Amateur Radio astronomy 21 cm hydrogen survey of M31 and M33 galaxies

Jean-Jacques MAINTOUX – F1EHN

Contact : jjm_f1ehn@wanadoo.fr

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Radio astronomy
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Introduction

Radioastronomie d'amateur :
Observation des galaxies M31 et M33 @ 21cm

Jean-Jacques MAINTOUX - F1EHN

Les résultats de l'observation de notre Galaxie (Voie Lactée) en 21cm, publiée dans l'Astronomie n° 54 et 55 (octobre et novembre 2012), ont montré que les performances de mon radiotélescope (RT) moyennant quelques adaptations pourraient permettre d'observer d'autres objets présentant un rayonnement de plus faible intensité. Notre groupe local [1] héberge quelques dizaines de galaxies. Le rayonnement H I (Hydrogène neutre à 21cm) est un outil très pratique pour étudier le milieu interstellaire (ISM) de ces galaxies. La note [2] présente les principales galaxies voisines et c'est NGC224 ou M31 et NGC45 ou M33 qui ont retenu mon attention de par leur étendue et leur niveau de rayonnement H I semblant accessible à mon RT. Cette note présente les techniques de mesure mise en œuvre ainsi que les principaux résultats obtenus.

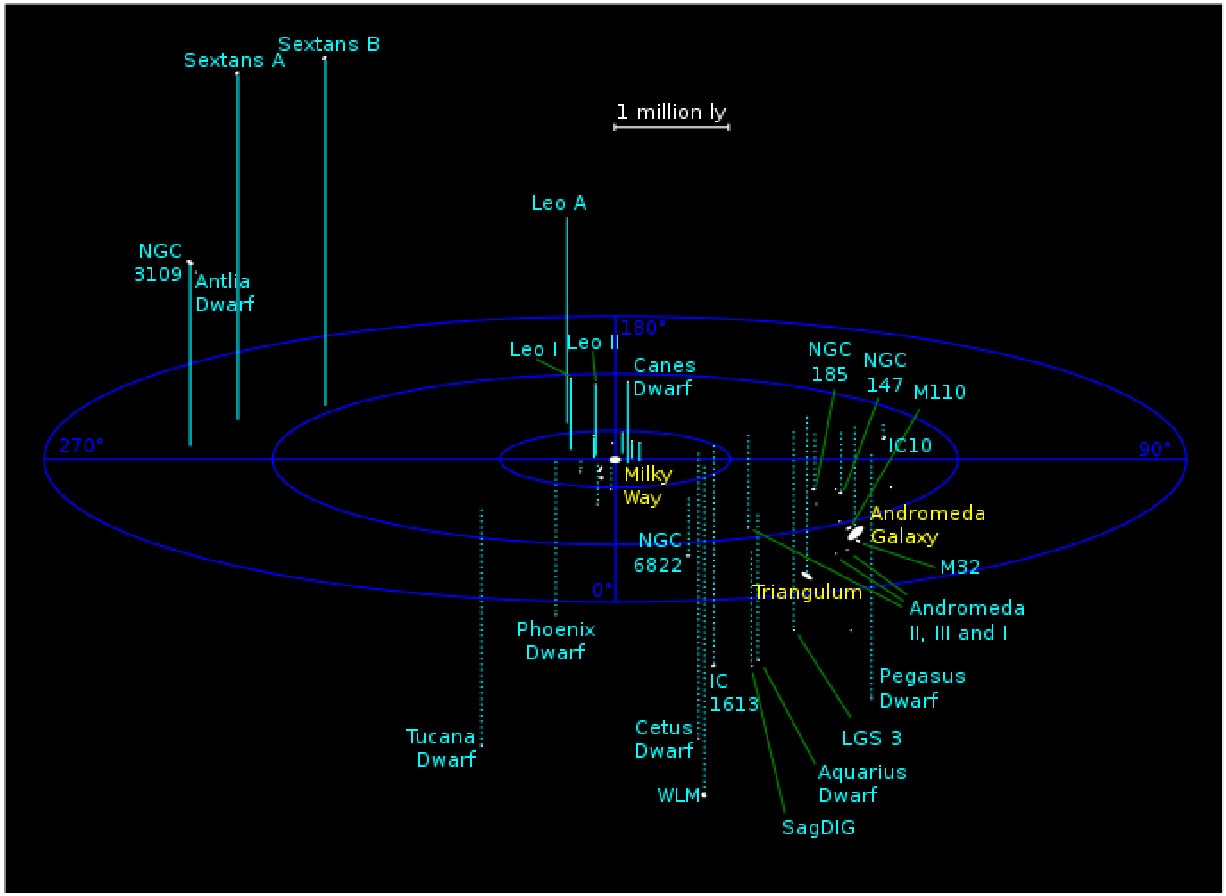
Amateur radio astronomy :
21 cm hydrogen survey of M31 and M33 galaxies

Jean-Jacques MAINTOUX - F1EHN

The results of the 21cm survey of our Galaxy (Milky Way), published in Astronomy n°54 and 55 (October and November 2012), showed that the performances of my radio telescope (RT) could allow, with some adaptations, the observation of other objects with fainter intensity radiation. Our local group [1] hosts a few dozen galaxies. The H I radiation (neutral hydrogen at 21cm) is a very practical tool for studying the interstellar medium (ISM) of these galaxies. The note [2] presents the main neighboring galaxies. NGC224 (M31) and NGC45 (M33) caught my attention by their size and the level of H I radiation seemingly accessible to my RT. This note presents the deployed measurement techniques as well as the main results obtained.

Local group

Wikipedia : https://en.wikipedia.org/wiki/Local_Group



Spiral galaxies

Name	Type	Notes
Andromeda Galaxy (M31, NGC 224)	SA(s)b	~220 kly in diameter, it is the largest and most massive galaxy in the group.
Milky Way	SBbc	As large as Andromeda galaxy, between 150 and 180kly, home 500-580 billion stars
Triangulum Galaxy (M33, NGC 598)	SA(s)cd	Third largest, only unbarred spiral galaxy and possible satellite of the Andromeda Galaxy. Triangulum Galaxy has mass of ~50 billion solar masses and is Home to ~60 billion stars.

21 cm Radio telescope

The radio telescope was tuned for more gain and a better stability to allow a large coding range of the noise and to mask the other phase and coding noise. The IF and digital bandwidths were widened from 2.5 to 5 MHz

The mechanical stability was improved to avoid lobe modulation by adding filtering position into the tracking system (dedicated version of F1EHN EME System).

Long time automatic acquisition and recording was added.

