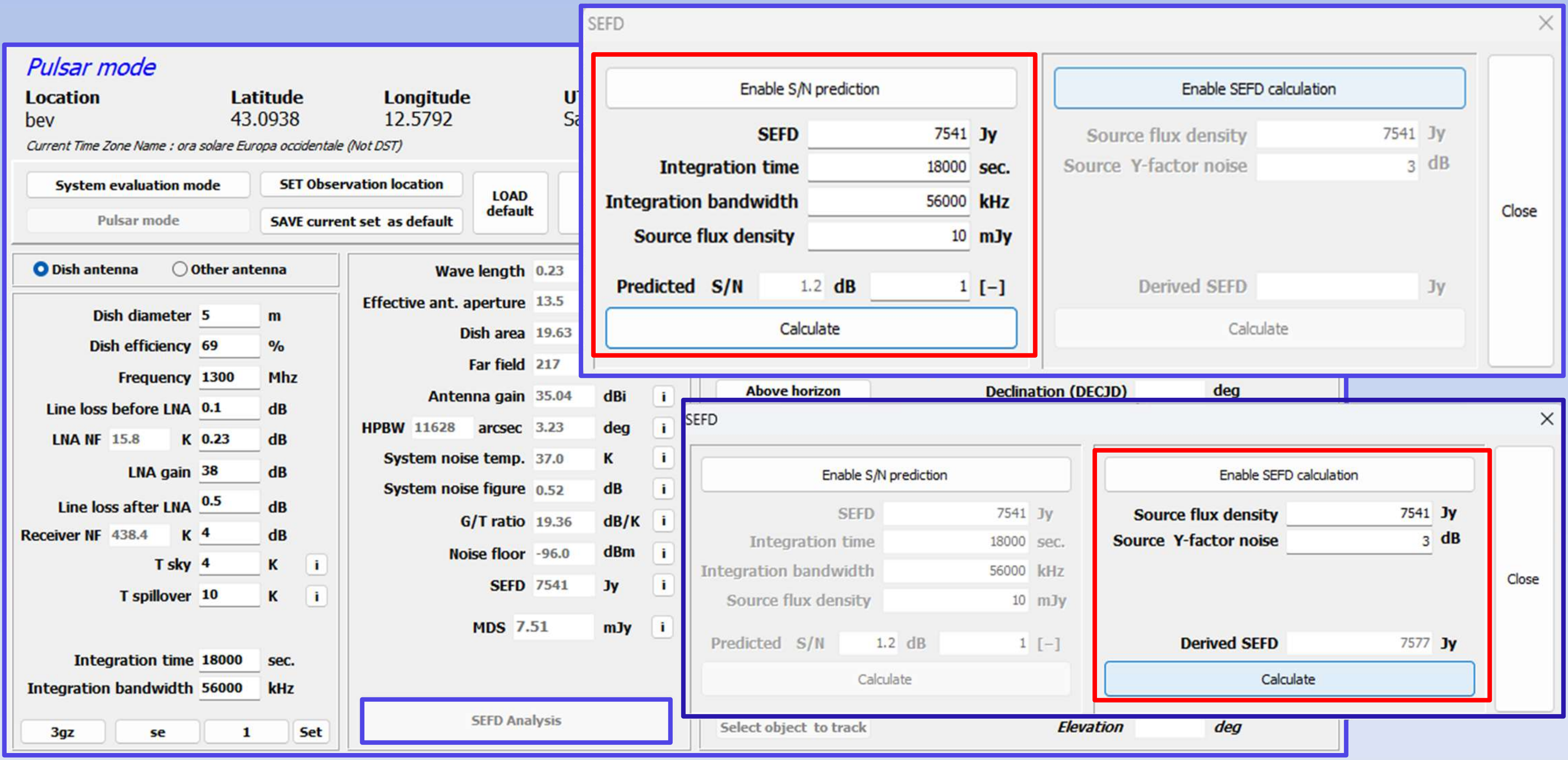
$$SEFD = \frac{F}{Y_{source} - 1}$$

The measurement of noise (Y_{source}) from a known cosmic source (F) allows SEFD estimation without knowing T_{sys} .

