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Netherlands Institute for Radio Astronomy

RFI monitoring: requirements, techniques, recent campaigns and results for the SKA

IUCAF, Fourth School in Spectrum Management for Radio Astronomy

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Agenda

RFI Monitoring, why, how, where, and what was found….

- Why do we monitor
- What is needed
- Techniques
- Campaigns
- Results
- Summary

Reasons for monitoring

Interference affects radio astronomical observations and science return in various ways and it is important that:

- the **astronomer** knows about the local statistics of interfering signals (presence, risk, strength, times, frequencies, etc),
- the **existing** observatory knows what is necessary to minimise the impact on observations (technical measures, scheduling, processing),
- the **existing** obsevatory has a means to check **self-interference**,
- the **planned** observatory (the SKA!) can find the best location in combination with legal protection and safeguarding the environment (Spectrum management, RQZ, an EMI policy),
- the **regulatory agencies** can be made aware of the electromagnetic environment in relation to the needs of astronomers, of violations of spectrum usage, etc.

Monitoring of the spectrum provides (some of) this information.

Reasons for monitoring

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In radio astronomy we call all **manmade** radio emissions "interference", where the telescope (or array) is the **victim**.

We can distinguish between:

1. Intentional transmissions (**RFI**)
    a. Broadcasting
    b. Communications (fixed, terrestrial, aeronautical and space mobile)
    c. Navigation, Location (GPS, radar, DME, SSR)
2. Unintentional emissions (**EMI**)
    a. Environmental, as a known or unknown unwanted by-product
    b. Self-generated, as an unknown unwanted accidental effect

Monitoring is intended to make an inventory of the electromagnetic environment at a given location, in contrast to *hunting* where a **culprit** must be found.

Characteristics of interference

When considering RFI monitoring campaigns and instrumentation understand that interference manifests itself in different ways, by:

- **Origin**, where does the interference come from, how is it influenced by the intervening path.
  - **Internal** in the system (*self-generated*), can be **radiated** or **conducted** interference. Interference originating from neighbouring parts of the system, such as from single member-telescopes is considered to be self-generated for the purpose of this classification because it is something within the control of the observatory. For the **SKA** the propagation of the interference from culprit to victim takes place over a range of distances, from metres to tens of kilometres.
  - **External** to the system (*the system is the victim*). This concerns all other interference beyond the control of the observatory, other than through regulation. Interference signal **propagation** usually plays an important role here.
  - **Stationary** (antenna masts) or **moving** (airborne, satellite, mobile), which determines whether the interference is changing direction, phase and level. Likewise propagation effects are of importance here.
- **Time** characteristics, how does the signal changes over time,
  - **constant**/**single event**/**intermittent**,
  - **cyclostationary**; can the signal be recognised by analysing its modulation type.
- **Frequency** characteristics,
  - **Narrow band**, such as in classical broadcasting and communication,
  - **Broad band**, such as in digital broadcasting,
  - **Ultra-wideband** (UWB), such as – short range radar (SRR), in anti-collision devices, ground- and wall-penetrating radar.

The impact of interference on radio astronomical observations, summarised

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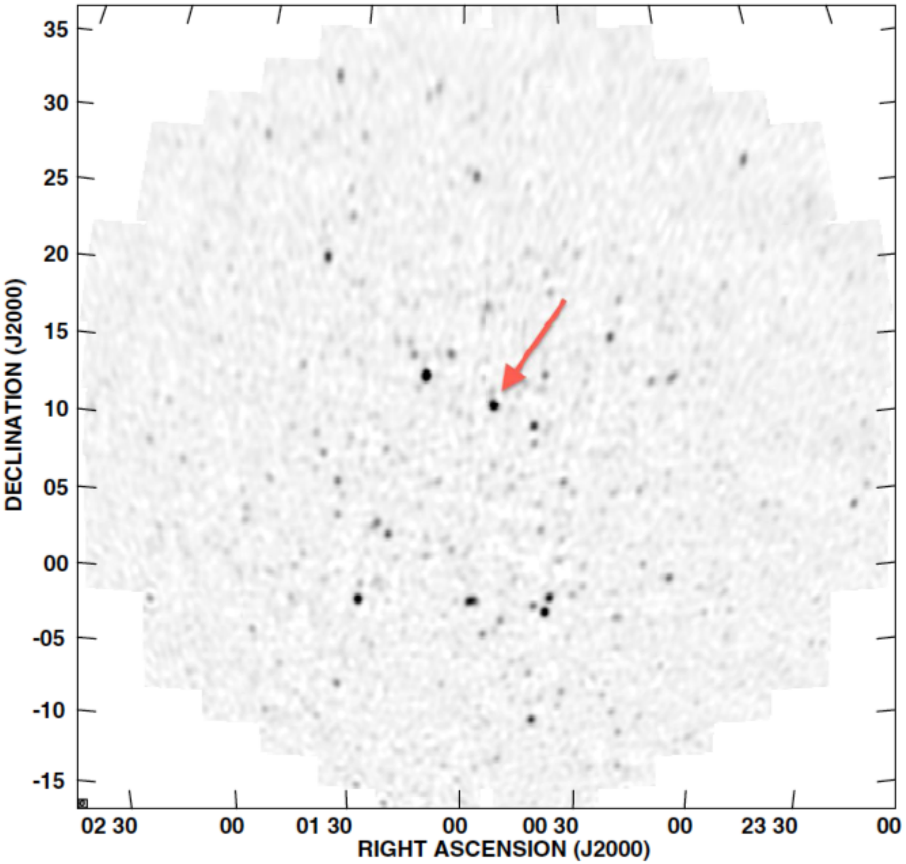
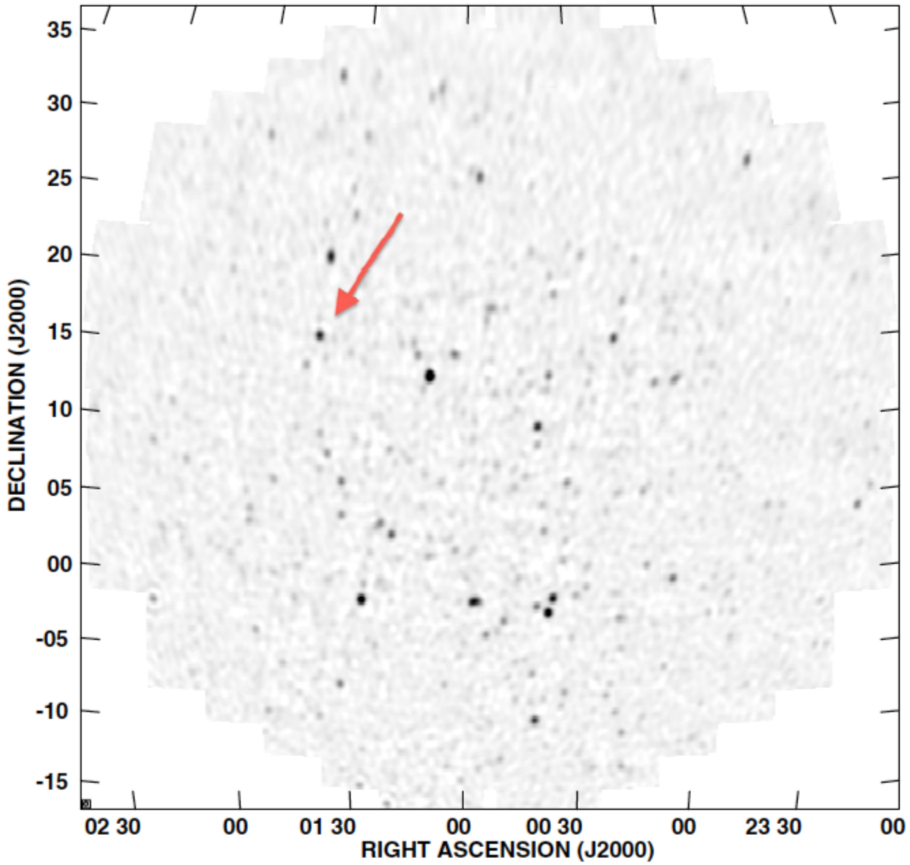
	Narrow band	Wide band
Weak	**1** Will pollute in the frequency domain. The interference may have insufficient I/N to allow flagging it as such, and thus produce artefacts.	**2** Cannot be distinguished from natural noise. Increases system noise temperature (T_{sys}), hence decreases sensitivity.
Moderate	**3** Interference may be recognisable and can be discarded.	**4** The presence of interference may be detected. Some loss in sensitivity results, which may be acceptable for certain kinds of observations.
Strong	**5** Causes saturation and harmonic distortion in parts of the receiver resulting in spurious signals in large parts of the spectrum. There may not be parts of the observed band that can be used.	**6** The astronomical signal is unobservable or severely affected by artefacts. Large increase in system noise temperature (T_{sys}), hence loss in sensitivity.