ANTENNA

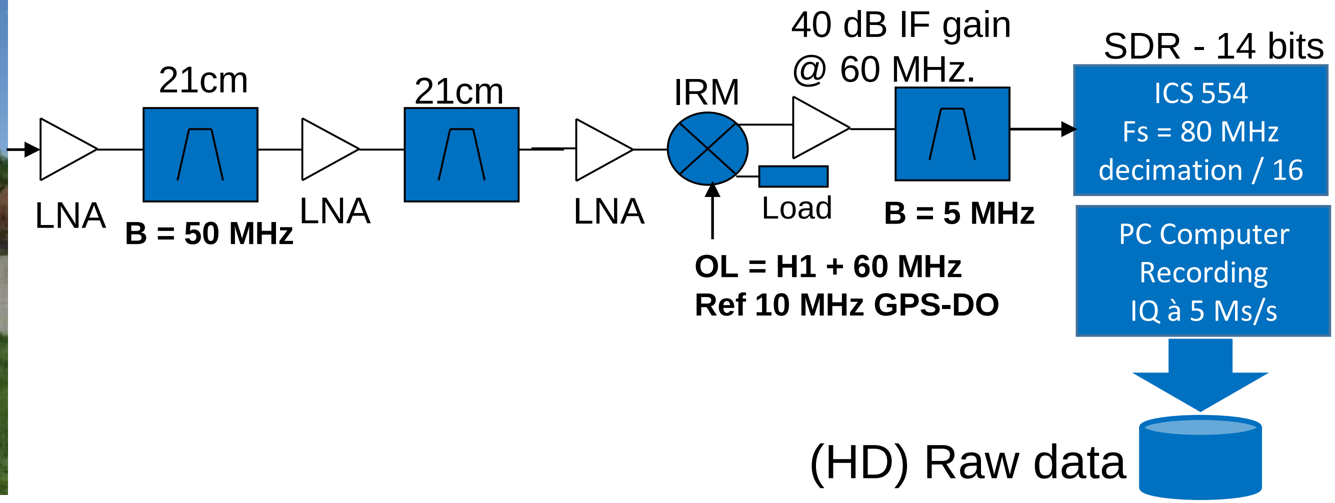
3.3 m dish - F/D 0.43

Super-VE4MA Feedhorn (0.77λ)

21cm Receiving chain synoptic

80 dB global gain

Image reject > 85 dB



Detection sensitivity

$$Sd = \frac{Tsys}{\sqrt{Bw * T}}$$

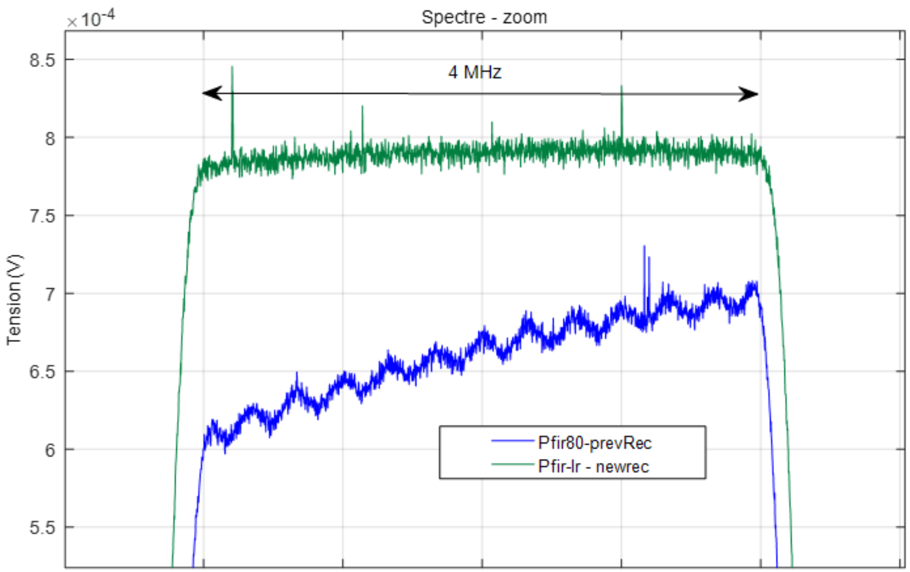
The reference 2 indicates an integrated flux of 40 to 100 Jy for M31 and M33 galaxies.
The sensitivity of my RT is around 3.2 mK/Jy.
That gives approximately an antenna temperature expected around 0.1 to 0.3K.
To observe correctly and resolve the spectrum of M31 & M33, the sensitivity should be around 0.005 K or 5 mK. This value is very low and is 10 000 time smaller than Tsys and a long integration time with a good stability in measurement are required.
The chart below resumes the main characteristics of my RT

Characteristic	Value	Comments
Antenna diameter	3.3m	alt-azimutal turret
Aperture (HPBW)	4.4 °	Half Power Beam Width
Effective Area (Ae)	4.46 m²	Calibrated on solar flux
System Noise Temperature Tsys	60 K	Includind antenna temperature losses
Observation frequency (central)	1422.40575 MHz	Offset 2 MHz / H I soit -422 km/s at center
Receiver bandwidth	4 MHz (844 km/s)	Sampling frequency Fs = 5 MHz
Doppler bin number	128	For 5 MHz => 103 for 4 MHz
Spectrale resolution (Bw)	39.06 kHz	Fs / BinFFT => 5 MHz / 128
Velocity resolution	8.2 km/s	Bw * λ (λ = 0.211 m)
Detection sensitivity	0.005 K	For 1h data recording (3h measurement)
RT constant	3.2 mK/Jy	Incluant correction et calibration

Improvement

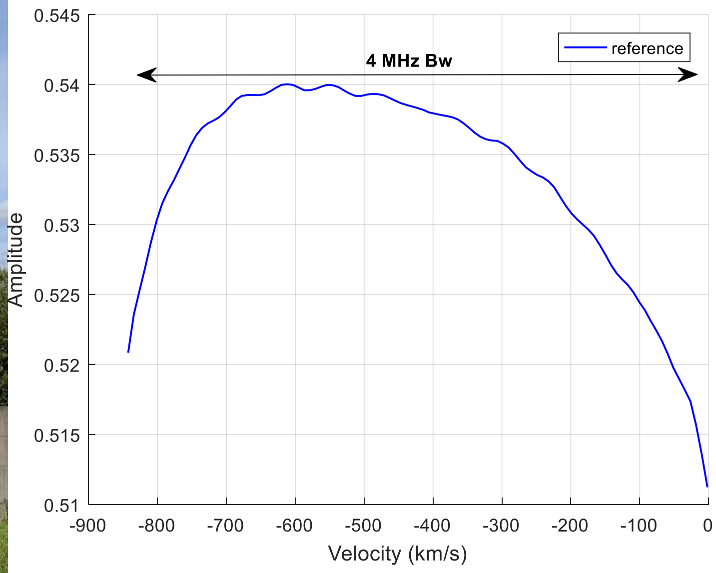
Because the expected signal is very low (10 000 time smaller than Tsys), the frequency response of the receiver must be as monotone as possible.
The improvement becomes with a new design of the digital receiver filtering to lower the amplitude ripple into the processing bandwidth (around 80% of Fs => 4 MHz).
The objective is to deliver a frequency response as flat as possible.