Putting noise to work

SEFD : Theoretical estimation with Murmur

Murmur not only allows the calculation of the system SEFD with the Y-method, but also enables the estimation of the expected SNR of a source as a function of bandwidth and integration time.



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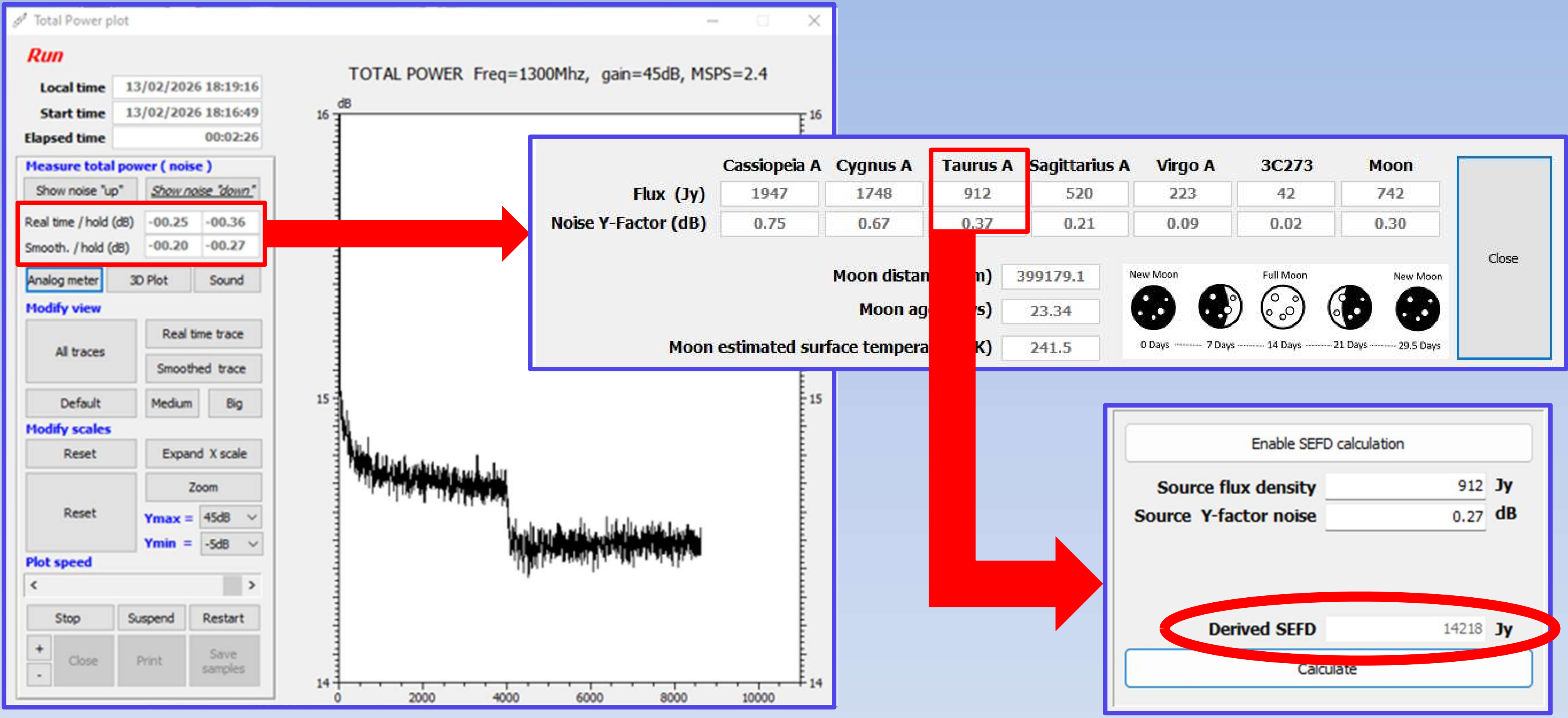
SEFD : Estimation Using Taurus A (Crab Nebula) noise



Taurus A noise measured using the Y-factor method, with the antenna off-pointed by 15° (~5× HPBW) at the same elevation (~30°). Data acquisition was performed with <u>TotalPower</u> ; numerical processing and SEFD computation were carried out with <u>Murmur.</u>