The impact of interference

An illustration – The MWA observing the Moon at 94MHz

Q: What is strange in this picture?





McKinley, B. et al, Low-frequency Observations of the Moon with the Murchison Widefield Array, arXiv:1211.1433

Basic Requirements of monitoring equipment

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Properties:

- Sensitivity
  - Depends on survey type (investigate strongest features or inventory of weak features)
  - Generally as high as possible, without compromising linearity and hence spurious responses
- Spectral resolution
  - Usually a compromise between survey speed, technical ease, a priori knowledge of the spectrum
- Time resolution
  - Integration time during measurement-time and in (post-)processing
- Coverage
  - Directions, polarisation, duration, locations
- Survey time
  - Depends on all of the above and hence drives those primary properties
  - And choice of equipment

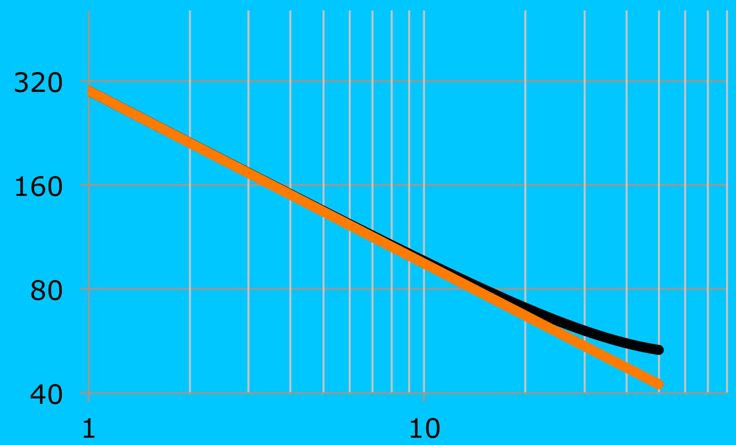
Sensitivity
the holy grail

The radiometer equation: $$\sigma_T = \frac{T_{sys}}{\sqrt{\Delta f \tau}}$$

shows that the measured rms noise increases with the system noise, and decreases with the root of bandwidth and integration time.

When T_{sys} and Δf are fixed one can only improve sensitivity by **integrating** longer.

But note: one cannot just keep increasing τ because of issues with system systematics, such as variations in Temp and/or Gain.



Increasing τ must go hand-in-hand with applying a proper calibration strategy: calibrate data taken on short timescales and only integrate the calibrated data. More on this in later slides.

System noise considerations

A monitoring system is built up generally as shown below.

Here input of SA or Receiver directly coupled to antenna. Note that T_{SA} will be high (1000's to 100,000's of K)

$$T_R = T_{SA}$$

But this gets worse in practice…

System noise considerations

A passive attenuating element between SA and antenna raises T_R

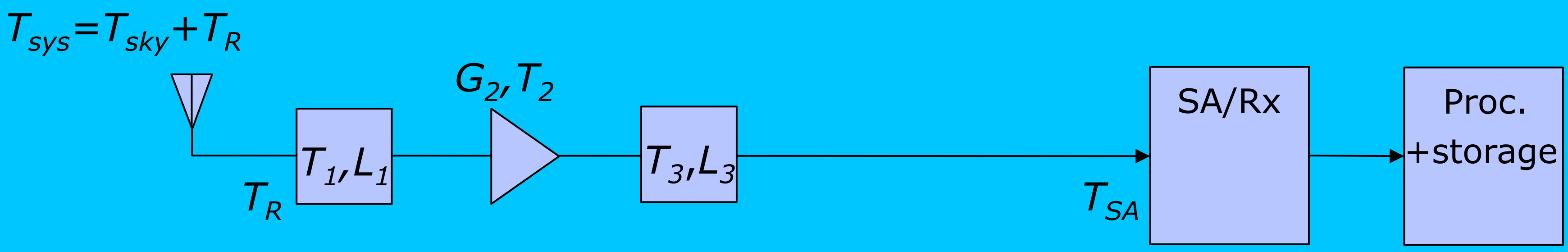
Think of coaxial cable, any filters, connectors.

$$T_R = T_a(L-1) + T_{SA}L$$

L is loss factor or attenuation ($\infty \leq L \leq 1$), T_a is physical temperature

System noise considerations

An LNA is added to lower T_R.

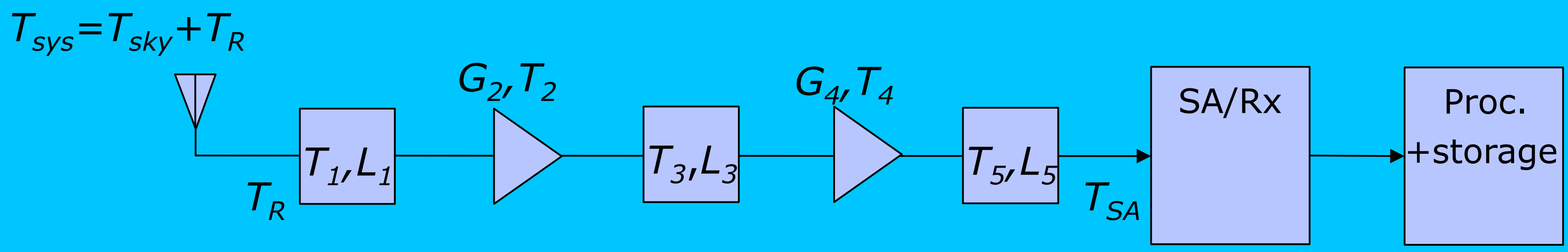


$$T_R = T_1(L_1 - 1) + T_2 L_1 + T_{SA}\frac{L_1 L_3}{G_2}$$

Where generally, but not always (think of cryogenic cooling) $T_1=T_3=T_a$

System noise considerations

Distributed amplification is used to deal with low-noise vs dynamic range (headroom) issues.

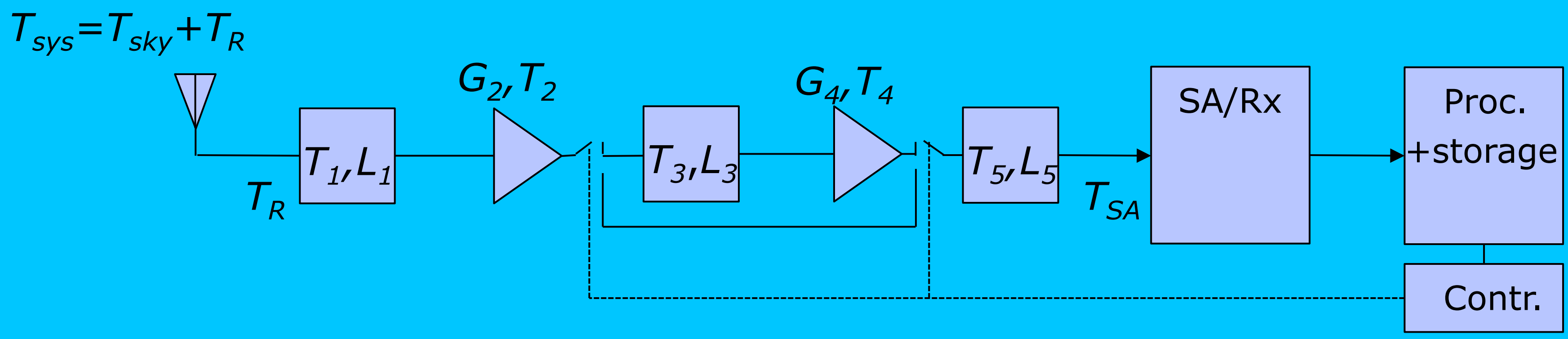


$$T_R = T_1(L_1-1) + T_2L_1 + T_3\frac{L_1(L_3-1)}{G_2} + T_4\frac{L_1L_3}{G_2} + T_5\frac{L_1L_3(L_5-1)}{G_2G_4} + T_{SA}\frac{L_1L_3L_5}{G_2G_4}$$

Where generally, but not always $T_1=T_3=T_5=T_a$. (More info in 'Kraus', ch. 7.2)