The new frequency response (newRec) is the green curve below compared to the previous one (prevRec). The slope came from the IF analog filter.



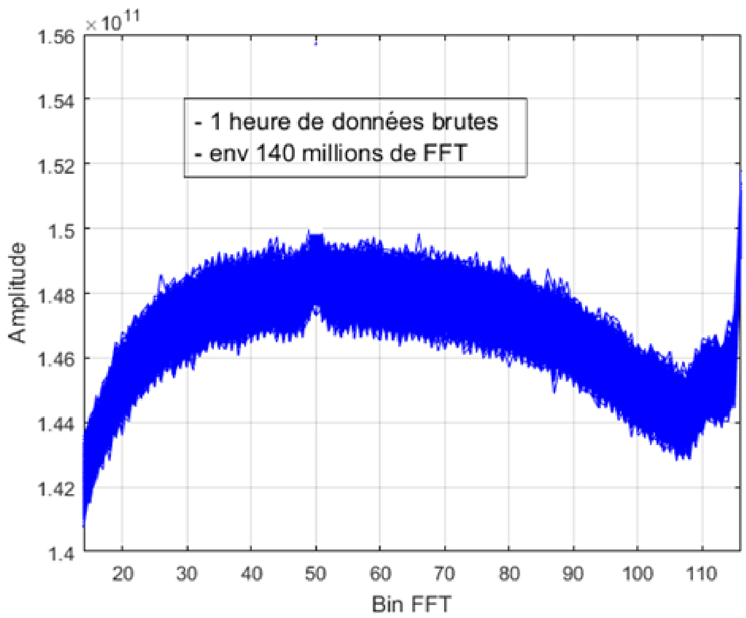
RT Calibration

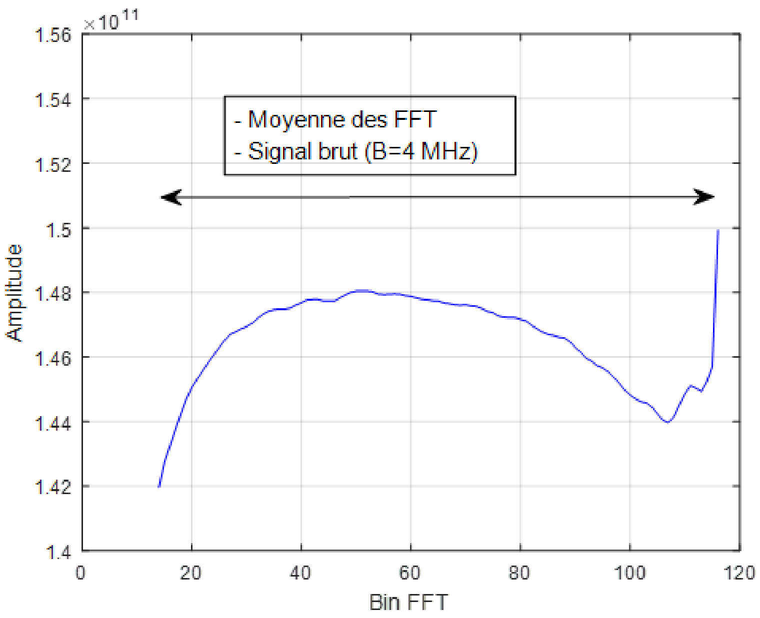
Like in optic for astronomy, the idea is to make a processing equivalent to the dark, flat and offset technics.
The mask was made with a panel of RF absorber. Its temperature was known and about 15°C equiv. to 288 K. The response of the RT was recorded with the same parameters as for M33 and M31 observations. With the same processing (see next slides), the reference (RT parasitic response) is shown below. This reference will be subtracted from the next measurements.



Data reduction

One hour data recording is truncated and processed into about 140 million of 128 bin FFT (Fast Fourrier Transform) like the example on left below.
Then a huge averaging of all FFT is done and gives the figure on the right.
This is totally raw signal with the parasitic response of the receiver and other H1 signals coming from our Galaxy (Milky Way or MW).
The figures show the 4 MHz bandwidth (Bw) or 103 FFT bins. Amplitude are relative (not calibrated).
We have to note the response is monotone but the base line is curved, like the reference ☺

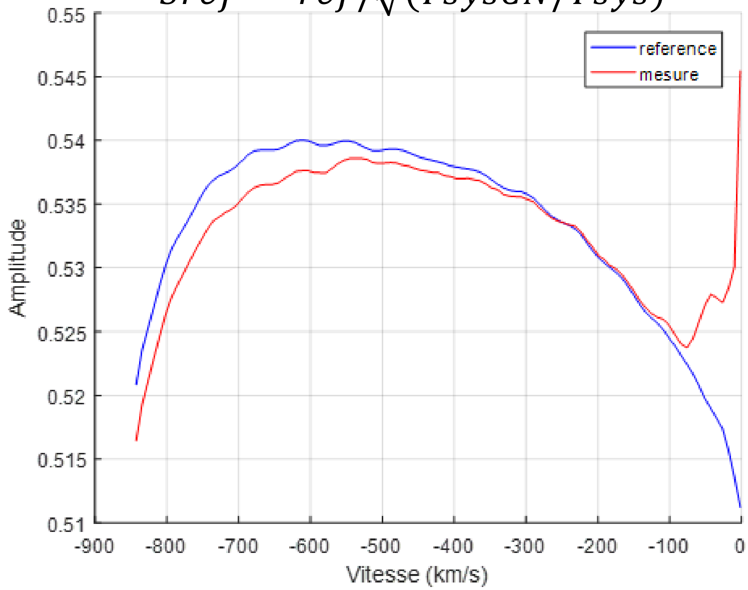




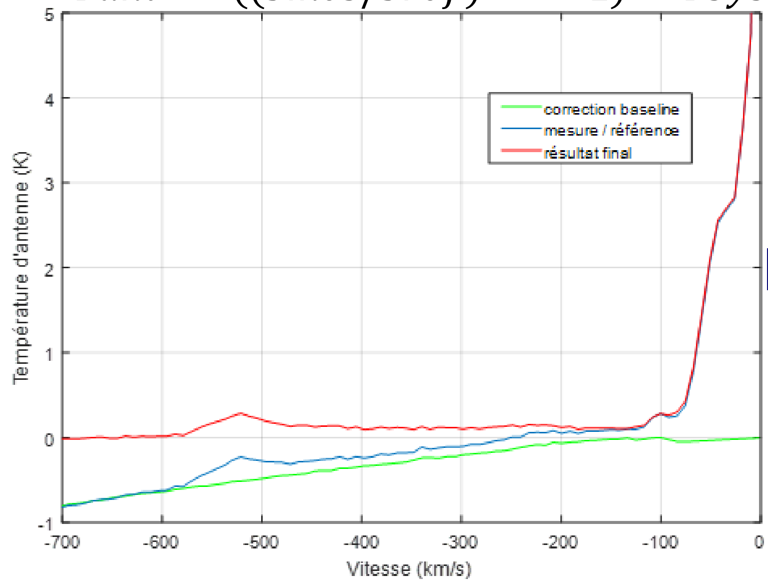
Data reduction – step 2

Next step is to compare the signal “mesure” to the “reference”. By using the formulae below, both curves are in the same referential (with TsysCN* = 288K and Tsys = 60K) on the left graphic. * *Tsys on RF absorber panel*
On the right, the antenna temperature is computed by using the second formulae and the result in the blue curve.
To correct the slop of the baseline, a second reference (flat) was done at the galactic coordinates 110/-62 far from the galactic plan and M31. The second reference (green curve) is then subtracted from the previous result and gives the final result (red curve). This is the raw signal of M31.

