ASTRON
Netherlands Institute for Radio Astronomy

The prospects for Apertif

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1. Introduction

Since 2006, Astron is developing Apertif, a possible upgrade to the WSRT. Apertif will enable many new types of radio astronomy, but on the other hand, several types of observations that can be done with the current WSRT will not be possible anymore. Therefore, if Apertif is installed in Westerbork, it will have major implications for the use of the WSRT for the period after 2010[1]. Apertif will turn the WSRT into (mainly) a survey instrument and the way in which the WSRT is used will also change significantly.

In this context, a number of issues should be discussed by the community and the community should evaluate whether Apertif will be a useful change or not. Issues in particular are "Are the new possibilities offered by Apertif interesting enough to give up the current WSRT?", "What should be observed with the WSRT before Apertif would be installed", and "Who wants to be involved in Apertif?". The aim of this document is to bring you up to speed about Apertif and to be a starting point for the discussions mentioned above. This document gives a brief description of Apertif, its expected performance, and, very importantly, it describes what is still needed to be able to realise Apertif. We briefly list some of the science that could be done with Apertif, and the start of a list of capabilities that will be lost once Apertif is installed. We strongly solicit input from the community for these inventories.

2. Description of Apertif

The main aim of Apertif is to significantly enlarge the field of view (FoV) of the WSRT in the L band. With Apertif, observations in other bands than L band will not be possible anymore with the full WSRT. One of the options is that observations on other bands than L will still be possible with one or two dishes. The idea is to replace each MFFE front-end (or most of them) with a focal-plane array (FPA). Each FPA consists of 8x8 dual polarisation antenna elements and operates in the 21-cm band only. The current WSRT backend will also be replaced to suit the needs of the FPAs. Replacing, in each dish, the current single-pixel detectors by arrays, makes it possible to form, for each dish *instantaneously*, multiple primary (i.e. single-dish) beams on the sky and turns each dish, effectively, into a "radio camera". Each of these primary beams can be imaged at the nominal WSRT resolution of about 15 arcsec, using normal aperture synthesis. Therefore, if the FPAs are used to form *N* primary beams on the sky, the output is *N* times that if the current WSRT. After the upgrade, the FoV of the WSRT will be about a factor 25 larger at 21 cm; it will be squarish of roughly 2.5 x 2.5 degrees, compared to the current circle of 0.6 degrees diameter.

Several radio telescopes, such as Parkes and Arecibo, have already installed multibeam receivers. The important difference between these multibeam systems and FPAs is that the spacing between the antenna elements in an FPA is much smaller than those of the existing multibeam systems. In fact, with an FPA the radiation field in the telescope focus is densely sampled, while a multibeam system is basically a set of independent receiver elements. This close element spacing makes that the beams of neighbouring elements overlap on the sky, contrary to multibeam systems where the different beams on the sky are independent. For Apertif, the spacing between the antenna elements will be about 10 cm. The big advantage of dense sampling in the focal plane (or, equivalently, overlapping primary beams on the sky) is that it allows one by combining the signals of several elements, to *optimise* the response of a dish in a certain direction. This signal combination is done using the signals in the backend and the combined signal is fed to the correlator so that the field of the combined primary beam, that has roughly the same size as the current WSRT primary beam, can be imaged. Another very important thing is that this optimised beam combining can be done many times *simultaneously* so that many primary beams can be made and many fields of half a degree in size can be imaged at the same time. For Apertif it is foreseen that with the 64 elements, 25 primary beams are formed so that 25 fields, each of the same size as the current WSRT FoV, are imaged. Interestingly, because of the large FoV, Apertif makes it more interesting to use the WSRT as a single dish because of the large FoV. Some examples of single-dish applications are given below.

