The LOFAR Sensor Network

and New Scientific Use of Old Spectrum

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Drive towards higher sensitivity in RA

Increase BW across other allocations on non-interference & no-protection basis

Reduce system temperatures $T_{sys}$

- close to quantum limit at bands up till 12 GHz
- Very active developments at frequencies 70 GHz - 1.5 THz

Increase collecting area

- 2009 - 2012 Atacama Large Millimeter Array (ALMA) = 50 (64) x 15m (30?) 70 GHz - 860 GHz => International with Europe, USA, Japan
- 2008 Low Frequency Array (LOFAR)
  30 MHz to 250 MHz => NL, DE, SE, UK, FR, (IT, SP ?)
- 2015 Square Kilometer Array SKA
  250 MHZ to 25 GHz => International with 20+ Partners
How to improve a good receiving system

- **Build more telescopes.** SRT, Yebes, Ireland, Greece, China, Rep. South Africa, Australia
- **Increase collecting area per telescope.** LOFAR, SKA
- **Improve receivers.** Current state-of-the-art close to the limit set by quantum physics
- **Increase the bandwidth at each telescope.**
ITU-R Radio Astronomy Service

Passive RAS among many active services without special regulatory conditions - high-sensitivity systems next to active systems (in-band, spurious, OOB)

**ITU RR 4.6** For the purpose of resolving cases of harmful interference, the radio astronomy service shall be treated as a radiocommunication service. However, protection from services in other bands shall be afforded the radio astronomy service only to the extent that such services are afforded protection from each other.

Active RAS participation in ITU-R, CEPT, and national regulatory fora

Number of well-placed bands & eight exclusive passive bands - all emissions prohibited - FN 5.340 (1400 - 1427 MHz & 23.6 - 24 GHz)

52 bands of interest with footnote protection (*admins are urged to take practical steps to protect*) FN 5.149

Non-interference & non-protection use of other (active) bands
Sensitivity of RA Systems

$$\frac{\Delta P}{P} = K / \sqrt{\Delta \text{freq time}} \quad \text{or} \quad \Delta T = \frac{\left( T_A + T_R \right)}{\sqrt{\Delta \text{freq time}}}$$

$K$ depends on equipment $\Rightarrow$ total power system $K=1$

ITU-R RA.769 for 2000 sec integration in allocated band
Data Loss in Radio Astronomy

RAS levels of detrimental interference in ITU-R RA.769

Relative Channel Capacity defines information handling capability of communication system

Net loss of 5% from all sources is maximum tolerable figure

A few dB => more integration time
At 10 dB => four times integration
Above 10 dB non-thermal noise will give total loss of service

RAS is vulnerable at low levels of RFI

-254 dBW/m²/Hz at L-band
Radio Interferometry for imaging

Resolution of single RT \( \theta = \frac{\lambda}{d} \)

Resolution of a pair of RTs \( \theta = \frac{\lambda}{D} \)

Resolution on the sky higher for increasing baseline
Sensitivity determined by the \textit{sum} of the RT collecting areas

Applications: array radio telescopes, Very Long Baseline Interferometry (VLBI) for astronomy & geodetics (> 9000 km), aperture radar systems
Upgraded WSRT

14 RT Westerbork Array
Effective 95 m RT
Most sensitive in world at L-band & C-band
1 of 3 big RTs in European VLBI Network

HI Cosmic Web
HI distribution M31
163 mosaic points reduced database = 10 GB

Braun et al 2002
LOFAR 2007- 2009
Initial Test Station & Prototyping Activities

25% of antennas in central 2 km core
50% within a 12 km diameter
75% within a 75 km diameter
**LOW Frequency ARRay**

- Frequency range => 10 - 240 MHz (minus FM band)
- *arcsec* angular resolution => total extent ~ 350 km
- Element antennas => factor 100 in sensitivity => 10000 ant
- High capacity fiber links ~ 25 Tb/s data rate
- Digital Beamforming => one beam w 32 MHz or up to 8 x 4 MHz simultaneous, independent beams
- Advanced RFI mitigation & calibration processing
- Central Processor
- Massive buffering for data look-back
- Operations by on-line community => Remote Science Operations Center(s)
25% of HB & LB stations within 2 km
Survey of the full sky with Initial LOFAR Test Station (ITS)

86 snapshots with 6.7 sec integration and 9.7 kHz channels between 29.5 and 30.5 MHz
European Extensions & Collaborations

Dedicated, national and GEANT data networks

CC-RUG Central On-line Processing
Astronomy 250 Tbyte/day
Blue Gene Streaming Computer @ 27 Tflops