$$Sref = ref/\sqrt{(TsysCN/Tsys)}$$

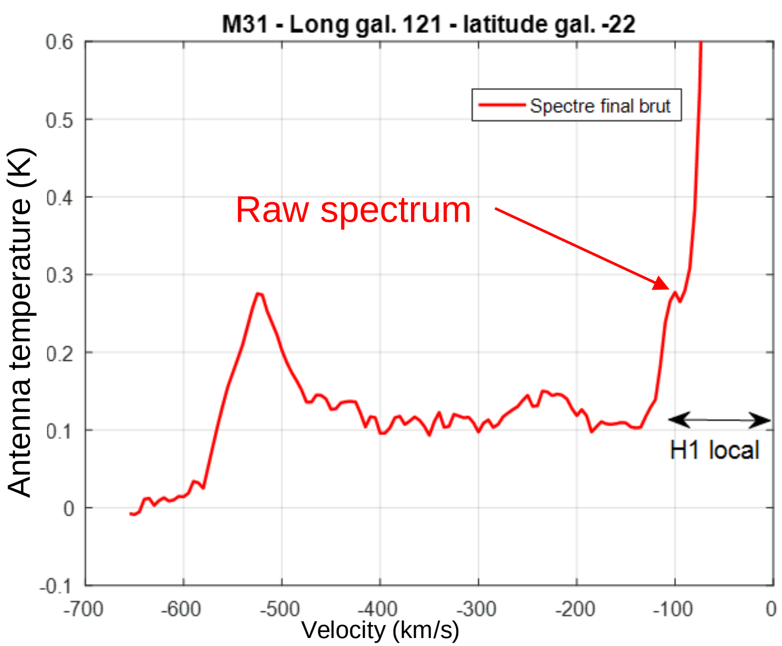


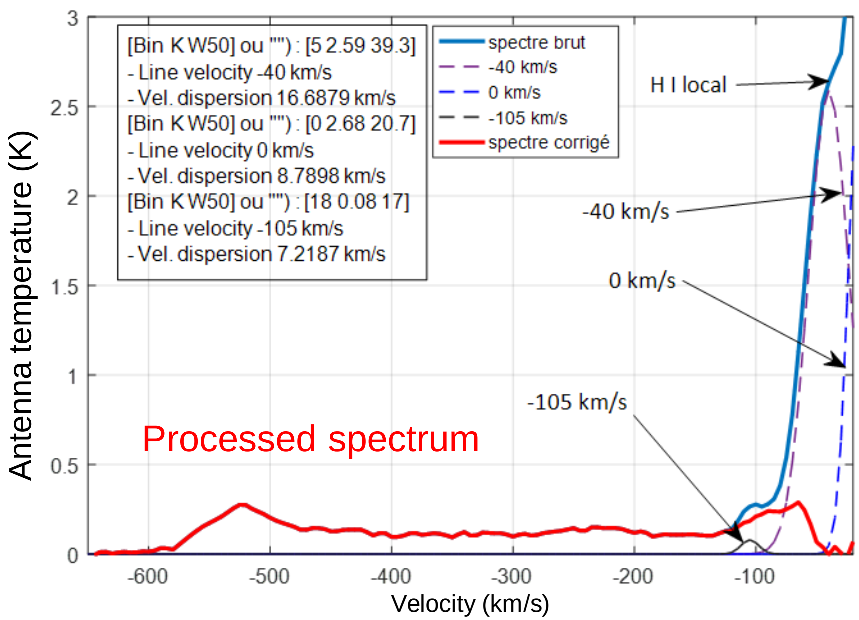
$$Tant = ((Smes/Sref)^{\wedge 2} - 1) * Tsys$$



Data reduction – step 3

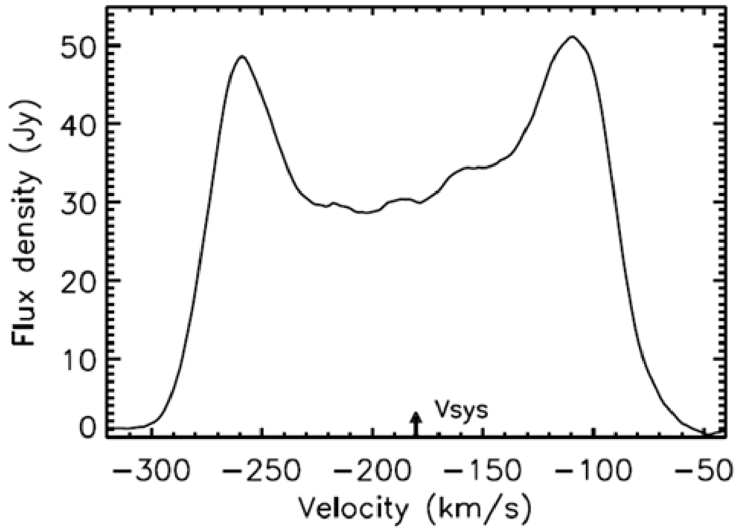
The left curve shows the final raw spectrum of M31 with a flat and horizontal baseline and a calibrated temperature. But this spectrum included parasitic signal (between 0 and -110 km/s) coming from our Galaxy (MW).
The last processing, the hugest, is to identify and remove the line coming from MW. The references 3 and 4 help to process these lines having 3 parameters, velocity, temperature and dispersion. These lines are gaussians.
The right curve shows an example of this processing for 1 spectrum of M31 by removing 3 parasitic lines at 0, -40 and -105 km/s (the Temp scale is 3 K).
Thereafter, all the M31 & M33 spectrum are processed with this method and velocities are relative to the Local Standard of Rest (LSR : reference 8).





