Radar astronomy and radioastronomy using the over-the-horizon radar NOSTRADAMUS

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- Thesis defense: 15/01/2014

« Space-time adaptive processing in heterogeneous environment. Application to radar detection and implementation on GPU. »

Other works:
- Use an over-the-horizon radar developped by ONERA to do astronomy
• The NOSTRADAMUS over-the-horizon radar

• Radar astronomy (radar mode)

• Radioastronomy (passive mode)
Skywave over-the-horizon radar interests

- Long range detection
- All altitude detection (including very low)
- No stealth target in HF band

Mission of OTH radar:
Monitoring sector at long range for early warning
Detection below ionospheric layers: Oceanography

Interest:  Weather studies (sea state over large area)
          Cyclone tracking
          Drifting objects tracking and forecasts
Ionosphere sounding with Nostradamus

Backscatter sounding with scanning in:

- Frequency
- Elevation
- Azimuth

Group range

Ionospheric forecasts → average conditions
No external sounders
→ radar mode alternated with sounding mode
Applications in Astronomy

• Why? :
- Diversification of the applications of the NOSTRADAMUS radar
  Few radiotelescopes operate in HF band (RDN Nancay, UTR-2) but renewed interest with new projects (LOFAR, LWA)
- Have Fun!!

Source: JPL
• Transmit and reception: radar principles for one antenna

« fast-time » dimension or range

« slow-time » Doppler frequency

Range-Doppler image
Detection of the Moon

- The moon is completely within the receiving beam
- Fixed beam (azimuth/elevation)
- Detection of the Moon when entering into the beam
- Radar frequency: 20.5 MHz (crossing the ionosphere and low bias at night)
- Ambiguous range measurement

- $T_e = 3\text{ms}$
- $B = 20\text{kHz}$, implying a range resolution of 7.5km
- $T_{Recu} = 30\text{ms}$, hence Form Factor is $FF = 1/10$
- Coherent integration of 256 récurrences, $T_{int} = 7.68\text{s}$
- Start scanning gate $Deb_{num} = 3.5\text{ms}$, $-> 525\text{km}$
- End scanning gate $Fin_{num} = 29.5\text{ms}$, $-> 3975\text{km}$
Detection of the Moon

Good Signal-to-Noise Radio (SNR) expected
Moon dimensions greater than signal wavelength
Radial extension of the backscattered echo (about 1700km)

Variation of echoes amplitude depending on the range
Detection of the Moon

Range-Doppler image (radial) for the beam steered towards the Moon

Low Doppler shift
Detection of the Moon

Range and Doppler profile

Applications:
- Radar calibration (localization)
- Ionospheric bias study
- Moon imagery using ISAR methods
- Moon reflectivity study (penetration of HF waves into the regolith)
Detection inside or beyond ionospheric layers:

Line of sight propagation (high frequency)
Ionospheric bias due to electronic content (angular deviation, range and Doppler bias)
Bias corrections

Interest:
Tracking objects through the ionosphere
Satellite detection
Calibration for radiotelescopes
Meteor detection

- Fast particles passing through the ionosphere
- Create an ionized channel
- Detection in radar mode

Ionospheric plasma density & frequency determine if echos are "overdense" or "underdense"

**Image range-slow time**
*(no ground echos)*

Typical reflexion on an “underdense meteor trail”

Applications:
Detection of Extensive Air Shower caused by cosmic rays
Coronal Mass Ejection (CME) measurement

Low SNR Ratio: requires long integration but wavefront is moving fast! Huge Doppler shift (~5-40kHz)

**Interest:** Estimate the density and the speed of CME
Astronomy applications: passive mode

• Passive mode: principle for one antenna

« fast-time » dimension  →  Receiver bandwidth

« Slow-time » dimension
Sun radio observation

- Measurement of noise generated by the Sun
- Passive mode at 25.6MHz (trans-ionospheric)
- The sun is entirely within a receiving beam
- Looking direction is fixed (azimuth/elevation)
- Detecting of the Sun when it enters the beam

- Experimentation: 14/10/2011 from 11h 10’ to 12h 20’ TU
- No increase of the background noise during the transit of the Sun into the beam
- Presence of bursts caused by solar flares
- This bursts were located in the Corona
Sun radio observation – 25,6 MHz – 14 oct 2011

Entry of the solar disk into the beam

Solar disc is at the center of the beam

Solar disk leaves the beam
Sun radio observation – 25.6 MHz – 14 oct 2011
Sun radio observation – 25,6 MHz – 14 oct 2011

RDN Nançay - WIND
Source: secchirh.obspm.fr/

NOSTRADAMUS
Sun imagery – 25,6 MHz – 14 oct 2011

Digital beamforming

Main lobe
- 1° azimuth
- 2° elevation
Observation of radio emissions from Jupiter

- Fixed beam, frequency = 21,437 MHz
- 14 December 2012, 21h15 – 23h00 TU
- Tracking mode
Observation of radio emissions from Jupiter

- Fixed beam, f = 21.427 MHz
- 14 December 2012, 21 h 15 – 23 h 00 TU
- Tracking mode

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kHz</td>
<td>21:15:00</td>
</tr>
<tr>
<td>20 kHz</td>
<td>21:30:00</td>
</tr>
<tr>
<td>20 kHz</td>
<td>21:45:00</td>
</tr>
</tbody>
</table>

Graph showing frequency and time with observed emissions.
Observation of radio emissions from Jupiter
Observation of radio emissions from Jupiter

Imagery
Digital beamforming
Pulsar observation at long wavelength

- Observation of pulsar **PSR0804+74**
- 26 avril 2013
- Frequency: 25.6 MHz

- Processing is more complex:
  - Very low SNR Ratio
  - Frequency dispersion of the signal
  - Temporal integration is difficult

- In processing…
An electromagnetic wave passing near a massive body (black hole) can acquire an orbital angular momentum.

The structure of NOSTRADAMUS is adapted to OAM detection.

**Goal:** detect OAM rays coming from HF radio sources.

}\[ l=+1 \]
Observation of Orbital Angular Momentum in radio

25MHz simulations

Reception pattern of Nostradamus at $f=25$ MHz for a plane wave with $\ell=0$.

Reception pattern of Nostradamus at $F=25$ MHz for an OAM with $\ell=1$.

→ To detect an OAM: compensate the phase due to the spatial spin
→ Limitation to $\ell=2$ due to the 3 arms configuration
→ Need for HF OAM with sufficient SNR
STAP processing for radioastronomy

Data: LOFAR Nançay (R. Weber)

Clear environment

Jammed environment
radio frequency intereference
Use multidimensional adaptive processing to remove RFI

Clear environment

Jammed environment after STAP processing
Conclusion

- Application in radar astronomy and radioastronomy of NOSTRADAMUS:
  - Moon radar detection,
  - Detection of a Solar Coronal Mass Ejection (CME)
  - Sun radio observations (bursts),
  - Jovian radio observations,
  - Observation of OAM in radio band,
  - Pulsar observation,
  - Cosmic rays detection,
  - ...

- Radar signal processing applied to radioastronomy
- Potential collaboration for the use of NOSTRADAMUS
- Was very fun and exciting
Thank you for your attention

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