Distributed LOFAR Science Centers
LOFAR Data Flow & Processing

=> Sensor Fields in 50 Remote Stations and Compact Core with 32 stations in ~ 2km

=> Per Station 100 High Band (120-240 MHz) antennas and 100 Low Band Antennas (30-80 MHz w hard filter at 80 MHz)

=> Current plans: in Core stations 13 three-axis vibration sensors (geophones), 3 micro barometers (infrasound), weather monitoring and GPS time/position

=> Digital processing at station level for beamforming, RFI mitigation, and reduce data flow from 400 Gbps to less than 10 Gbps (1.6 Tmul/s)

=> Transport 10 GbEthernet WAN over +40km to central processor with dedicated network from core to Central Processor (CEP)

=> Streaming Supercomputer IBM BlueGene/L system (14000 processors) surrounded by PC clusters with Infiniband backbones for large sustained data rate (flow processing) located in Groningen

=> Typical Astronomy data set: 6 TB of raw visibility data for an 8 beam, 4 hour synthesis observation, after integration for 1 sec and over 10kHz. One month of observing in this mode results in a PetaByte of data
From LOFAR & VLA at low freq to VLBI in M87
LOFAR, wide-area sensor network
LOFAR research infrastructure at each station

- Astronomy:
  - > 85 phased array stations
  - Combined in aperture synthesis array
  - 8500 small “LB” antennas
  - 8500 small “HB” tiles

- Geophysics:
  - 13 vibration sensors per station
  - Infrasound detector per station

- Weather sensors

- Agriculture research

- Water level monitoring

- GMES (Global Monitoring for the Environment and Security)

- Space Research - Ionosphere
LOFAR spectrum bands using WSRT LFFE

- Europe densely populated, affluent & strong pressure on spectrum use
- Operation outside RA allocations and across active bands

WSRT Experiment
- Eight 2.5 MHz wide bands in 115-180 MHz band
- Selection of cleanest bands
- BP and notch filters TV, FM, pager
- Less than 20% data loss (in cleanest bands)
LOFAR frequency range in Drenthe province
RFI sources to be reduced to strong celestial sources by mitigation and then subtracted in regular data processing

⇒ Combining data to reduce noise levels and mitigate RFI
⇒ Regular operation at 90+ dB below antenna noise floor
RFI Mitigation Strategy LOFAR (1)

RFI excision in time & freq domain (12 bit) with 1 kHz channel width. Multiple levels of excision at station level & CEP level.

Excision of 1 kHz, 1s - 200 ms blocks keeping track of excised samples apply gain corrections steady and intermittent signals. Excision at <200 ms: data loss due to IO limit in freq. channels or telescopes.
RFI Mitigation Strategy LOFAR (2)

All sky above horizon visible for all antennas
Full-sky calibration procedures and full sky RFI management

Spatial filtering at station and for array
- Deterministic / adaptive digital beamforming
- Prefer at same timescales as excision scale
- As part of ionospheric and system calibration

RFI monitoring statistics at 1 kHz level (for decision making)
Spatial filtering using a reference beam (sacrifice one of LOFAR beams)

No spatial filtering (26 MHz) after spatial filtering
International LOFAR Connections

German GLOW Consortium
Uni Bochum, MPI Radio-astronomie - Bonn, Uni Köln, Uni Potzdam, Uni Hamburg, Uni Bremen
Rechnung Zentrum Julich, MPI Extraterrestische Physik - Garching, and others

Build 7 remote stations & 6 Sci Centers 2006 - 2012

Planned:
2-3 French Stations
2-3 UK stations
1-2 Sweden stations
Spain, Poland, Italy
The European VLBI Network
Connecting telescopes into a global array
Europe, South Africa, China and USA

High-sensitivity & high resolution
baselines up to 9000 km for
Central engines of galaxies & masers

Basic operation - disk-based recording
e-VLBI - internet data transport
Real-time data recording and processing
Data processing
16 Gbps (2005)
1 Tbps (2010)
Dynamic spectrum, horizontal axis - frequency bins, 110 mHz per bin, vertical axis - time bins, 4.2 s per bin (50% overlap)
(2008-2012) Chilean Andes
Array
(2015)
150 MHz to 25 GHz
Possible Locations: West
Exciting Times for Radio Astronomy with new generation instruments

Increased instrument sensitivity by factor 100 with larger BW and larger collecting areas

Opening new spectral regimes (high and low freq)

Digital processing of RFI allows operation outside RAS bands

Continued spectrum management effort to protect existing and one-of-a-kind future instruments

Allocated bands must be kept clean