M33 - The Triangulum Galaxy

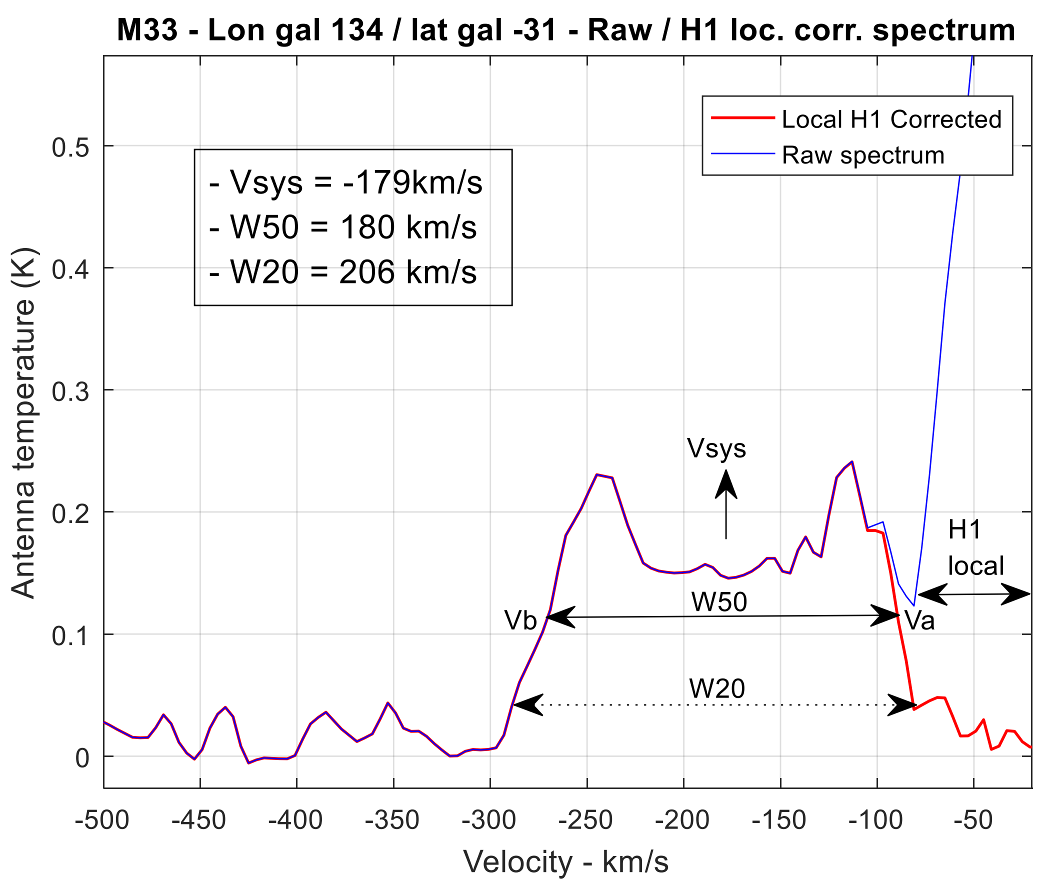
The Triangulum Galaxy is a spiral galaxy approximately 2.7 million light-years (ly) from Earth in the constellation Triangulum. M33 is the third-largest member of the Local Group of galaxies, behind the Milky Way and the Andromeda Galaxy.
Its galactic coordinates are 134° / -31° with an apparent size of 73*45 arcmin.
Regarding the RT aperture (4.4°), M33 cannot therefore be resolved (HPBW > size) and only one measurement will be carried out to reveal its H1 radiation spectrum. In return, no additional details of M33 can be revealed.
Its mass is around 60 to 100 billions of solar mass.
The flux (integrated spectrum profile) is shown on the graph below. Taking account of the RT constant, the expected signal is estimated from 0.1 to 0.16K.



From Reference 4

M33 - The Triangulum Galaxy

The M33 Triangulum Galaxy spectrum is shown below. The result is very closed to the expected one. The noise ripple is a little bit higher than expected and probably reveals the RT limits.

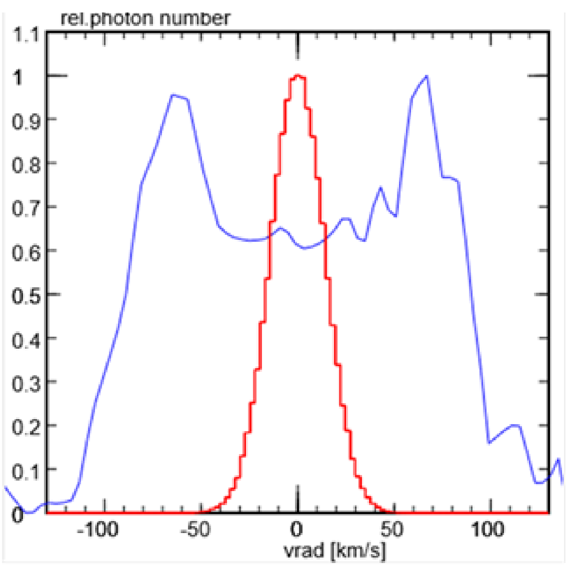


- ✓ Va = -89km/s
- ✓ Vb= -269km/s
- ✓ W50 = 180 km/s
- ✓ W20 = 206 km/s
- ✓ Vsys = -179 km/s
  Vsys = mean(Va,Vb)
- ✓ Vr = 103 km/s
  Vr = W20/2

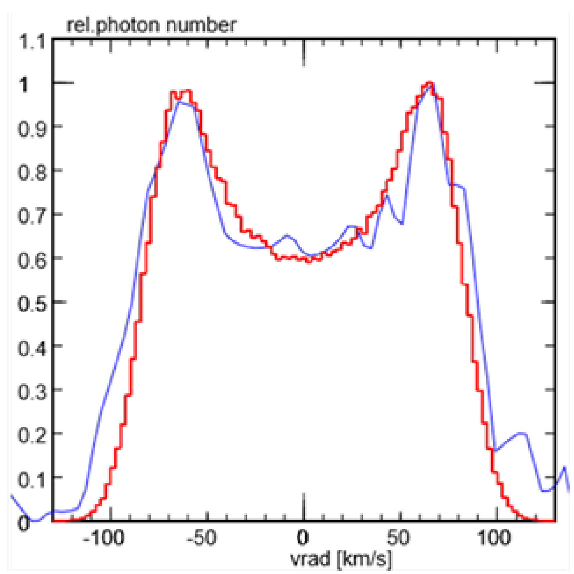
M33 - The Triangulum Galaxy

The figure below shows 3 simulations done with the tool (reference 5) developed by Joachim Köppen.
The simulation shows the effect of the M33 inclination plan relative to the line of sight (Z).
Thank to this inclination, we are able to observe the spectral distribution of M33.
The central view for the inclination at 55 ° shows that the measurement coincides perfectly with the simulation but this result is not very accurate.
With i = 55°, Vr = W20/2 = 103 km/s, the max rotation speed of M33 is Vr/sin(i) => v = 126 km/s.