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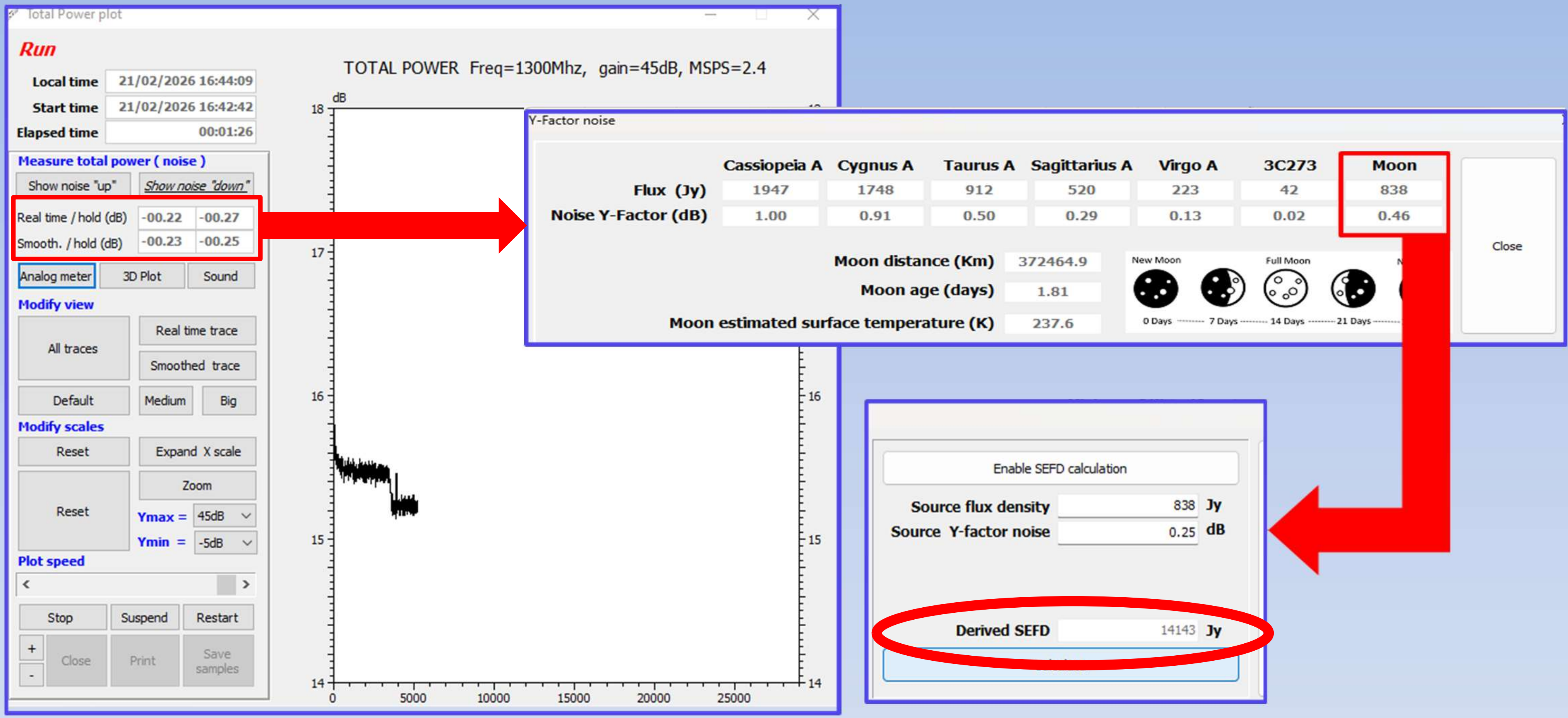
SEFD : Estimation Using Moon noise



Moon noise measured using the Y-factor method, with the antenna off-pointed by 15° (~5× HPBW) at the same elevation (~55°).