Completing the monitoring system

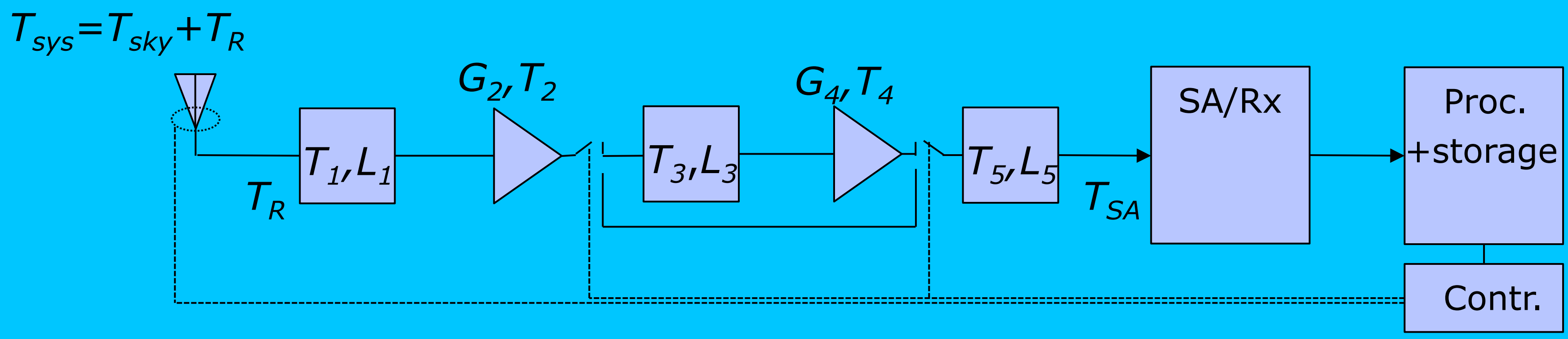
Additions for system automation and circuit flexibility.



Using low-loss terminated coaxial switches to bypass an LNA that would mess up things in high signal conditions, or parts of the system that have a differing frequency range, or switch filters in and out.

Completing the monitoring system

Adding antenna rotation control.



Using a two-axis rotator to change direction and polarisation.

Completing the monitoring system

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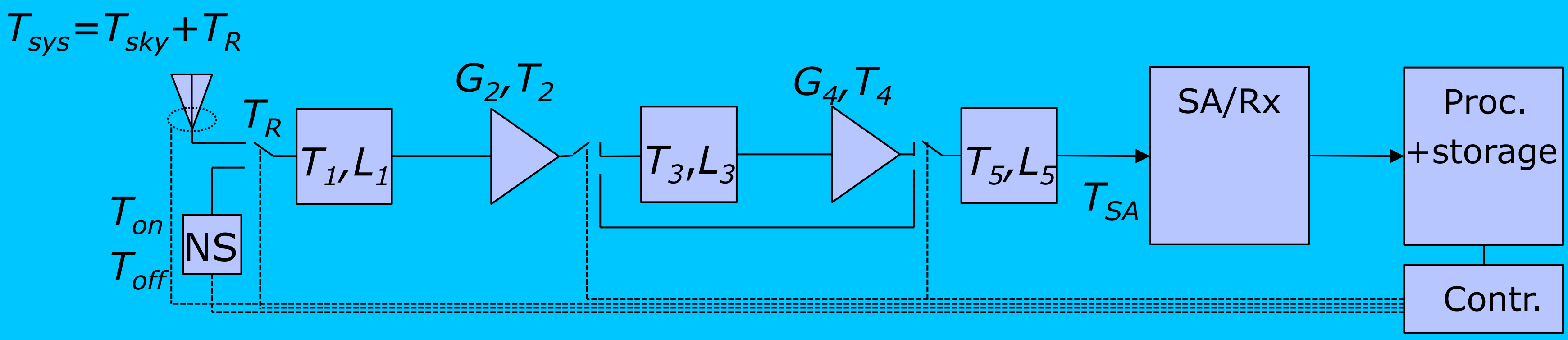
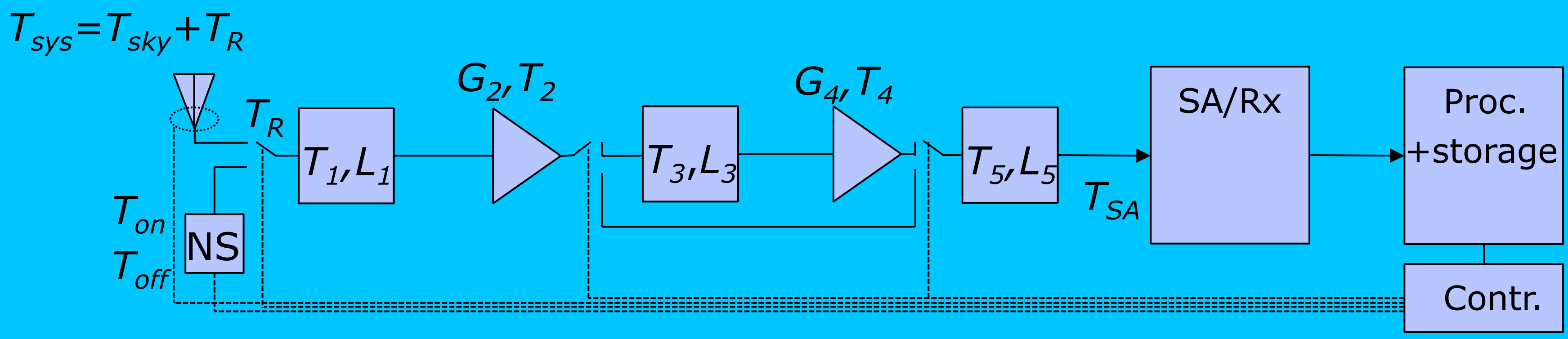
Adding calibration facilities. Using a noise source, a coaxial switch and NS on-off control to create 3 measurement phases.



1. Measure antenna signal
2. Measure noise source off ➔ $T_{off}=T_a$
3. Measure noise source on ➔ $T_{on}\cong T_a(ENR+1)$ where *ENR* is the noise source *Excess Noise Ratio*

Completing the monitoring system

The time penalty of two additional measurements (2 and 3) can be minimised by using a RBW >> than for 1.



1. Measure antenna signal
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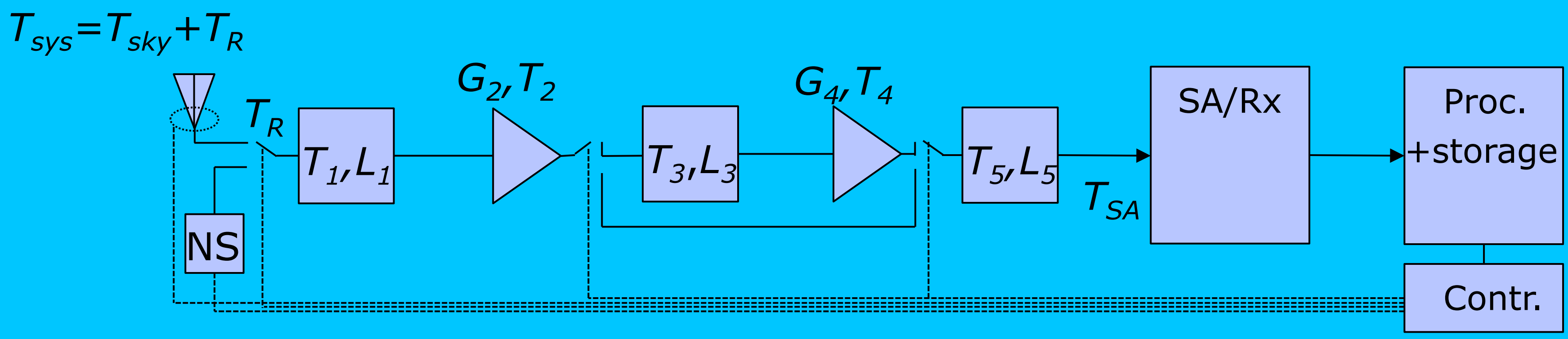
Completing the monitoring system

Use brief enough integration so system does not change properties, then solve for system gain (G) and receiver temperature (T_R) per period, apply calibration, then integrate results.



Note that in this scheme the coaxial cable attenuation and matching to the antenna is not calibrated which can give rise to ripples in the calibrated spectrum baseline.