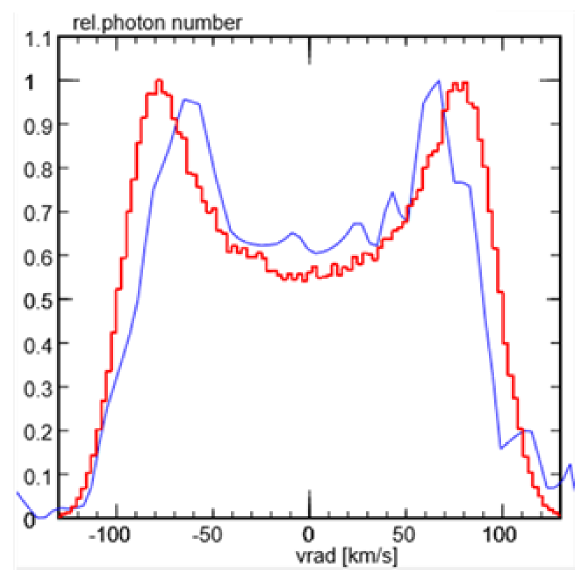
Inclination 0°



Inclination 55°



Inclination 90°



M33 - The Triangulum Galaxy

Regarding the reference 6, with v = 126 km/s, we can estimate the M33 mass.
$M = 2.3 * 10^5 * v^2 * r$ solar mass $M_{\odot}$ => M = 8.4 10^{10} $M_{\odot}$ (*for r = 23 kpc from reference 4*)
With the same reference, we can estimate the neutral hydrogen mass M(HI) with taking account the integrated flux on W20 interval (dv) => S(v)*dv = 10200 Jy.Km/s (coming from 204 km/s * 0.16 K/3.2 mK/Jy).

$M(HI) = 2.36 * 10^5 * D^2 * \int S(v) * dv$ => M(HI) = 1.72 10^9 $M_{\odot}$ with D = 0.845 Mpc.

The chart below shows the main results of this M33 survey compared to reference 4.

M33 parameters	Observation results	Reference [4] results
Center coordinates	Long. Gal. : 134 / Lat. Gal : -31	RA 01h33m33.1s / Dec 30°39’18"
System velocity (heliocentric)	-180 km/sec	-179 +/- 3 km/sec
Distance	--	0.845 Mpc
Inclination	55° (estimated by simulation)	52° +/- 3°
Angular position (axe majeur)	--	202° +/- 1°
W50 Spectral width @ 50%	180 km/sec	183 km/s
W20 Spectral width @ 20%	206 km/s	200 km/s
Max rotation speed Vrot	126 km/s	125 km/s
Dynamic mass (r = 23 kpc)	8.4 10^{10} $M_{\odot}$	7.9 10^{10} $M_{\odot}$
Neutral hydrogen Mass M(HI)	1.72 10^9 $M_{\odot}$	1.95 10^9 $M_{\odot}$

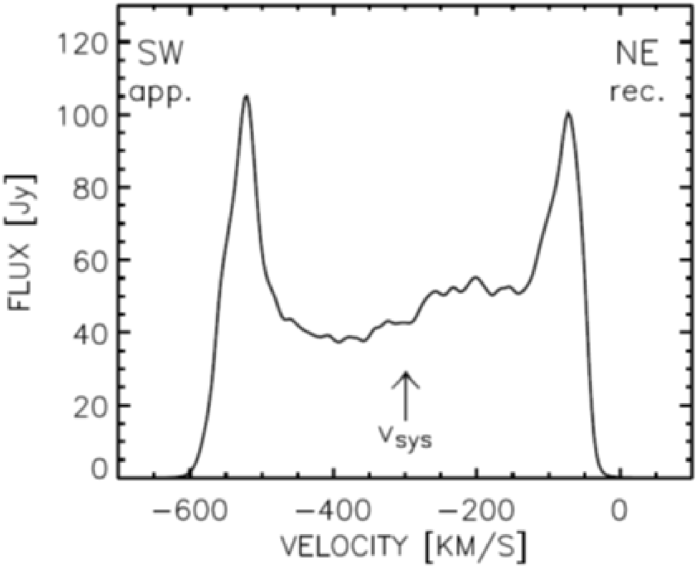
M31 - The Andromeda Galaxy

The Andromeda Galaxy is a spiral galaxy approximately 2.5 million light-years (ly) from Earth in the constellation of Andromeda. M31 is the second-largest member of the Local Group of galaxies, behind the Milky Way.

Its galactic coordinates (center) are 121° / -22° with an apparent size of 190*60 arcmin. Regarding the RT aperture (4.4°), M31 is enough extended to allow some measurement to reveal additional detail of this galaxy (HPBW near M31 size).

Its mass is around 1000 billions of solar mass.

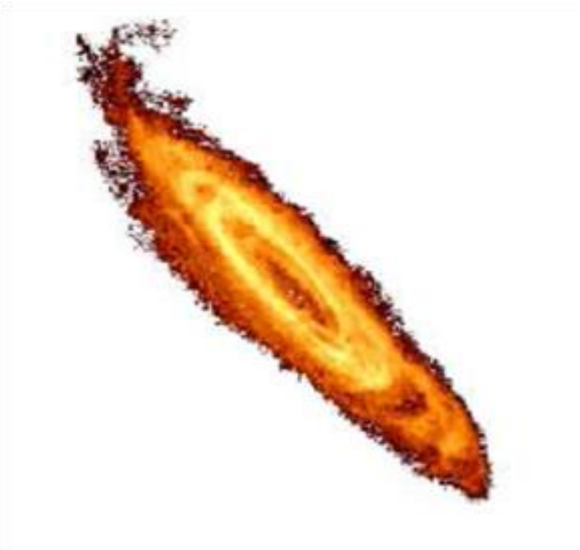
The flux (integrated spectrum profile) is shown on the graphic below. Taking account of the RT constant (3.2 mK / Jy), the expected signal is estimated from 0.13 to 0.32 K.