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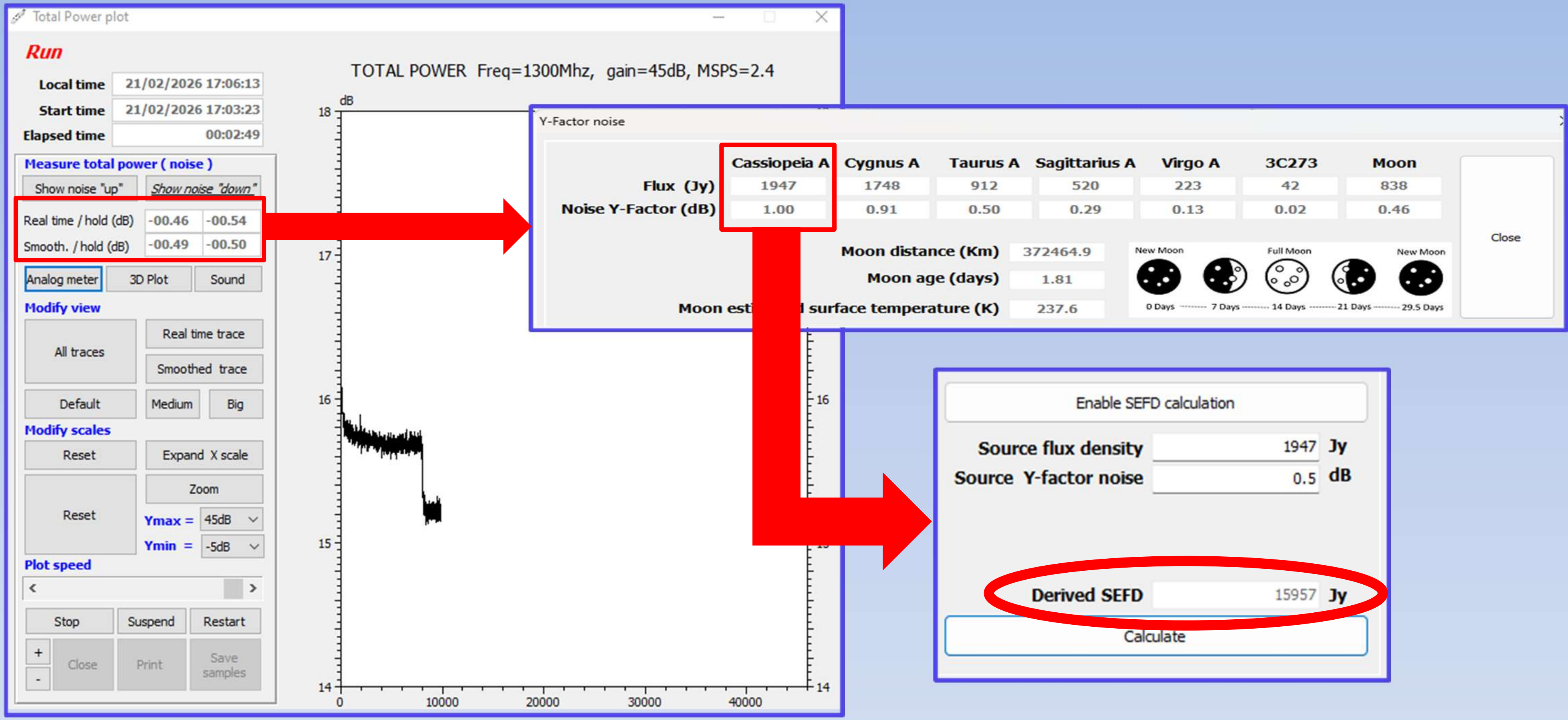
SEFD : Estimation Using Cassiopeia A noise



Cassiopeia A noise measured using the Y-factor method, with the antenna off-pointed by 15° (~5× HPBW) at the same elevation (~53°).