Equipment options

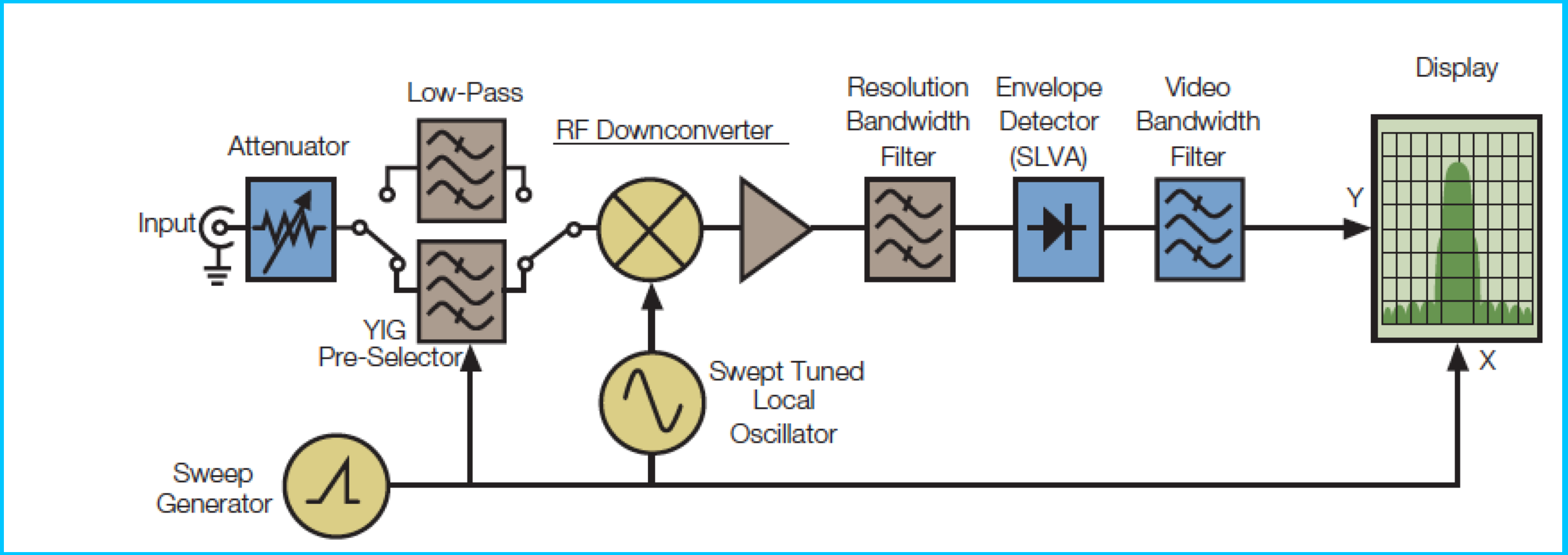
Generation 1: Monitoring of the spectrum has traditionally been carried out using **scanning spectrum analysers** (or scanning receivers). Many times in combination with a low noise frontend (lna's, filters, frequency conversion).

Generation 1.5: Using (optional) similar frontends, with a **Real Time Spectrum Analyser**

Generation 2: Using similar frontends, with **digital spectrometer** (backend) systems.

Scanning Spectrum Analyser

Example block diagram:



Scanning Spectrum Analyser

The traditional workhorse instrument.

Many advantages; most prominent drawbacks:

- Low sensitivity without a low noise frontend
- Time inefficient, because:

Sequential measurement of N channels of Δf channel-bw (=*RBW*) in a band B, each with a 'dwell' time of t_d requires: $$t_{sweep} = t_d N = t_d \frac{B}{\Delta f}$$

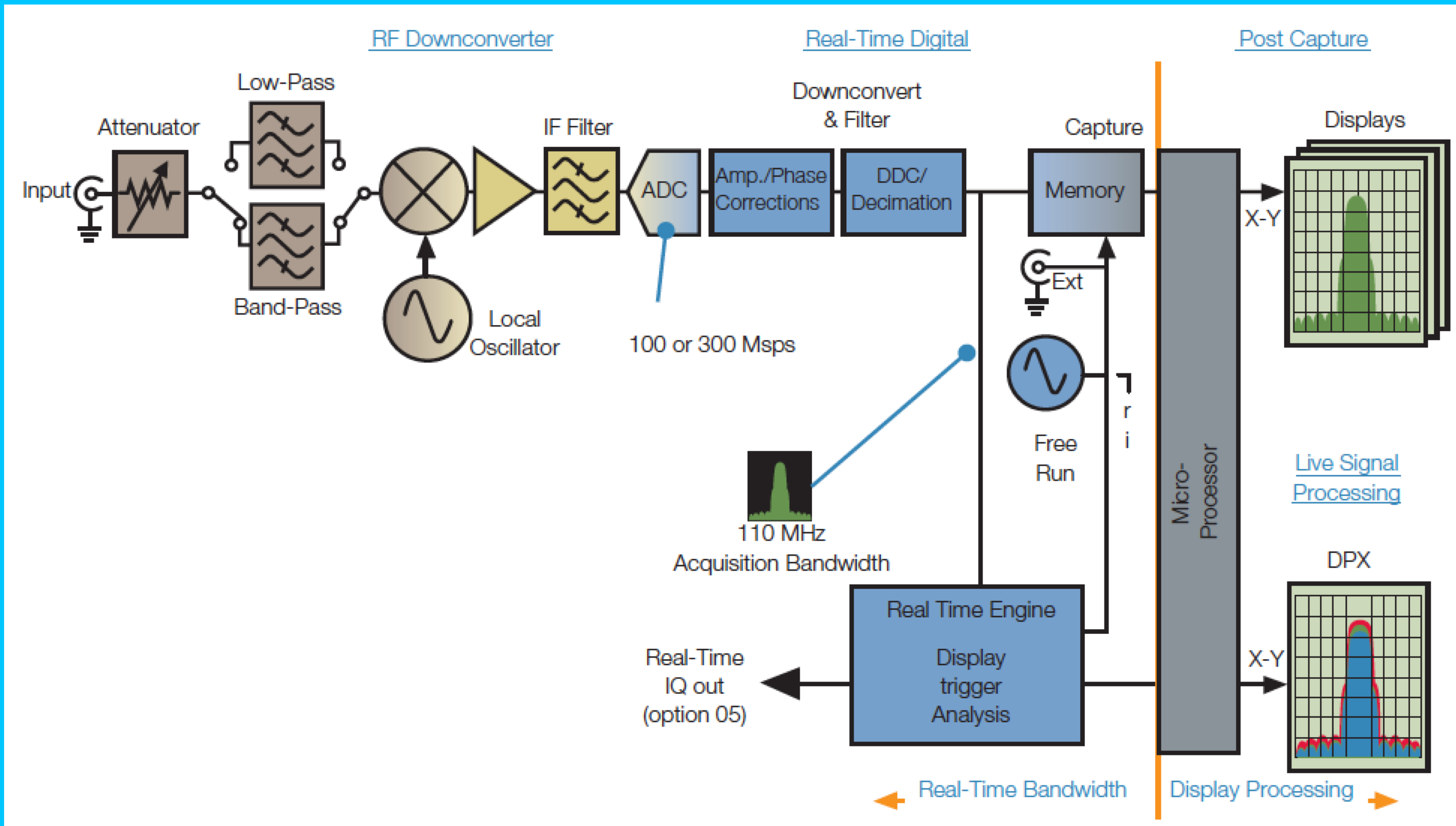
It does get worse, because in practice for a traditional spectrum analyser the integration time $\tau < t_d$, as a result of the type of filters and detectors. The effective integration time is: $\tau = \frac{p}{\Delta f}$, where p is a proportionality factor which depends on type of filter (called the 'k-factor', example R&S $1<p<2.5$).

Furthermore additional delays because of acquisition methods in the instrument causes a further increase in sweep time (up to 20 times overall).

Ref: SSM System Design Considerations, R.P. Millenaar, ASTRON, 26-8-2005, ASTRON-RP-013

Real Time Spectrum Analyser

Example block diagram:

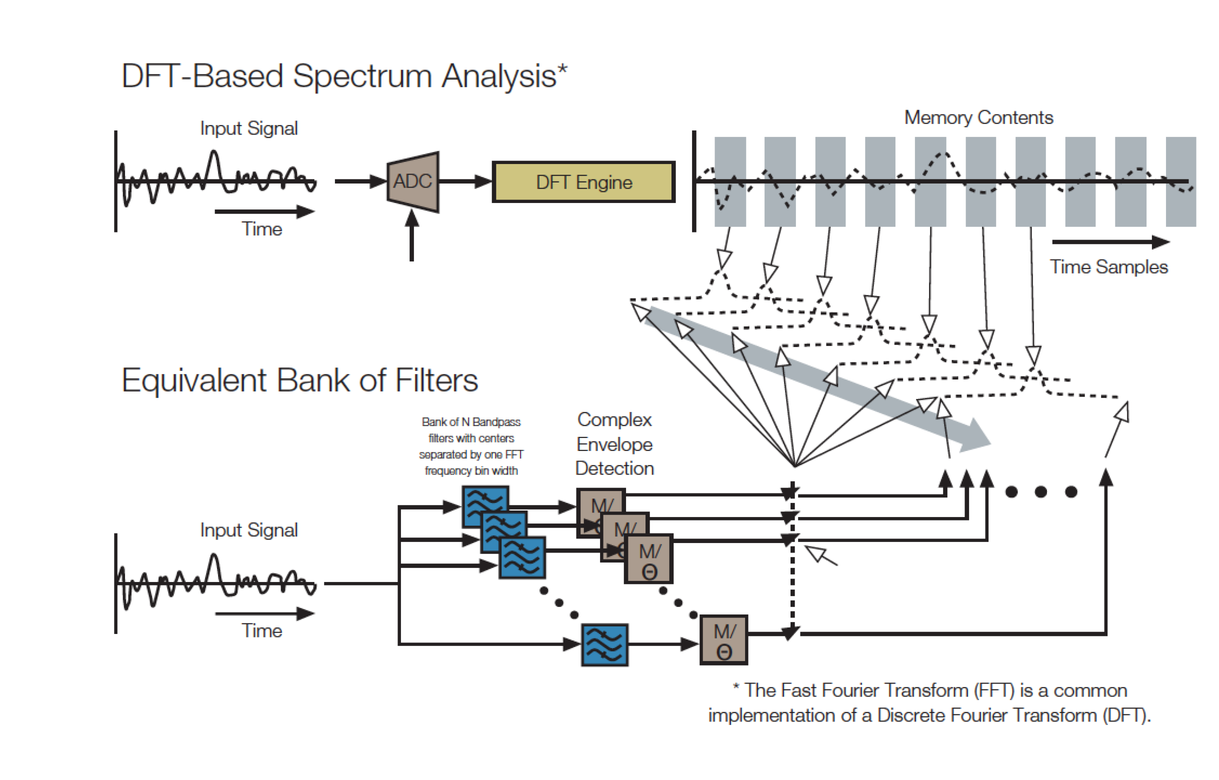


Real Time Spectrum Analyser

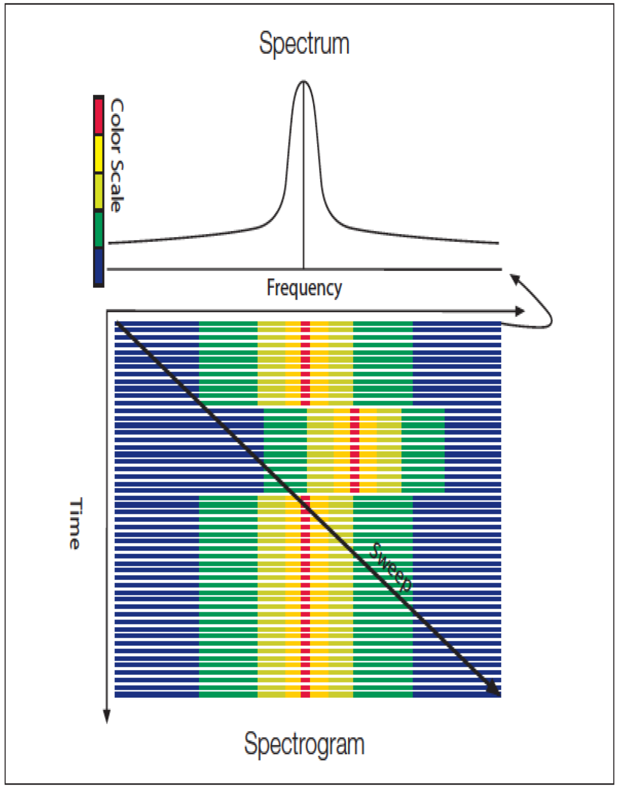
Samples the input signal fast enough to satisfy Nyquist.

Calculates a complete spectrum of bw *B* per cycle.

Has sufficient memory and DSP power to enable continuous real time acquisition.



* The Fast Fourier Transform (FFT) is a common implementation of a Discrete Fourier Transform (DFT).



Real Time Spectrum Analyser

A RTSA has much functionality that is of no importance to high sensitivity monitoring purposes, such as elaborate display, modulation analysis and trigger functionality. But the advantage lies in the much better time efficiency.

Digital Spectrometer

'The best spectrum monitoring system is a radio telescope.'

While that is not always true or possible for the antenna and RF part, the advanced spectrometer backends are well within reach today.

Instantaneous processing into frequency channels + integration of spectra into memory + buiding up statistics on the spectra on-the-fly are examples that have become possible for relatively modest cost in the last few years.

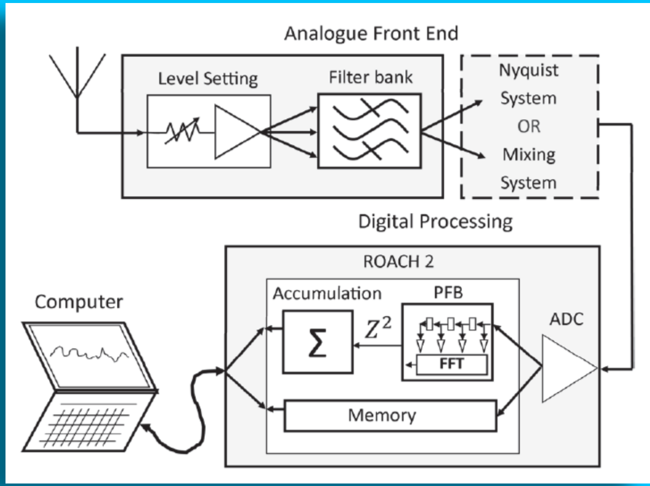
Digital Spectrometer
available systems 1

Apart from commercial boards, some spectometer boards are available from colleagues:

- Casper boards (Collaboration for Astronomy Signal Processing and Electronics Research), https://casper.berkeley.edu

Includes the ROACH board series that is being used for monitoring equipment.

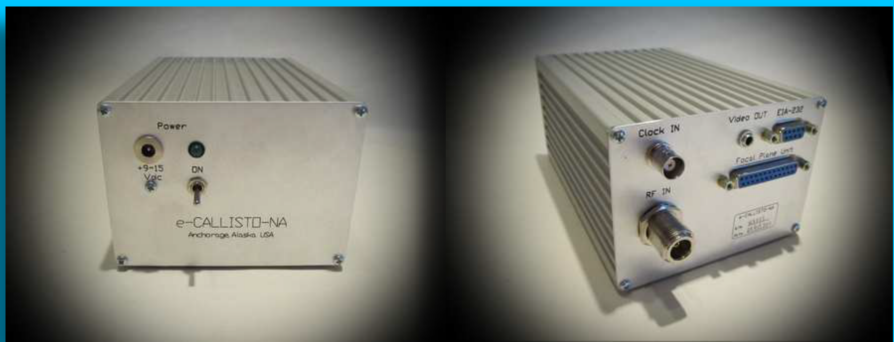
Example: RATTY2 (Ref. 'Dynamic RFI Measurement Systems on a ROACH-2 Platform', 10.1109/ICEAA.2013.6632287)

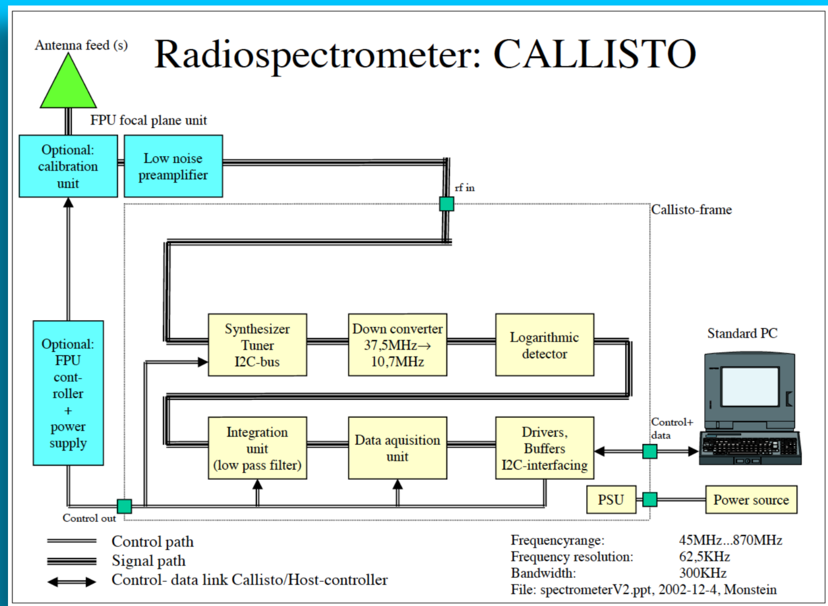


Digital Spectrometer
available systems 2

Apart from commercial boards, some spectometer boards are available from colleagues:

- CALLISTO: a small, cost effective spectrometer for spectrum monitoring, also finds much use for solar observations. World wide network of Callisto users.