From Reference 3

M31 - The Andromeda Galaxy

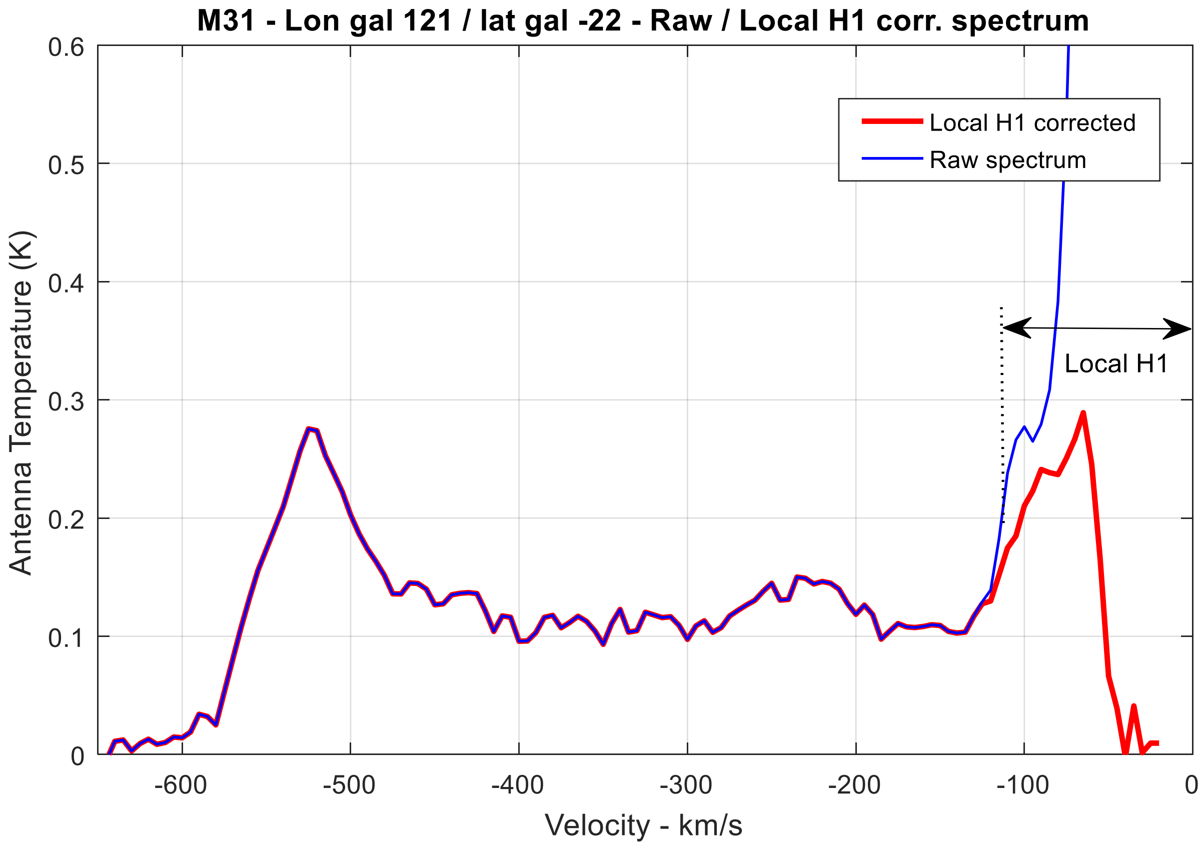
The Andromeda spiral galaxy M31 is well known in astronomy whether it is in optical observation or in radio as shown in figure below.



On the left : photo from Philippe Bernhard – AAV [http://aav-astro.fr/]
On the right : H1 distribution on 21 cm – Refer to figure 4 / Reference 3

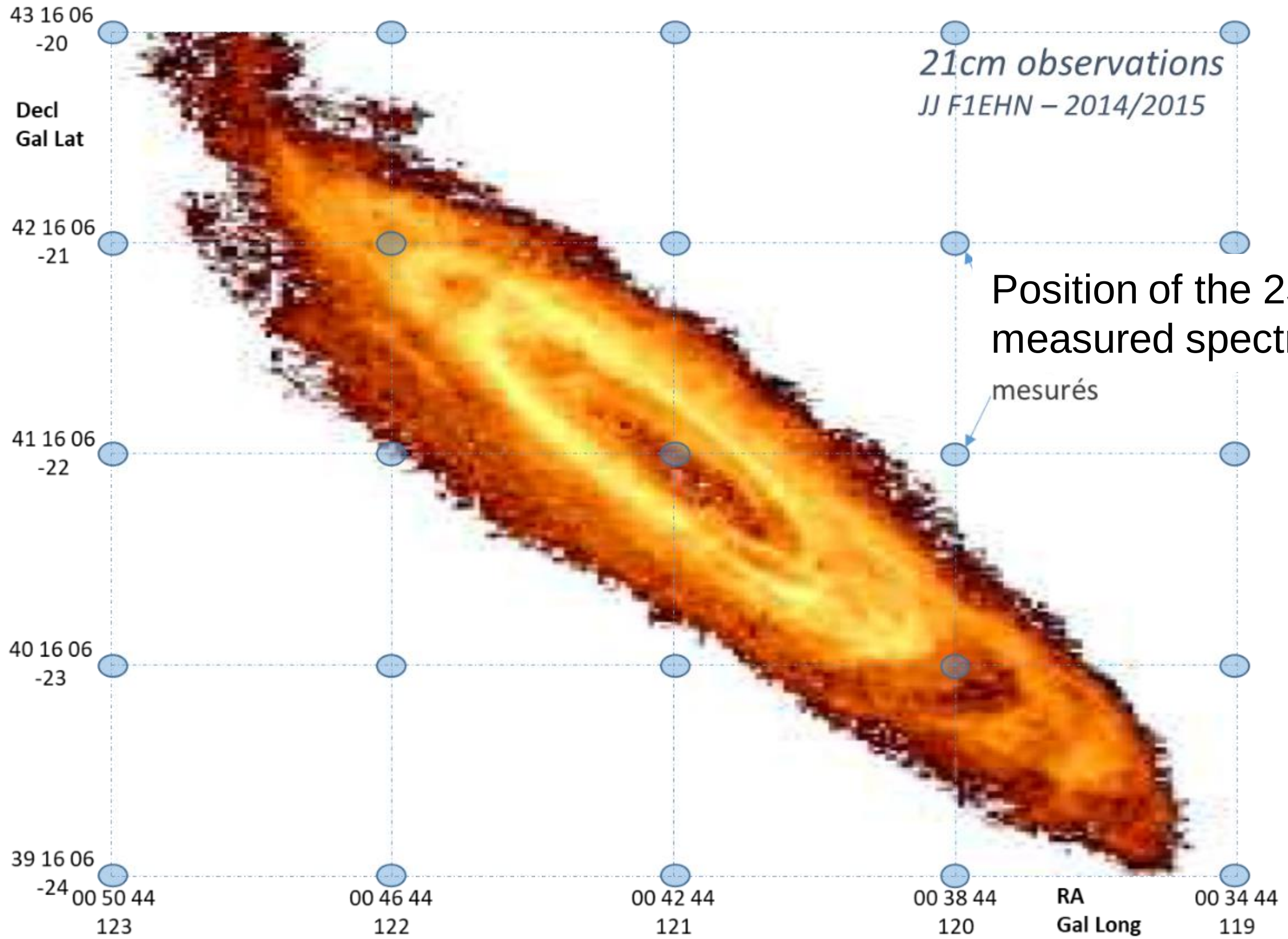
M31 - The Andromeda Galaxy

The M31 spectrum, done with the same parameters as for M33, is shown below. This first result is very close to the expected spectrum but with a slightly lower antenna temperature. The size of M31 is well above that of M33 and it seems that the RT does not capture all the radiated radio flux by M31 in a single measurement. A measuring plan is therefore programmed, see next slides.