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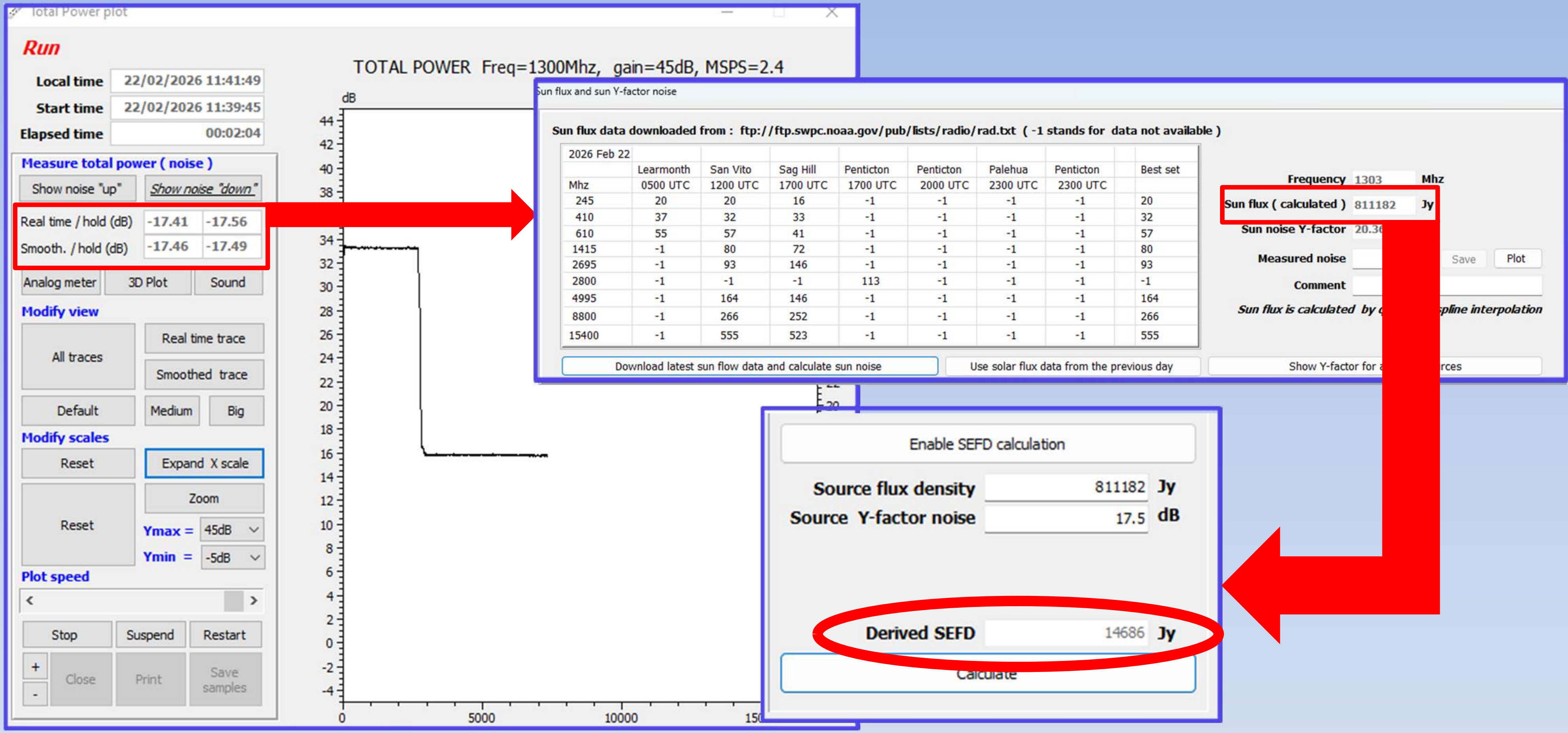
SEFD : Estimation Sun noise



2026 Feb 22	Learmonth	San Vito	Sag Hill	Penticton	Penticton	Palehua	Penticton	Best set
Mhz	0500 UTC	1200 UTC	1700 UTC	1700 UTC	2000 UTC	2300 UTC	2300 UTC	
245	20	20	16	-1	-1	-1	-1	20
410	37	32	33	-1	-1	-1	-1	32
610	55	57	41	-1	-1	-1	-1	57
1415	-1	80	72	-1	-1	-1	-1	80
2695	-1	93	146	-1	-1	-1	-1	93
2800	-1	-1	-1	113	-1	-1	-1	-1
4995	-1	164	146	-1	-1	-1	-1	164
8800	-1	266	252	-1	-1	-1	-1	266
15400	-1	555	523	-1	-1	-1	-1	555

Sun noise measured using the Y-factor method, with the antenna off-pointed by 15° (~5× HPBW) at the same elevation (~50°).