Ref: http://www.e-callisto.org/GeneralDocuments/Callisto-General.html

Units of radio power

Engineers read dBm's at the receiver input. In a band *B* wide:

$P(W) = kT_{sys}B$ or $P(dBm) = 10\log(kT_{sys}B) + 30$ (per polarisation)

Astronomers prefer to use the Power Flux Density (PFD) which is the intrinsic flux arriving at a given area, usually expressed in W/m^2. Or Spectral Power Flux Density (SPFD), which is per Hz, usually expressed in Jansky. By defnition:

$1Jy = 10^{-26}Wm^{-2}Hz^{-1} = -260\,dBWm^{-2}Hz^{-1}$ (sum of both polarisations)

The link between these two domains is the antenna: by definition, the power available from antenna equals PFD captured by an effective area of 1m^2: $P = A_e SB$ (*S*=*SPFD*)

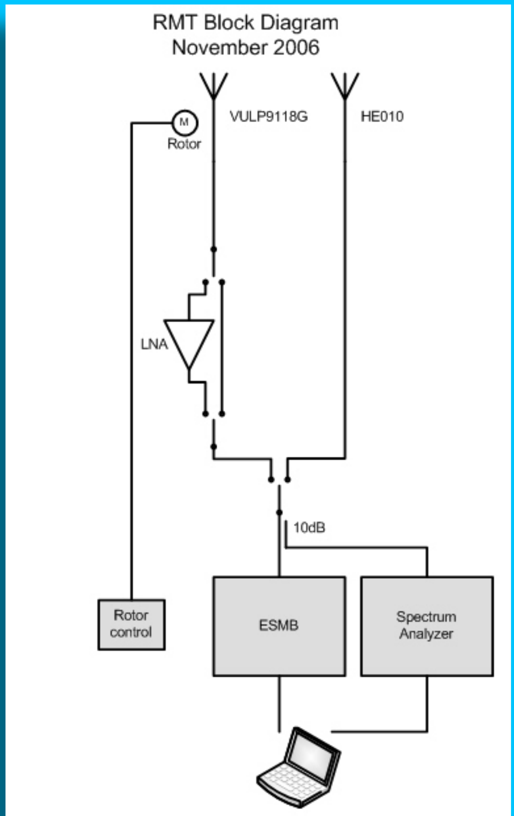
And $A_e = G_i \dfrac{\lambda^2}{4\pi}$ (m^2), so $P = SBG_i \dfrac{c^2}{4\pi f^2}$ G_i is isotropic antenna gain

And the bottom line: $S = P\dfrac{4\pi f^2}{BG_i c^2}$

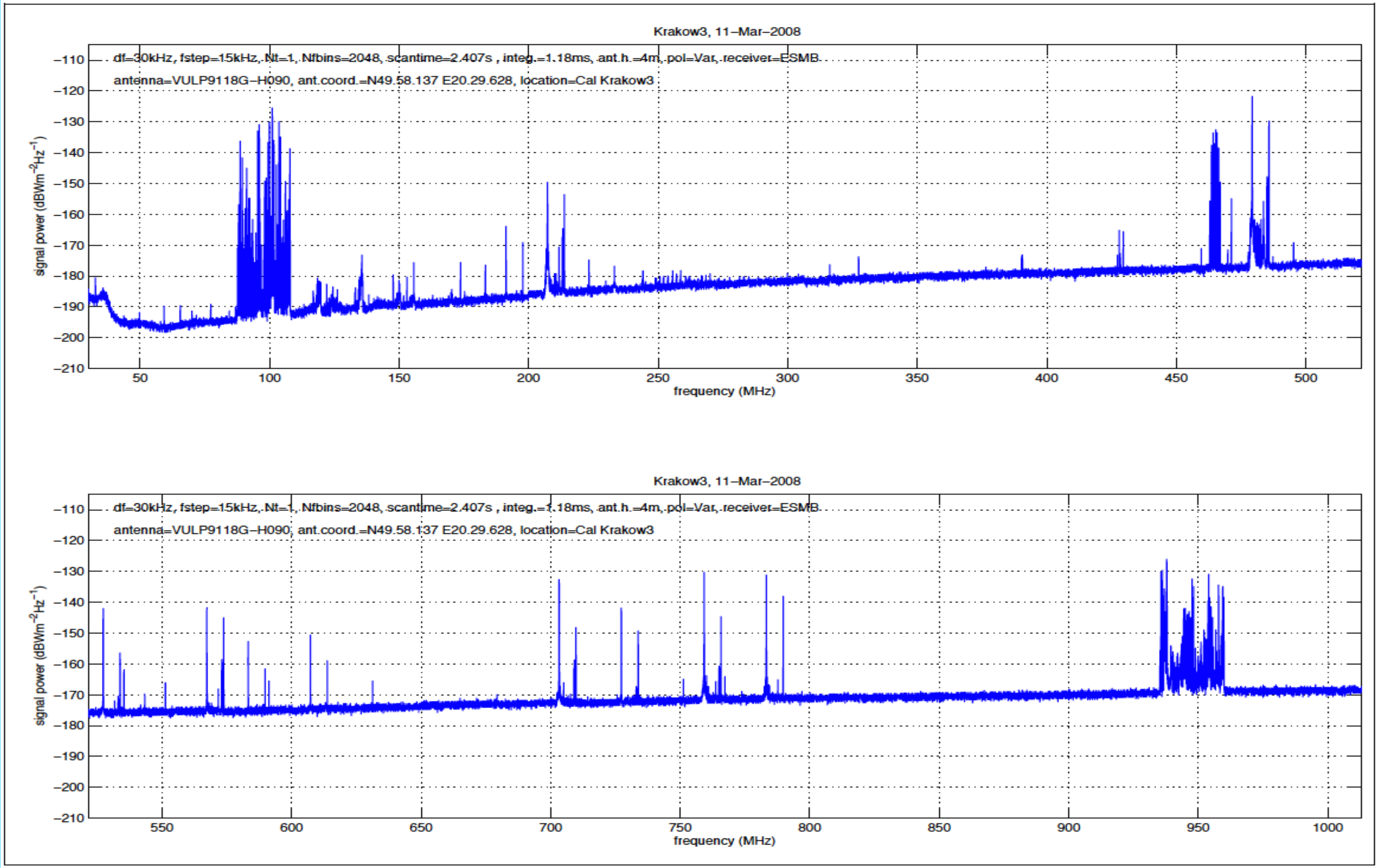
Example Monitoring Systems

Example Monitoring Systems:
LOFAR sites 2002-2008

An extensive campaign to examine potential sites for **LOFAR** stations in The Netherlands and several European countries.



Example Monitoring System Spectrum:
LOFAR sites 2002-2008 (30-1000MHz)