Apertif will only work in the L band, the frequency range it will cover is 1000 - 1700 MHz. Apertif will (almost) double the bandwidth of the WSRT, to 300 MHz (although keeping it at 160 MHz, or making it 200

[1] it is important to realise that not installing Apertif may also have important implications for the WSRT

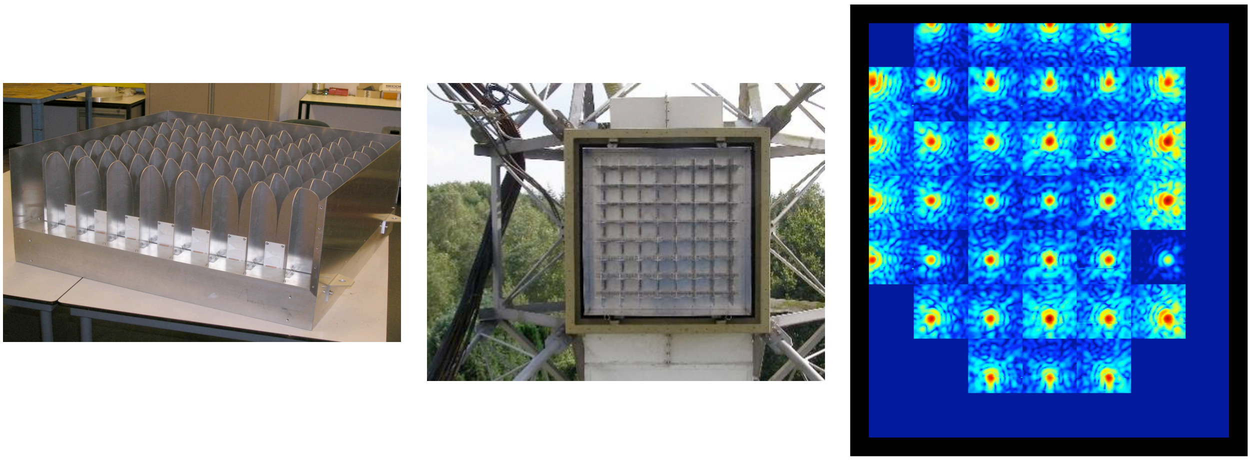

Figure 1*: left:* The array of 8x7x2 Vivaldi elements used for the prototype currently installed in RT5. *middle*: The same array installed in the focus of RT5. *right*: Beam patterns on the sky of a subset of the elements of the prototype. Each panel covers 3x3 degrees. The large optical distortions of the elements near the edge of the array can clearly be seen. Making compound beams by combining these element patterns will reduce these distortions.

MHz is, in principle, an option; see below). Although the specs of the correlator are not completely defined yet, the spectral resolution will, over the entire 300 MHz, be good enough for extragalactic H I work (i.e. will be better than 10 km s^{-1}). Smaller bandwidths with higher spectral resolution are also foreseen**.**

Because of the large physical size of the Apertif FPAs (about 1m x 1m), we cannot afford to cool the LNAs cryogenically. Therefore, the system temperature will be higher than the current T_{sys} of 30 K and is expected to be 50-55 K[2]. This loss in sensitivity is partly offset by a higher aperture efficiency due to the optimisation in the beam forming (or equivalently dish illumination) referred to above. A_{eff} will increase form the current 55% to 75%. The combined effect of higher T_{sys} and higher A_{eff} is that the A/T of a dish with Apertif is about 0.7 times that of a current WSRT dish.

Scientifically, the main benefit of the larger FoV (and the larger bandwidth) is a large increase in the survey speed[3]. Depending on the options discussed below, the survey speed of Apertif will be 10-25 compared to the current WSRT. With this large FoV, it becomes conceivable to survey a large fraction of the sky at high spatial resolution to much deeper detection levels than what is currently possible. In this sense, Apertif is a SKA Pathfinder and some of the (types of) SKA science can be started to be addressed. Some of the surveys that one could do are discussed in section 4.

Finally, the connection of Apertif with SKA is not only science. FPAs are a technology that might be used for SKA. Astron is currently one of the world leaders in FPAs at cm wavelengths, and developing Apertif will ensure that this leading position is maintained. Therefore it is of strategic interest for Astron, and the Dutch astronomical community as well, to be working on Apertif.