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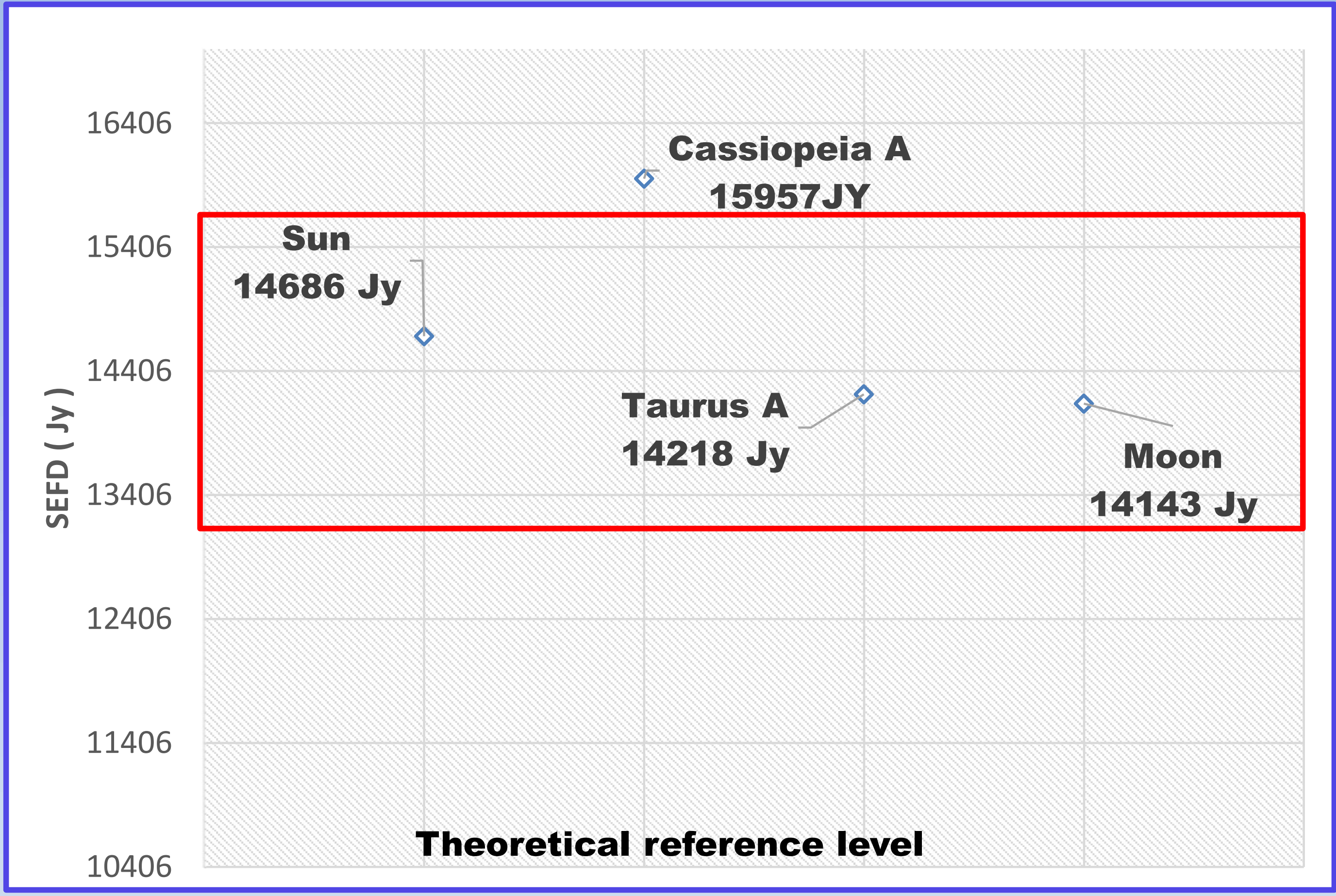
SEFD : Summary



- ➢ **Sun, Taurus A and Moon data are quite aligned (std dev= 240 Jy, ≈ 1.7%).**
- ➢ **Cassiopeia A is worst by 12-13% compared to the "cluster" 14,100-14,700 Jy.**
- ➢ **The theoretical reference level is much more optimistic (by > 30%).**

