HI imaging surveys

Marc Verheijen
+ Apertif team
APERTIF

HI imaging surveys

- Apertif specs & performance
- HI science ‘requirements’
- prospects from existing blind surveys
- HI survey definition
- forthcoming activities
After 45 years of service, transform the WSRT into an efficient 21cm survey facility using phased-array technology.

Winning community support + 3 NWO/NOVA investment grants + 3 ERC grants + 2 NWO grants:

- HHistoryNU - van der Hulst, 2.5 M€
- RadioLife - Morganti, 2.5 M€
- ALERT - van Leeuwen, 2 M€
- TOP - Oosterloo, 0.7 M€
- VICI - Verheijen, 1.5 M€
2006: *Apertif* grant (PAF development & construction)
2007: Digestif PAF prototype in RT5
2008: *Apropos* grant (correlator, pipeline, archive)
2009: Preliminary Design Review
2010: - Call for Expressions-of-Interest
    - workshop with EoI teams
2012: workshop with EoI teams
2013: - ARTS grants (pulsar/transient backend)
    - start refurbishment of dishes
Oct 2014: Critical Design Review
Jun 2015: ‘Go’ for APERTIF-10 roll-out
Jul 2015: Call for participation, Draft Survey program
Array of Vivaldi antennas fully samples the focal plane.

### Specifications

<table>
<thead>
<tr>
<th></th>
<th>APERTIF</th>
<th>WSRT</th>
</tr>
</thead>
<tbody>
<tr>
<td># antennas/dish</td>
<td>121</td>
<td>1</td>
</tr>
<tr>
<td># primary beams</td>
<td>37</td>
<td>1</td>
</tr>
<tr>
<td>field-of-view [deg²]</td>
<td>8</td>
<td>0.3</td>
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<tr>
<td>freq. range [GHz]</td>
<td>1.13−1.75</td>
<td>0.12−8.7</td>
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<tr>
<td>T_sys [K]</td>
<td>70</td>
<td>30</td>
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<tr>
<td>aperture efficiency</td>
<td>75%</td>
<td>55%</td>
</tr>
<tr>
<td>bandwidth [MHz]</td>
<td>300</td>
<td>160</td>
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<tr>
<td># channels</td>
<td>24576</td>
<td>1024</td>
</tr>
<tr>
<td># dishes</td>
<td>12</td>
<td>14 (13)</td>
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**APERTIF Resolution:**
\[
\Theta = (1+Z)^2 \times 15 \times 15 / \sin(\delta) \text{ arcsec}^2 \quad (10 \text{kpc} @ D=150 \text{ Mpc})
\]
\[
R = (1+Z) \times 5.2 \text{ km/s} \quad \text{(after Hanning smoothing)}
\]

**APERTIF increases survey speed of WSRT 15−30x**
specifications & performance

PAF : 37 ‘compound’ beams - 8 deg$^2$ FoV
12x25m-dishes, $\Theta = 15'' \times 15'' / \sin(\delta)$
1130–1730 MHz, 300 MHz bandwidth
24,576 channels, $R=5.2$ km/s, full pol.

RFI : digital TV, airplanes
→ pre-/post-LNA filters
→ $T_{sys} \leq 70$K (25% increase)

Some bad luck :

Lots of good news :
• standing waves eliminated
• 75% aperture efficiency
• 8 deg$^2$ confirmed
• beam & pol. stability OK

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<th>BW</th>
<th>SS</th>
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<tr>
<td>ASKAP</td>
<td>0.62</td>
<td>3.7</td>
<td>1</td>
<td>2.5</td>
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<td>MeerKAT</td>
<td>23</td>
<td>0.096</td>
<td>1.7</td>
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<td>JVLA</td>
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<td>0.028</td>
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specifications & performance

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hardware developments

top level block diagram

12 dishes

121x coax

calibration

Receiver

Filterbank & Beamformer

Correlator

Storage & Offline processing

T" F

S

T" F

C
hardware developments

top level block diagram

12 dishes

calibration

121x coax

Filterbank & Beamformer

Storage & Offline processing
on-sky performance

\[ \frac{A_{\text{eff}}}{T_{\text{sys}}} \]