3. Options

In 2006, an NWO-Groot proposal was submitted to obtain funds for building the frontend systems of Apertif. This proposal was successful and was awarded 5 M€ (of 6.9 M€ requested). Taking everything into account, of this 5 M€, about 3 M€ can be spent on the hardware of the frontends, and 2 M€ will go toward manpower, developing costs etc.. The amount of 3 M€ is, strictly speaking, not sufficient to build the

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[2] recent developments with room temperature low-noise amplifiers may perhaps lower this by 10 K, but this is still all very uncertain.

[3] the survey speed is the reciprocal of the time needed to observe a given region in the sky (or volume in space in the case of spectral-line observations) to a given noise level . The survey speed is proportional to $\mathrm{FoV}\cdot(A/T)^2\cdot\Delta\nu$

N_{dish}	N_{beams}	Δν [MHz]	Noise line	Noise cont	Sspeed	Cost per dish	Total cost
14	25	160	1.39	1.39	12.9	€216743	€3034402
12	25	300	1.64	1.20	17.7	€262484	€3149808
14	25	300	1.39	1.01	24.1	€262484	€3674776

Table 1: Cost of some options for Apertif

frontends according to the specs of the original proposal and some de-scoping may have to be considered. For a while, this de-scoping seemed to have a major impact on the performance of Apertif and many options have been investigated. However, with the most recent costings the situations is not so bad as was thought and the discussion about the options for Apertif is much more limited. In the table above we give a few of the options considered and the costs of the frontends of these somewhat de-scoped Apertifs. The most important options to reduce cost are: fewer frontends (most likely option in this case: 12) or less bandwidth. It appears that to realise Apertif on 14 dishes, the bandwidth will have to be reduced to 160 MHz, while sticking to 300 MHz means that only 12 WSRT dishes can be fitted with an FPA (while going slightly over 3 M€).

Apart from money, another reason for considering installing Apertif frontends in fewer than 14 dishes is that the remaining dishes could keep the current MFFEs and the WSRT would continue to provide, although at much reduced sensitivity, some of the current capabilities. This is an issue that we would like to discuss at the usermeeting.

3.1. Expected performance

The FoV of Apertif will be about 6 degree^2. To image the entire sky above declination +30^o with this FoV requires 1500-1800 Apertif pointings (depending on the exact configuration of the FPA beams on the sky). To give an idea of the scale of projects that one could embark on: using 300x12 hr per year for a survey and spending 1x12 hr on each pointing, in 5 years one can more or less image the entire sky above declination +30^o. Although none of the possible Apertif surveys have been worked out in any detail, a big survey will probably involve 1000-1500 x 12 hr.

3.1.1. Spectral-line work

From Table 1 one can see that the noise level of Apertif for spectral-line observations will be 40-70% higher compared to the current WSRT. This implies that, to reach the same noise level, integration times with Apertif are 2-3 times longer.

To give a feeling for what Apertif can see, we give some detection limits and other numbers. The current WSRT can detect, in a single 12 hr observation, a galaxy with an H I mass of $10^9 M_\odot$ out to $z = 0.05$ and an M_* galaxy (i.e. 5 x $10^9 M_\odot$) out to $z = 0.1$. For Apertif with 12 dishes (Apertif-12), $10^9 M_\odot$ of H I can be seen out to $z = 0.04$, while M_* can be seen out to $z = 0.08$. With deeper observations of 10x12 hr, these redshift limits for Apertif-12 are $z = 0.07$ and $z = 0.14$.

Depending on details of, e.g., how galaxies will be searched for in the data, in a single 12-hr observation Apertif-12 will detect, in the 25 fields combined, about 150-200 galaxies in H I [4], almost all with redshift below $z = 0.1$. In a 10x12 hr observation Apertif-12 will see about 1000 galaxies, with many detections above $z = 0.1$ (see Figure 3). Note that in order to cover this redshift range in one observation, the 300 MHz bandwidth is required. If one would embark on a large survey of the order of 1000x12 hr, one would detect 1-2x10^5 galaxies in H I in emission.