The true SEFD of my station is around 14,300 Jy

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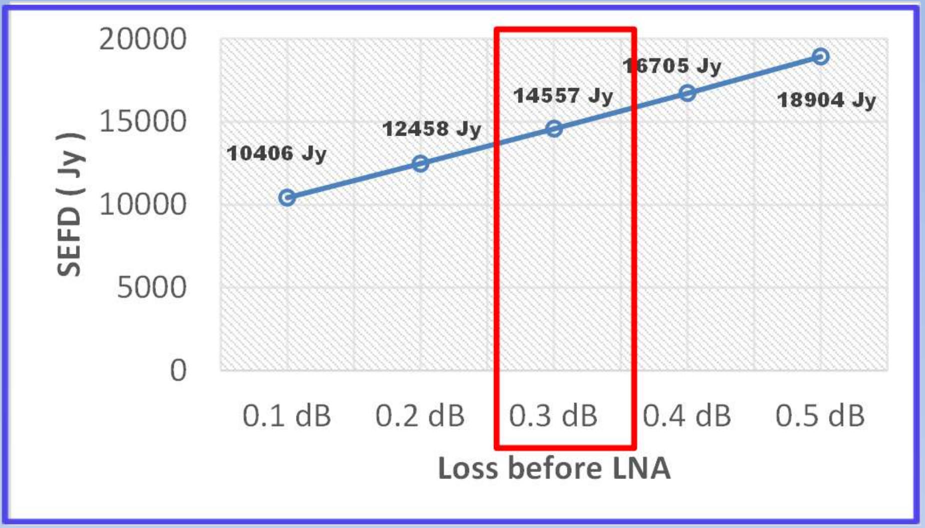
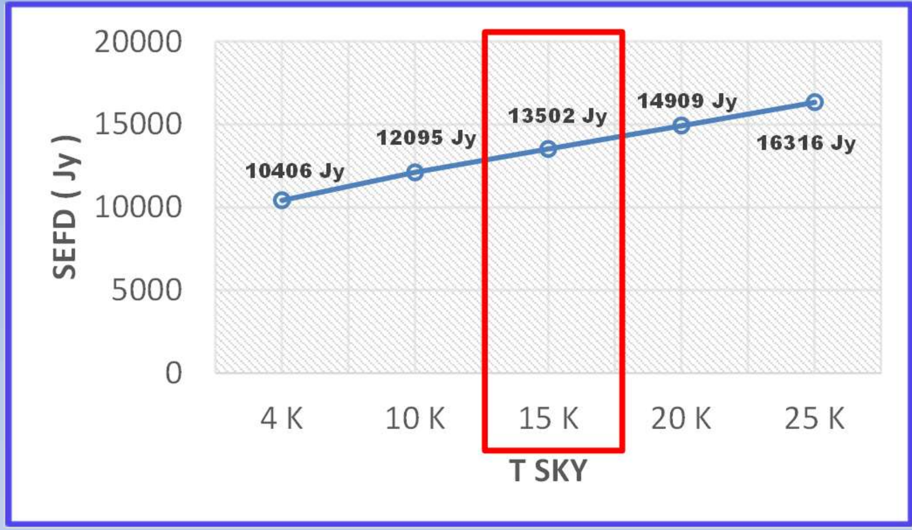
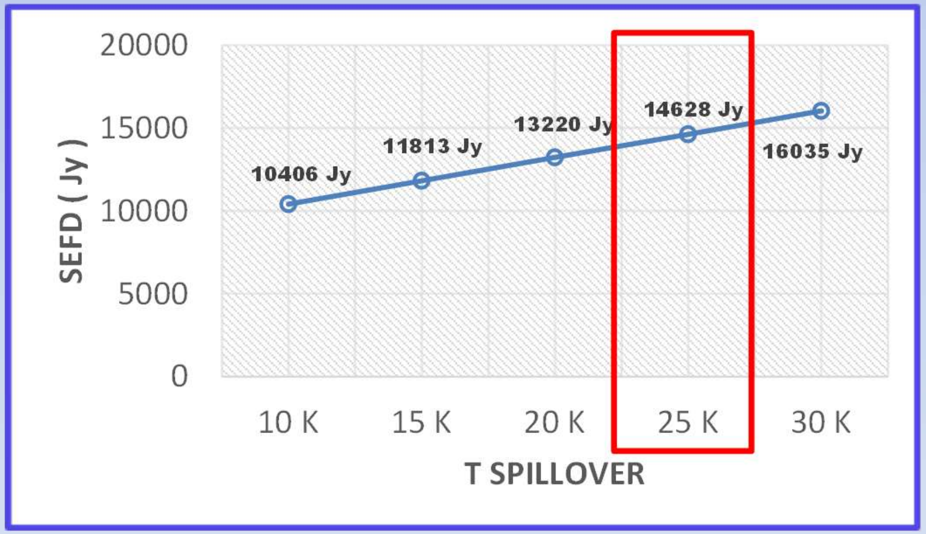
SEFD : Analysis