Relative FoV sensitivity

MFFE

Apertif
Radio Frequency Interference
The promise of Apertif

$10^5$ HI detections, $10^4$ resolved HI disks
The promise of Apertif

$10^5$ HI detections, $10^4$ resolved HI disks

Abell 2192  
Abell 963

Chiles

APERTIF

Alfalfa

HIPASS

redshift

0.25 0.20 0.15 0.10 0.05 0.00

0 10 20 30 40 50 60 70 80

10,000 20,000 30,000 40,000 50,000 60,000 70,000 80,000

cz
HI mass limits & detection rates

Based on Alfalfa HIMF

$\Omega_M = 0.3 \quad \Omega_\Lambda = 0.7$

$8\sigma$-detection, spatially unresolved

$H_0 = 70$ km/s/Mpc

$1 \times 12^{\text{hr}}$: $M_{\text{HI}}^*$ at $z = 0.08$, $1 \times 10^{11}$ $M_{\odot}$ at $z = 0.25$

$12 \times 12^{\text{hr}}$: $M_{\text{HI}}^*$ at $z = 0.16$, $3 \times 10^{10}$ $M_{\odot}$ at $z = 0.25$
Note: smoothing to half the angular resolution reduces the survey volume at a particular linear resolution by a factor 8.
Column density limit: \( N_{\text{HI}} < 5 \times 10^{19} \)

Accretion, depletion and removal of gas

- Extra-planar gas
- Tidal stripping
- Ram-pressure stripping

Gas disks are responsive to environmental influences and reveal processes not easily observed otherwise.
Blind WSRT Survey of CVn
86 deg², 1372 pointings
60x12 hrs, 80 min/pointing

Where are these low HI-mass dwarfs?

APERTIF will efficiently survey local volumes to greater depth.

HI mass limits
Broad HI absorption

Requires a stable bandpass.

Morganti et al

LocalGas, Dwingeloo, 4 Sept 2015
A blind HI imaging survey of Ursa Major

**VLA-D**
54 pointings

1414-1417 MHz
\[ \Theta = 45'' \]
\[ \Delta V \approx 8 \text{ km/s} \]
\[ \sigma = 0.8 \text{ mJy/bm} \]

\[ M_{\text{HI, min}} = 2 \times 10^7 M_{\odot} \]

See poster by Eva Busekool
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See poster by Eva Busekool
Detecting & characterizing 3D structures

Visualization by
Davide Punzo
Kapteyn Institute
A blind HI imaging survey of Perseus-Pisces

VLA-C mosaic
44 pointings
117 channels

1395-1408 MHz
Θ = 15”
ΔV ≈ 20 km/s
σ = 0.8 mJy/bm

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See poster by Eva Busekool
A blind HI imaging survey of Perseus-Pisces in the Zone-of-Avoidance

WSRT mosaic
35 pointings, 1x12 hr
1717 channels

1346-1409 MHz
Θ = 16’’x23’’
ΔV ≈ 16 km/s
σ = 0.6 mJy/bm

includes 3C129

200+ HI detections

PhD: Mpati Ramatsoku
Renee Kraan-Korteweg
Gyula Jozsa ++
A blind HI imaging survey of Perseus-Pisces in the Zone-of-Avoidance

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Rendering by Davide Punzo (Kapteyn Institute)
Guiding principles:

- public, legacy-type surveys based on ideas from 18 Expressions-of-Interest++
- collaborate, compromise, consolidate
- be ambitious yet realistic
- simplicity
  - few observing modes, fixed pointing grid
- staged delivery of data and science
- maximum ancillary data availability
- community involvement & commitment
20 years of Apertif survey time required...
Based on community input via EoI’s:

- shallow wide-area survey
- medium-deep survey
- pulsar search survey
- Galactic plane survey
- commensal transients search survey

Realistic: 4-year survey period (2017–2020), 15% DD time, 75% observing efficiency, 1/4 of time dedicated to a survey