[4] for the redshifts considered here, cosmology and evolution are not very important. Therefore, the number of H I detections goes as $\sigma^{3/2}$ so Apertif with 14 dishes and 300 MHz will see $(1.64/1.39)^{3/2}$ times more galaxies, i.e. 200-250.

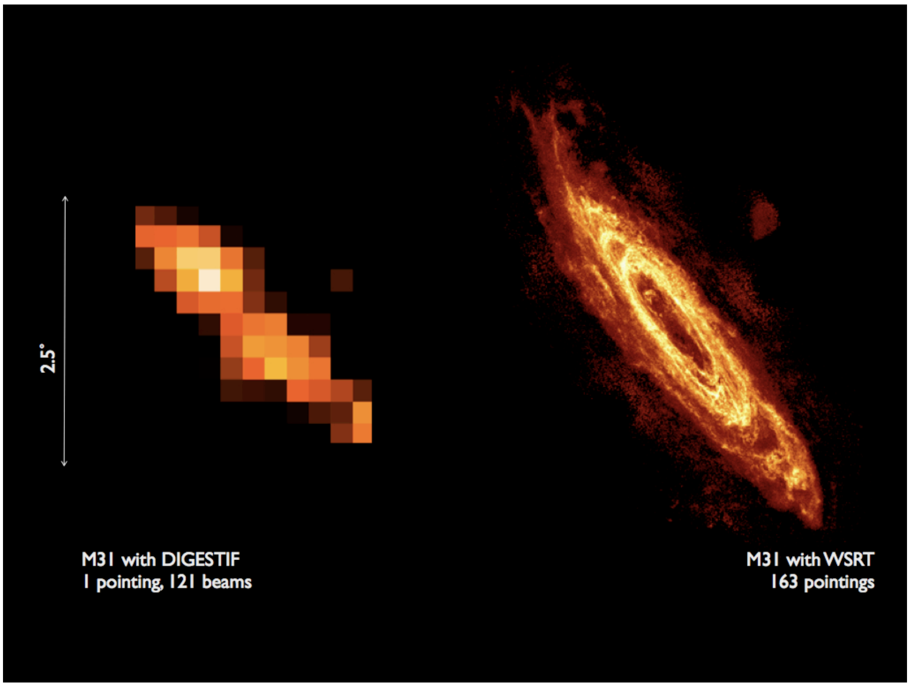

Figure 2. M 31 observed with the WSRT. *left***:** A single-pointing measurement with the Apertif prototype, yielding the resolution of a single dish. *right:* A 163-pointing observation in interferometric mode, yielding the full resolution of the 3-km array. If all WSRT antennas are equiped with an FPA, the same high resolution can be achieved over the full FoV of Apertif.

3.1.2. Continuum

With a bandwidth of 300 MHz, the continuum sensitivity of Apertif will only be slightly worse than that of the current WSRT. This means that with a single 12-hr observation, a noise level of about 15-20 μJy beam^{-1} can be reached. With a 160-MHz band, the noise level will be about 20-30 μJy beam^{-1} and all integration times will double. The Apertif noise levels are a factor 15-30 deeper than the NVSS. The confusion limit for the WSRT at 21 cm is about 5 μJy beam^{-1} so the continuum images of deep H I observations will be confusion limited (in Stokes I, not in polarised emission!).

The number density of continuum sources brighter than 75 μJy beam^{-1} is roughly 400 degree^{-1}. Therefore, a single 12-hr observation with Apertif will result in about 2000-2500 detections. A large survey of order 1000 observations will detect a few x 10^6 continuum sources.

3.2. First observations

A prototype consisting of a dual-polarised Vivaldi array of 8×7(x2) elements has been completed and installed in the focal plane of one of the WSRT 25-m telescopes. The spacing between the Vivaldi elements is 10 cm (λ/2 at 1500 MHz). With this arrangement one is very close to reaching the ideal situation where the element beams overlap at their -3dB points while obtaining a dish illumination with minimal spillover. Each Vivaldi element has its own LNA. The data is sampled at 12 bits and the beamforming is all digital. The Lofar ITS has been recycled and serves as backend for this prototype. A close up of this prototype in the focal plane of RT5 is shown in Figure 1.