Example Monitoring Systems:
SKA candidate site monitoring system, 2005

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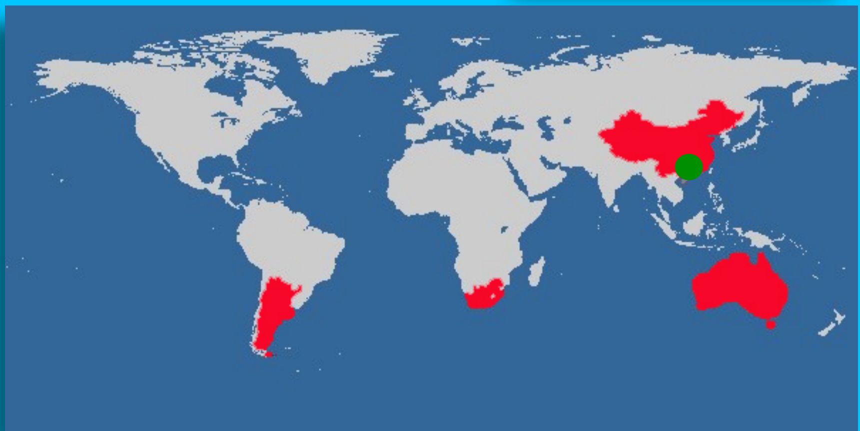
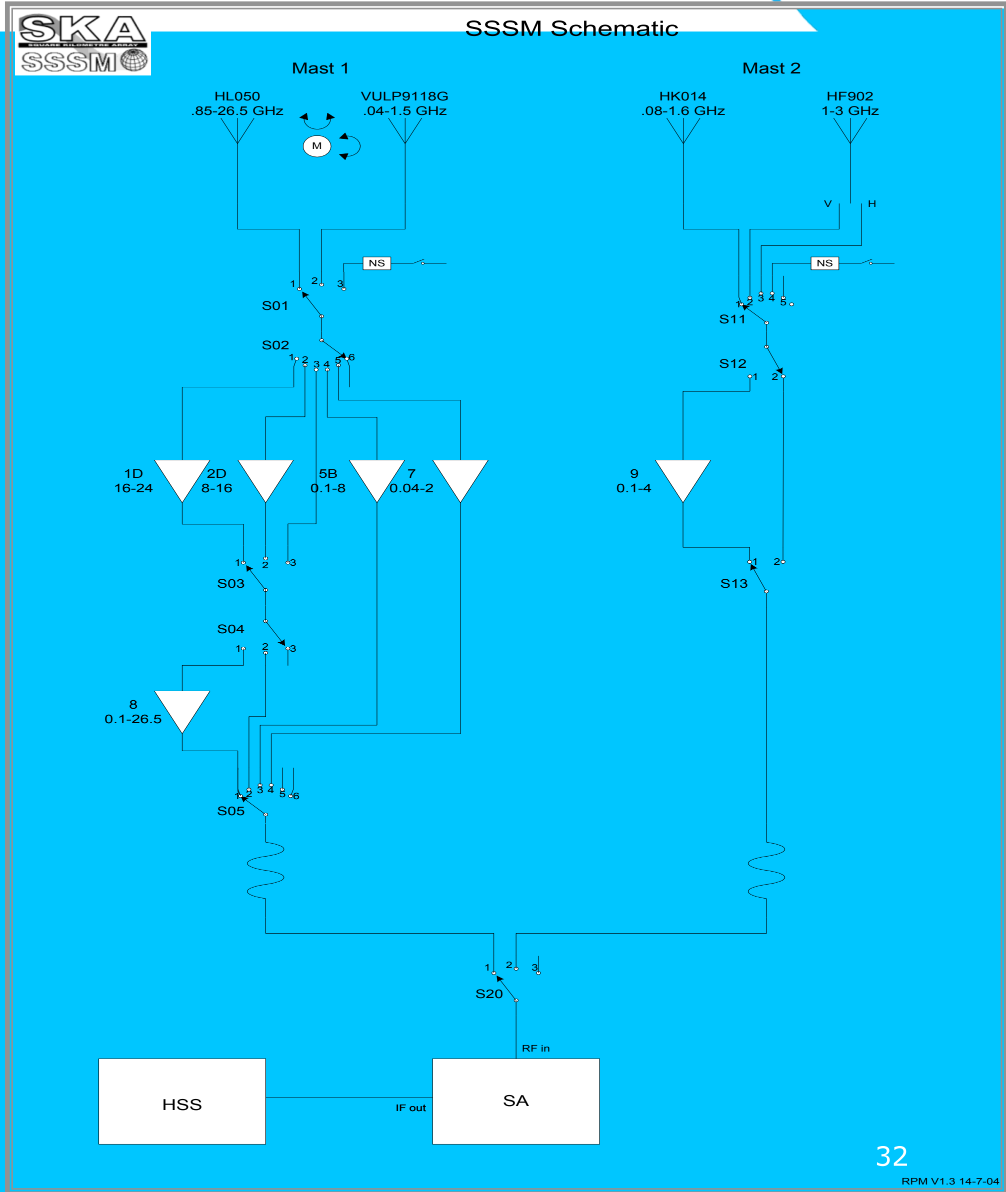
System used to monitor sites from 100MHz to 26.5GHz.

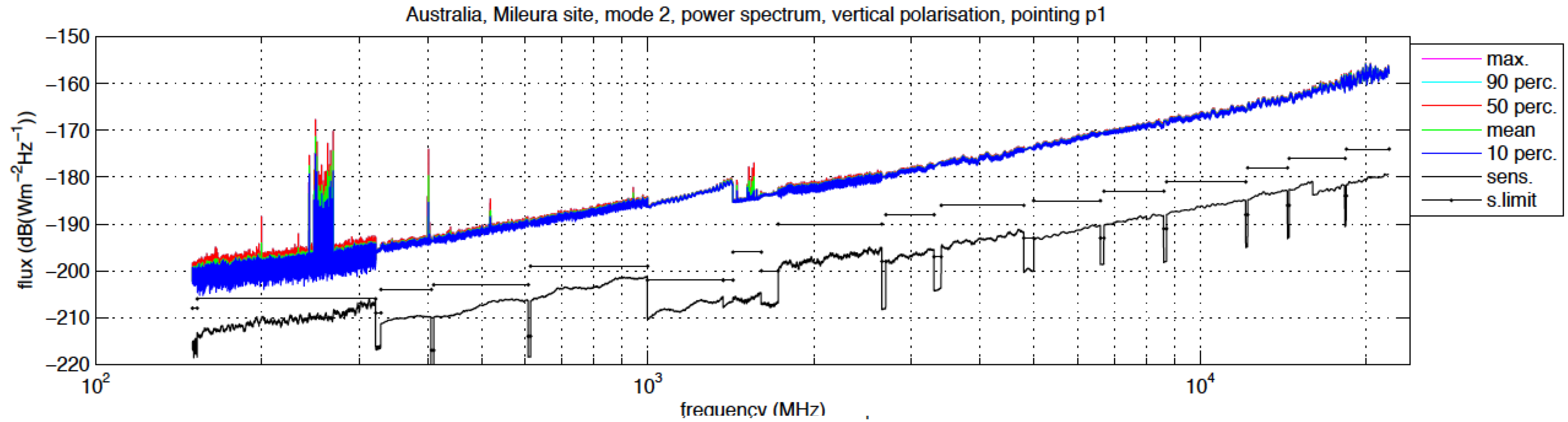


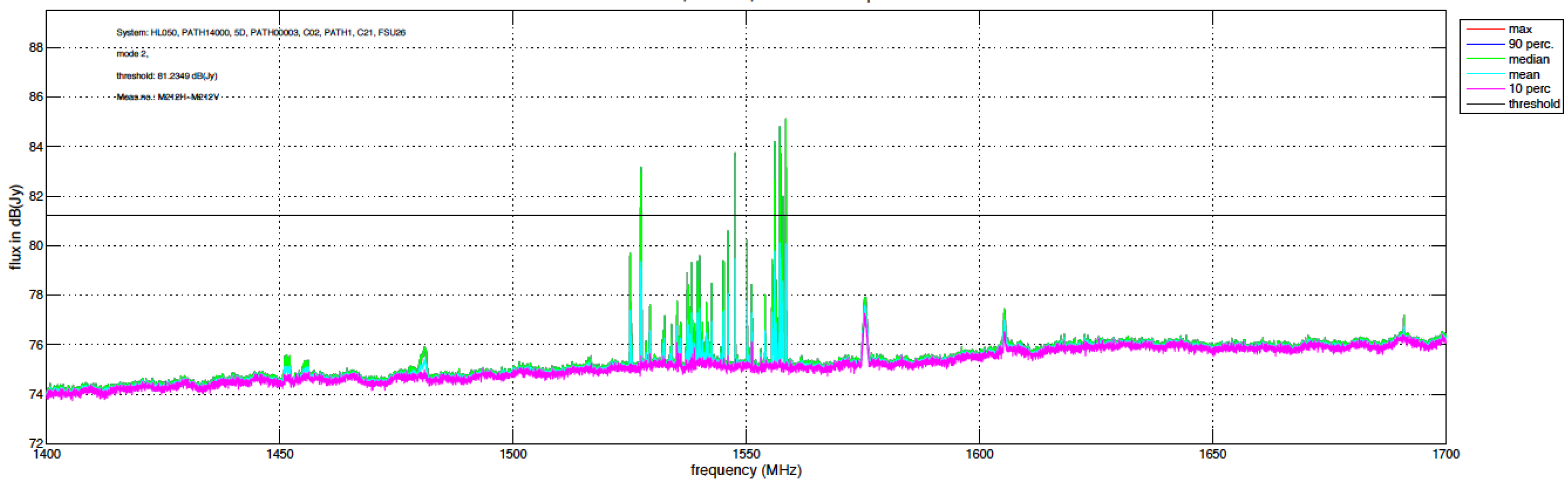


At the Chinese candidate SKA site: Dawodang, the location of FAST

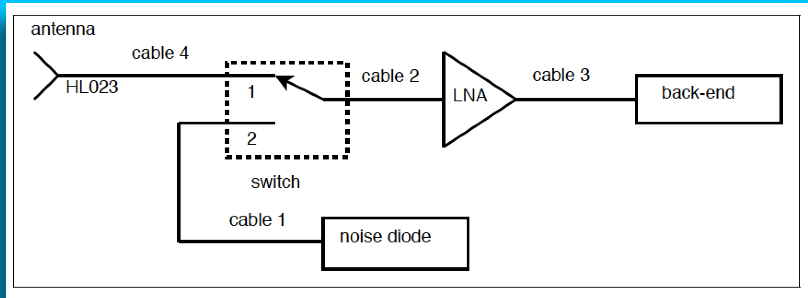
Example Monitoring System Spectrum:

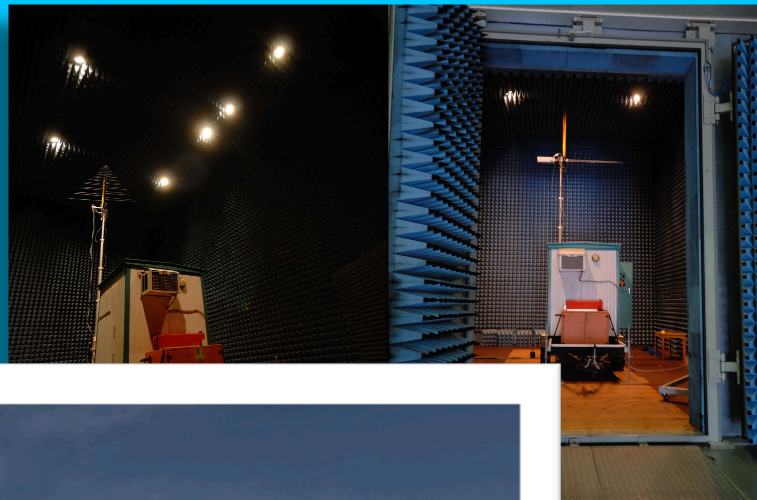
SKA candidate site monitoring system, 2005





Example Monitoring Systems:
SKA site characterisation 2010





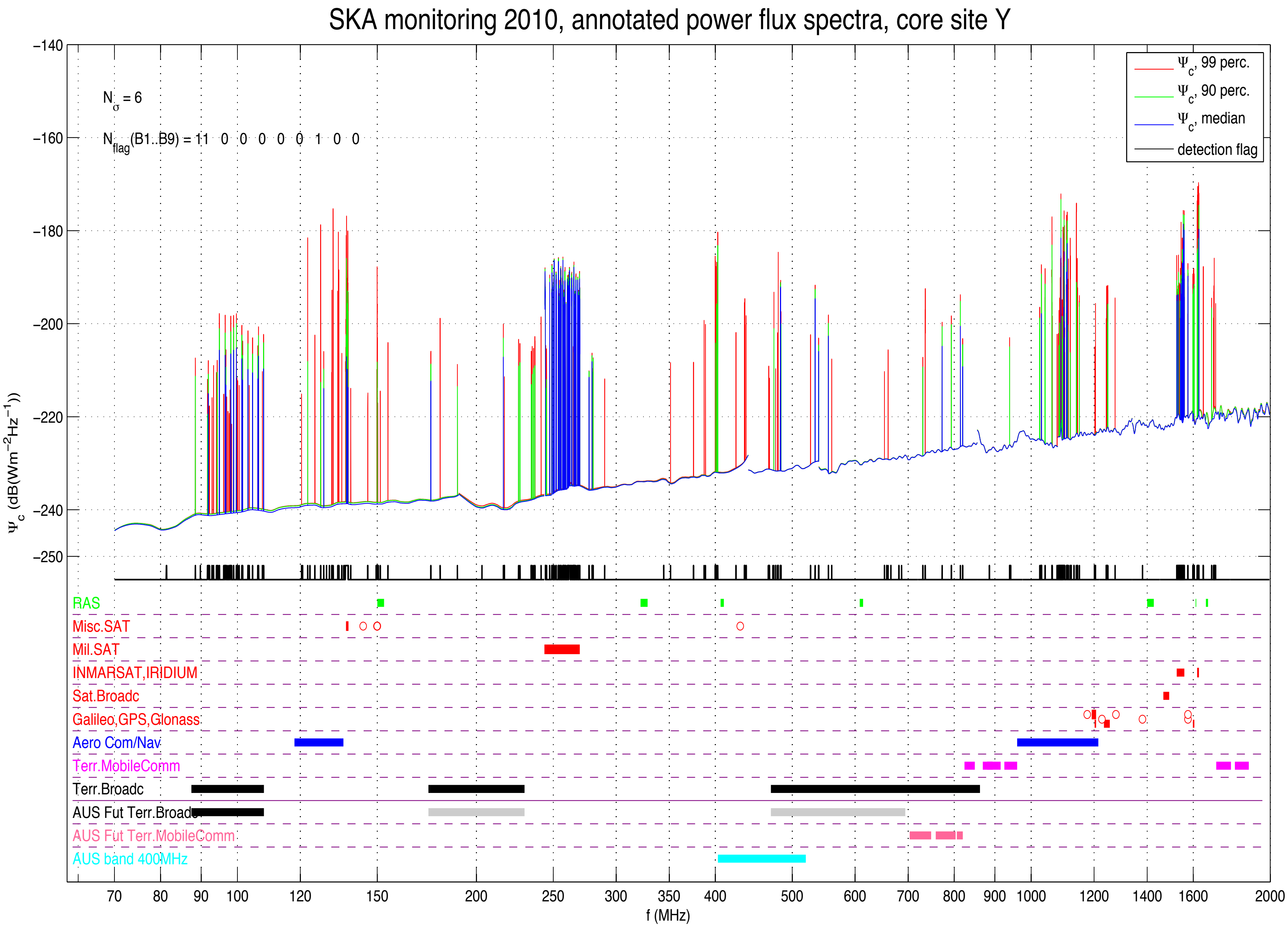
A system for 75-2000MHz. Robust and simple, yet very sensitive. Deployed in WA and SA core sites, plus a selection of 4 remote sites each.

Example Monitoring System Spectrum: SKA site characterisation 2010

From the report:

Overview of RFI at Candidate SKA Core Sites, R.P. Millenaar

The following plot presents an overview of the RFI measured at one of the core SKA sites. Vertical polarisation, azimuth 0°.



SKA monitoring 2010, annotated power flux spectra, core site Y
$N_\sigma = 6$
N_{flag}(B1..B9) = 11 0 0 0 0 0 1 0 0
Ψ_c, 99 perc.
Ψ_c, 90 perc.
Ψ_c, median
detection flag
Ψ_c (dB(Wm^{-2}Hz^{-1}))
−140
−160
−180
−200
−220
−240
−250
RAS
Misc.SAT
Mil.SAT
INMARSAT,IRIDIUM
Sat.Broadc
Galileo,GPS,Glonass
Aero Com/Nav
Terr.MobileComm
Terr.Broadc
AUS Fut Terr.Broadc
AUS Fut Terr.MobileComm
AUS band 400MHz
70
80
90
100
120
150
200
250
300
350
400
500
600
700
800
900
1000
1200
1400
1600
2000
f (MHz)

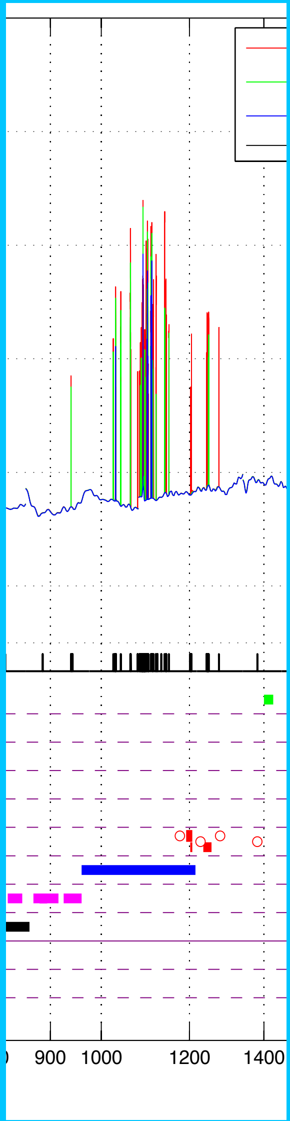
Concluding remarks:
On pulse behaviour

It must be noted that most surveys measure with relatively small RBW. And integrate the power per frequency bin over ~1s timescale minimum.

What does that mean?

- It means that any pulse shorter than *1/RBW* will be underestimated.
- It means that averaging out over $\tau >> t_{pulse}$ will further reduce the estimated power in the pulse.

So it means that most surveys (not dedicated to pulsed emissions) will not give a correct representation of, for example, the aeronautical navigation the spectrum (DME, SSR).



Concluding remarks
summary

Monitoring the spectrum is important but not simple:

- An observatory needs to know the radio environment.
- Designing monitoring equipment will be done with a target application in mind
  - weak/strong radio environment
  - frequency range
  - need for correct pulsed radiation sensus
  - stationary/mobile
  - check for self-generated interference
  - cost!
- New systems can build on experience and can reuse concepts and available components in the radio astronomy community.