$\rightarrow 6600^{\text{hr}} = 550 \times 12^{\text{hr}}$ per survey

Ambitious: 8-year survey period until 2024 (SKA-1 is ready 😊)
shallow wide-area survey

Survey the northern sky at $\delta>+27^\circ$

Observables of interest:
- HI redshifts, line widths, gas masses and kinematics
- HI absorption statistics and properties
- radio continuum sources (LOFAR counterparts)
- OH mega-masers
- rotation measure grid
- fast radio transients

(requires \(~1600\) pointings, or \(20.000^{\text{hr}}\) if \(12^{\text{hr}}\)/pointing...
shallow wide-area survey

Science of interest:

- HIMF, velocity function, (B)TF relation, angular momentum
- Large scale structure, spin alignments, cosmic flows
- AGN outflows/feedback
- Star formation vs AGN (spectral index of LOFAR sources)
- Starbursts and (major) merger rates
- The Galactic magnetic field
- Extreme physics and rare objects
- + ...
Survey 500 deg$^2$ at $N_{\text{HI}} \lesssim 5 \times 10^{19}$ with 15”x20”x25km/s resolution.

(Requires $\sim 60$ pointings or 8.640 hr if 12x12 hr/pointing…)

Survey area is required to minimize cosmic variance.

Observables of interest:
- all shallow-survey observables but 5x deeper
- low $N_{\text{HI}}$ structures in outer disks, filaments, tails
- slow transients ($\sim 12$ epochs)
- polarized extended continuum
- RRL’s in external galaxies
- $M^*_{\text{HI}}$ at $z=0.2$
Science of interest:

- low-mass end of the HIMF at $<10^6 \, M_\odot$
- properties of the ISM and resolved SF in external galaxies
- gas accretion and minor merger rates
- environmental influence on gas in/around galaxies
- extra-planar gas, warps, streaming motions
- $\Omega_{\text{HI}}$ at $z=0.2$
- faint continuum sources (viz-a-viz LOFAR)
- magnetic fields in external galaxies
- radio halos in galaxy clusters
- the variable radio sky (in concert with Palomar Transient Factory)
Four areas comprise footprint of medium-deep survey, maximising use of existing ancillary data.

- The HETDEX survey area
  \(~10^5\) optical redshifts, stacking
- CVn group of galaxies
  low-mass end of HIMF
- Herschel-Atlas Northern Field - SF, gas & galaxy evolution, Coma cluster
- The Perseus-Pisces supercluster - environmental effects, magnetic fields

Spring fields are in SDSS with coordinated overlap with MaNGA and HetDex, delivering resolved information on Stellar Pops, ISM, kinematics, metallicities etc.
Ancillary data - HetDex

A blind IFU survey using VIRUS on HET

22% fill factor over 300 deg²

- 1.5” fibers
- 448 fibers/IFU, 78 IFUs
- 350-550 nm
  - Ly-α: Z=1.9–3.5
  - [OII]: Z= 0–0.48
  - Hβ: Z= 0–0.13
  - [OIII]: Z= 0–0.10
- R=700

~10^5 [OII] redshifts in Apertif bandwidth (Z≤0.25)
LocalGas, Dwingeloo, 4 Sept 2015

Ancillary data - H-Atlas

Blind Herschel PACS/SPIRE imaging of North Galactic Pole region (~150 deg²)

PACS: 110, 170 μm
SPIRE: 250, 350, 500 μm

Θ=18” at 250 μm

~500 sources/deg²

1/12th of NGP field, including Coma

Complete SED reconstruction:
› Total energy output
› Star Formation Rates
› Dust masses and temperatures

All data are publicly available.
Ancillary data - MaNGA

A SDSS-IV multi-IFU survey of $10^4$ nearby galaxies at $z \approx 0.03$

- 2" fibers
- 17 IFU's per 7 deg$^2$ field
- 12"–32" FoV per IFU
- 360-1000 nm
- R=2000
forthcoming activities

late 2015 : Apertif-6 roll-out & performance tests
early 2016 : roll-out of remaining 6 PAFs, full correlator shake-down, commissioning, science verification ramp-up of science teams
late 2016 : Early Science programs
early 2017 : Start of surveys