The first astronomical observations with the Apertif prototype were performed on a number of sources: Cygnus A, H I in the Milky Way and H I in M 31. Especially the latter is an excellent demonstration of the power of the FPA system and is shown in Figure 2. The right panel shows a *163-pointing* mosaic of M 31 obtained by Braun using the existing WSRT with single feeds. The left panel shows the same part of the sky from a *single pointing* with the Apertif prototype on a single telescope. A total of 11x11 compound beams were formed with the Vivaldi signals of this single telescope pointing. The implication is that when all

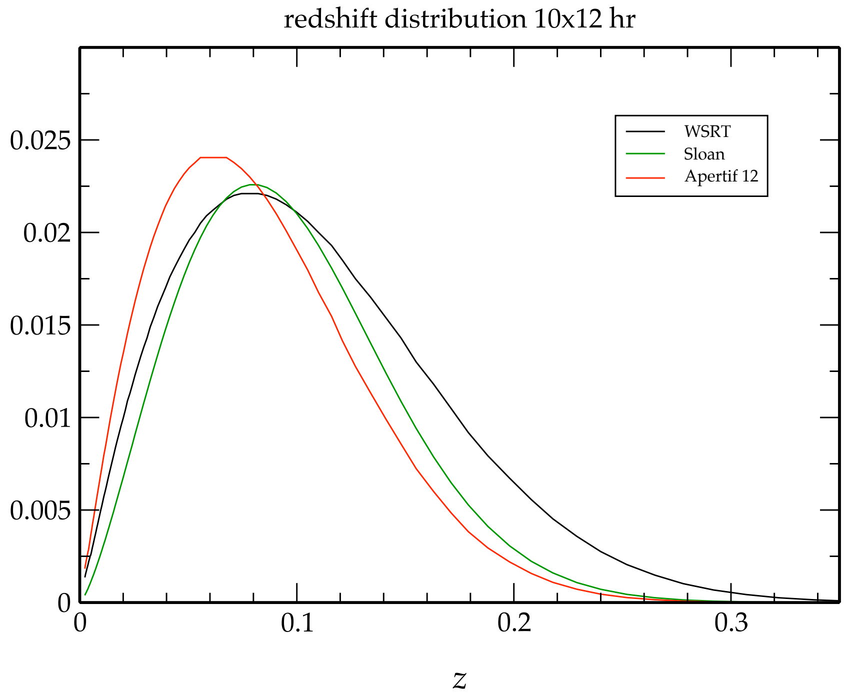

Figure 3: Redshift distribution of H I detections after 10x12 hr with a 12-dish Apertif, compared to the redshift distribution of the SDSS galaxies and of a 10x12 hr WSRT observation

WSRT telescopes are equipped with a FPA system, the 163 pointing observation can be carried out in only one pointing, demonstrating the impressive increase in survey speed.

4. Possible science

From the previous section it is clear that the WSRT+Apertif will be a survey instrument and (very) large-area surveys with good sensitivity will be possible.

Below a few remarks on the kind of projects that could be done. This is not intended to be complete, and input from the community on other projects (or the ones mentioned) is very welcome.

4.1. H I surveys

To illustrate the impact of an Apertif H I survey: currently, the H I properties of about 20,000 galaxies are known, almost all detections are below z = 0.1. Moreover, the large majority of the detections are from single-dish observations, therefore the spatial resolution of almost all these detections is a 3 (Arecibo) to 15 (Parkes) arcminutes. An Apertif H I survey would give the H I of about 10 times more galaxies, with spatial resolution a factor 10 better and (depending on type of survey) a large fraction of the detections would be above z = 0.1. It is clear that an Apertif H I survey would be a major step forward.

An H I survey could, depending on survey strategy, give 1-2 x 10^5 detections. A (relatively) shallow survey aimed at covering the largest possible region on the sky, would give the largest number of detections. One possible survey would be to survey a large region on the sky with 1x12 hr pointings. This would give the definitive inventory of H I in galaxies in the local Universe, and issues like the dependence of the H I properties as function of environment and the relation with star formation/morphological type can be addressed.