INPUT PARAMETERS

Frequency = 1303 Mhz
Dish diameter = 5 m
Efficiency =0.5
Line loss before lna = 0.1 dB
LNA NF= 0.23 dB
LNA gain= 38dB
Line loss after lna=0.5 db
Receiver noise figure = 4 db
Tsky = 4 K
Tspillover = 10 K

- ✓ **SEFD shows strong sensitivity to pre-LNA losses; minor changes in this parameter can reconcile theoretical predictions with measured results.**
- ✓ **SEFD is also depends on $T_{sky}$and $T_{spillover}$, though less strongly.**

Putting noise to work

SEFD : Action plan

First checklist

- **Check source flux assumptions.**
- **Verify that the SDR is not affected by AGC action or front-end compression .**
- **Verify that selected T_{cold} antenna pointing position represent a "cold" sky reference condition.**

First countermeasures

- **Repeat T_{cold} measurement at +15° East and +15° West (same elevation).**
- **Repeat the T_{cold} measurement with the antenna offset by +25° in order to evaluate potential sidelobe contamination.**
- **Measure the in-situ parameters of the feed-to-LNA path in the actual installed configuration.**

SEFD compresses antennas, feeds, LNAs, spillover, and all our mistakes into a single number that is extremely effective for optimizing and comparing EME stations !!

Putting noise to work

SEFD : Setting the goal …

Instrument	SEFD (Jy)	Notes / definition	Reference
Effelsberg 100 m	15.2 Jy @ 1.41 GHz	Single dish; receiver-dependent (P170mm table reports SEFD vs frequency)	Effelsberg receiver page "P170mm … Calibration Information" (SEFD table).
SRT (Sardinia, 64 m)	36 Jy (L-band)	Single dish; derived SEFD table for the L/P coax receiver	Navarrini et al., *The Sardinia Radio Telescope Front-Ends* (table "Derived SEFD", L-band).
GBT (Green Bank, 100 m)	650 Jy (L-band)	Single dish; receiver table value (depends on receiver/config)	*GBT Proposer's Guide* (Table "GBT receivers' parameters", L-band row).
Medicina (Italy, 32 m "Grueff")	458 Jy @ 1.4 GHz	Single dish; stated explicitly for the observing setup used	Pelliciari et al. 2024 (A&A paper PDF): "SEFD … 458 Jy at 1.4 GHz …".
MeerKAT (per 13.5 m dish)	≈ 400 Jy per dish (L-band, band centre)	Explicitly "for an individual dish"	Padmanabh et al. 2023 (MMGPS): "SEFD … 400 Jy for an individual dish at the centre of the band."
SKA1-MID (per dish)	≈ 305 Jy per dish (Band 2 + L)	Derived from official array SEFD and official dish count: 1.55 Jy (array) × 197 dishes = 305 Jy	Array SEFD (Table 3) in Pellegrini et al. 2020: 1.55 Jy for "Band 2 + L-band". + Dish count (133 SKA + 64 MeerKAT = 197) from SKAO telescope specs page.

Putting noise to work

What's next …

Forthcoming Developments:

- ✓**Murmur will incorporate extended data-logging capabilities, enabling structured storage and multi-parameter visualization of measured system variables for advanced post-processing and comparative analysis.**

- ✓**TotalPower will expand hardware compatibility, providing support for additional SDR platforms.**

- ✓**Further EME–astrophysics cross-fertilization ideas are under development … because the Moon is visible only a few hours per day … but we invested a lot on money in our systems.** 😉

Grazie !

Thank you !

Ich habe fertig ... ☺