Another strategy could be to integrate deeper per pointing but then cover less area on the sky. One would obtain information on the H I statistics out to z = 0.2, so one can start addressing the redshift evolution of H I in galaxies and relate this to the evolution star formation. Overlap with the SDSS would be important. To obtain good overlap between the H I samples and the SDSS sample one requires integrations of about 10x12

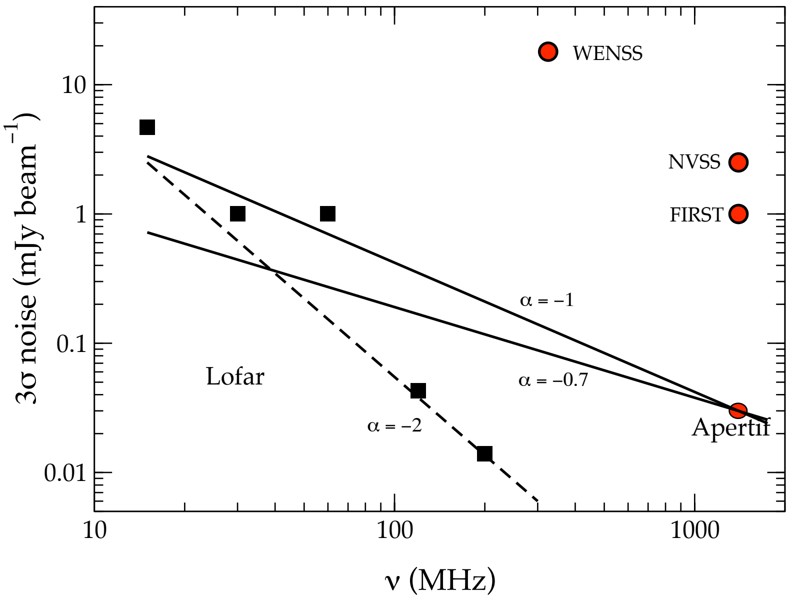

Figure 4. Detection limits for various Lofar surveys and the Apertif continuum survey. The lines indicate the various spectral indices.

hr per pointing (see Figure 3). To be able to profit from the high survey speed of Apertif, the 300 MHz bandwidth would be needed, otherwise the redshift range z = 0 - 0.2 cannot be covered in one observation.

Both surveys, but in particular the medium deep one, will also give a large improvement of the data on the low end of the H I mass function and one can study the properties of the smallest H I galaxies. The deepest surveys now go down to several times $10^6\ M_\odot$. With Apertif this can be brought down a factor 10 and one starts to cover the type of objects between galaxies and Compact High-Velocity Clouds.

One possibility we are investigating at the moment is whether Apertif can be used to observe the 21-cm H I intensity field (Pen et al, arXiv:0802.3239). This is a new technique to detect cosmic structure on very large scales (100 kpc and more). For this, only the autocorrelation spectra are needed and Apertif+WSRT would not have to be used as an interferometer.

4.2. Continuum surveys

Continuum surveys can be combined with H I surveys. Such surveys would give a million or more detections. A nice aspect is that many of the detections will be star forming galaxies in the same redshift range as covered with medium deep H I surveys and the combined datasets will be very suitable to study the star formation properties in relation to gas content and other parameters.

Another interesting aspect is that an Apertif continuum survey is a nice complement to Lofar surveys. Figure 4 shows the relative detection limits of Apertif and some of the Lofar surveys planned. The relative detection limits of the low-band Lofar surveys and the Apertif survey correspond to a spectral index of −1. This implies that there will be large overlap between the sources detected in these surveys. The figure also underlines the enormous improvement an Apertif continuum survey would give over the NVSS or FIRST.

4.3. Magnetism

In L band, a few percent of the extragalactic continuum are polarised. Moreover. Apertif will detect the polarised signal of many pulsars in the Galaxy. Therefore, a large area continuum survey can be used to help construct construct an all-sky Rotation Measure Grid with a spatial a spacing of order 10 arcminutes, much higher than currently available. The large sample of pulsar RMs obtained with Apertif can be inverted to yield a complete delineation of the magnetic field in the spiral arms and disk on scales ≥ 100 pc. Magnetic field geometries in the Galactic halo and outer parts of the disk can be studied using the extragalactic RM grid.

The Global Magneto-Ionic Medium Survey (GMIMS) is a project to map the entire sky (north and south) with single-dish telescopes from 300 to 1800 MHz (as much as is permitted by RFI) in narrow frequency bands. Several telescopes are being used, such as Parkes in the south and the DRAO 26-m dish in the north (1300-1800 MHz). Apertif could be used to map the northern sky from 1000-1300 MHz for this project.

Recent WSRT work on Rotation Measure Synthesis on nearby galaxies in the L band has given interesting results (Heald et al.). With Apertif this can be done on a much larger sample, basically on every galaxy in the FoV. One can use the 300 MHz data taken for the HI/Continuum surveys, but one could also observe the entire 700 MHz band in a dedicated survey to obtain better resolution in Rotation Measure.

4.4. Pulsars surveys

Apertif is a very interesting instrument for pulsar astronomy. The nominal, wide-field continuum survey sensitivity of Apertif will permit detection of a large fraction of Galactic pulsars beamed in our direction. All pulsars out to 10 kpc can be detected, while the brightest pulsars will be seen out to 100 kpc. The large FoV means that these pulsars can be searched for over a large region of the sky and a survey could result in a few thousand new pulsars.

What is important to realise is that, compared to other synthesis arrays, the current WSRT is an efficient pulsar survey telescope and that this is 25 times more so the case for Apertif. Due to the combination of the regular, linear layout of the array and the powerful backend, the primary beam of the WSRT can be covered with a set of tied-array fanbeams. Each fanbeam can be searched for pulsar signals. Due to the rotation of the Earth, the way the fanbeams cover the primary beam changes with time. Therefore, a pulsar first detected in one fanbeam will later be detected in another fanbeam. This can be used to localise a pulsar on the sky. The big advantage of this technique (called *8gr8* and currently exploited by Stappers et al.) is that while one uses the collecting area of the entire array (equivalent to a 90-m dish), the field-of-view is set by the size of an array dish and not by the size of the array which is the case for other synthesis arrays. Hence the FoV for pulsars searches is larger. Apertif, provided one has the right backend (!), can in principle be used in a similar *8gr8* mode, but then fold 25-fold faster.

4.5. Transients

Transients is likely going to be a very exciting part of radio astronomy in the next few years. Although the FoV of Apertif is much smaller than that of Lofar, Apertif may still be an interesting instrument to search for transients. The sensitivity is very good, while the higher observing frequency permits detection of sources that could otherwise be shrouded by thermal absorption. An interesting aspect is that transient detection with Apertif can be done (provided the right backend is available) in piggy-back mode on other imaging surveys.

5. What do we loose

Section 4 illustrates the new capabilities Apertif will give to the WSRT. At the same time, with Apertif several types of observations will not be possible anymore, while some will still be possible but only at (in many cases much) reduced sensitivity. We expect the community to play an important role in making the inventory of what is lost and how important this loss is. Below we list some of the impact of Apertif, but we expect that the WSRT users will help us making this inventory more complete. If you care about something, please speak up!!!

In this context, one option should be discussed, namely whether Apertif-12 can reduce somewhat the impact of Apertif, i.e. if 1 or 2 WSRT dishes keep the MFFE, would that capability still be useful.

5.1. Pulsars

Currently, WSRT pulsar observations are done in several bands. Particularly important are timing experiments at 92 cm. At present it is the only low-frequency instrument available as part of the European Pulsar Timing Array (EPTA) project. The reason why this is interesting and important is the need to correct for the dispersive delays in the ISM and variations therein. The saving grace in all this might be the Sardinia telescope. They are planning on having a dual 92-cm/21-cm feed system. While they will not have the same gain as the WSRT, they might have enough observing time and bandwidth to take up the slack as far as the EPTA is concerned.

The other problem of course is that because the instantaneous gain of the Apertif system will be worse, this would mean need longer integrations to achieve the current high precision, unless wider bandwidths are available and a pulsar backend to deal with this. So this may not be too much of a problem.

Regarding Apertif-12: having two dishes available for the pulsar work is not more useful than having one because of the automatic gain controllers of the WSRT, the pulsed signal is lost, unless you have more than a few telescopes.

5.2. VLBI

Currently, about one third of VLBI observations are done in the L band, while another 10% is done a 5 cm (for which only 1 WSRT dish is used). Therefore, about 60% of VLBI observations will be affected. These 60% will still be possible if Apertif will be installed in fewer than 14 dishes, but at much reduced sensitivity.

In the discussions of VLBI and Apertif, it is important to also note that VLBI will evolve significantly in the next few years. Things will not stay the same, regardless of Apertif. An important question is what should be done at the WSRT to follow this evolution. To what extent Apertif is a problem and to what extent an opportunity?

5.3. Deep HI

A niche of the current WSRT is to do very deep H I observations (20-100 x 12 hr), either of nearby galaxies, or of distant clusters. Although the WSRT is less sensitive than the VLA (about a factor 3 in integration time), the WSRT correlator is much better suited for H I work (a statement also true for not-deep H I work). Once the EVLA is completed, this advantage will disappear. Note that for H I work, the EVLA will not be more sensitive than the current VLA and deep EVLA H I work will still require long integrations. It may be difficult to get the required amounts of observing time on the EVLA to do similar observations.

5.4. Lofar related

Soon Lofar will produce the first scientifically useful images. One can imagine that it will be useful to be able to image some regions observed by Lofar with the WSRT at other frequencies. This can of course also be done with the EVLA, but, as for H I work, the user interest in the EVLA may be such that it will be beneficial to have 'one's own' instrument to do this.

6. Open issues

The above discussion summarises Apertif and what it can and cannot do. It is important that the community discusses the issues mentioned above so that a clear picture emerges about the desirability of Apertif. However, there are also some other practical matters that are important.

6.1. Money Matters

At the moment, Apertif has funds to construct the frontend systems. No money has been secured yet for the correlator, nor for the pulsar and VLBI backends that will be needed. With regard to software, the plan is to recycle as much as possible Lofar software, but still quite some Apertif specific development will have to be done. Also for the software sufficient funds are lacking. This is of course serious, and may kill the project in the end, but in the project we still feel that there may be ways to obtain the necessary funds. One possibility would be to embark on a new correlator together with Lofar and e-VLBI. Discussions on this possibility have started. Another option would be to find a European context for Apertif.

6.2. How to use the WSRT+Apertif

Given that Apertif will turn the WSRT in mainly a survey instrument, one has to decide how the instrument will be used. Do we have to start KeyProjects, perhaps in a similar way as for Lofar? This would require that several groups get formed, each of which would run and exploit a survey. This would likely require involvement from outside The Netherlands in order to be able to form groups of sufficient size. The other extreme would be that a number of surveys would be done in a service mode, and the data would be freely available to everybody shortly after the observations. This would require much less organising and would probably give more science. A related question is what fraction of the observing time would be dedicated to the surveys and what fraction to open time.

6.3. Transition WSRT → Apertif

If it is decided to install Apertif, how should the transition go? Is it worth considering a period in which, say, half Apertif would be installed while the other half of the WSRT would observe with the MFFEs?

6.4. What has to be done before Apertif?

Are there observations that should be done before Apertif would be installed? For example, are there Lofar fields for which additional data at MFFE wavelengths would be desirable?

6.5. What will happen with WSRT if no Apertif?

To what extent is the future of the WSRT linked to Apertif? The WSRT seems to be secure until 2012, but to keep the WSRT open after that date will require a new discussion. Apertif, and its SKA context, could be an argument to keep the WSRT open. Is the scientific potential of the current WSRT_MFFEs strong enough to get its life extended beyond 2012? How long will the current backend (physically) last?