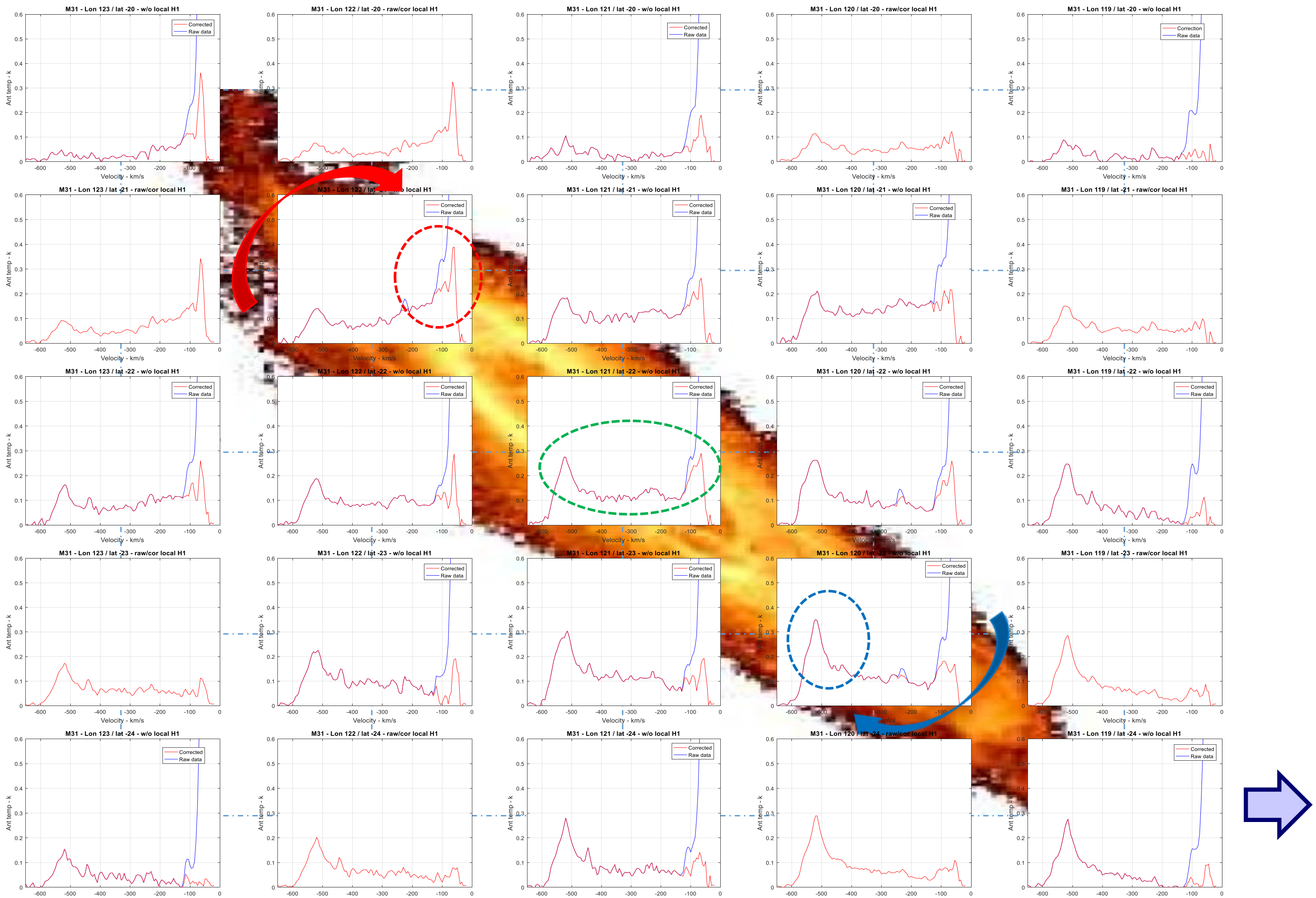
M31 - The Andromeda Galaxy

To reveal more details and the total radiated flux of M31, see below the measuring plan to catch 25 spectra around the center of M31. This sequence allows to cover the entire surface of M31 and look at its major axis inclined in the order of 35 to 40 °.



M31 - The Andromeda Galaxy

Below find the global view of the 25 spectrum performed every 1°…



M31 - The Andromeda Galaxy

First observation and comment :

Circled in red, the positive spectrum in relation to the centre shows that the NE[1] part of the Galaxy approaches us less quickly (equivalent to a redshift) and conversely, circled in blue, the SW[1] part of the Galaxy approaches us faster than the center of the A galaxy (circled in green).

These 2 spectra (red and blue circled) also confirm that :

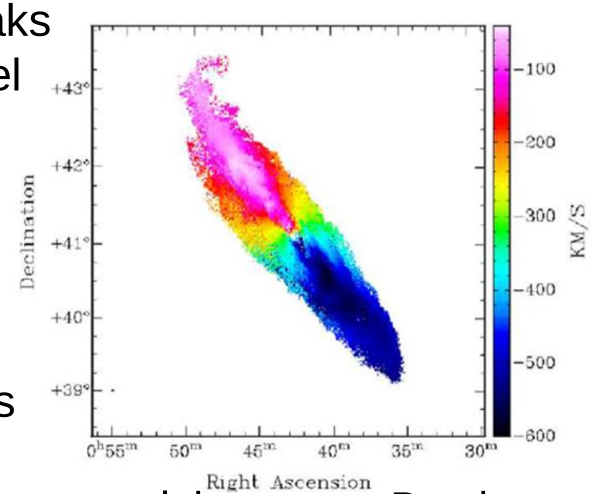
- ✓ The fluxes of the 2 peaks are higher than on the central spectrum
- ✓ M31 is more extensive on its main (or major) axis than the RT angular size
- ✓ These 25 measurements bring additional information.

The measurement campaign took place over 1 year and half. This sequence of measurements covering 5 ° by 5 ° in 2 plans and every 1°allows to cover the entire surface of M31 and to save a 4D data cube (Temperature, Velocity, Longitude, Latitude) (only 1 single spectrum for M33). This data cube includes 25 spectra that have been corrected of the local H1 as shown previously. From this 4D data cube, it is possible to present the results in the form of maps of radial velocities of M31, or to calculate the integrated global spectrum of M31.

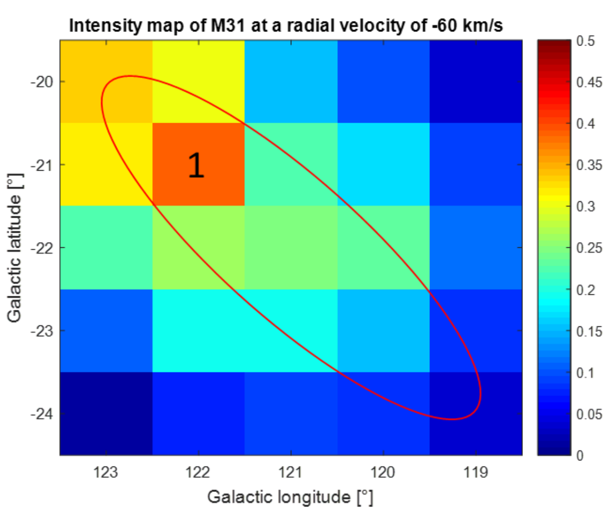
[1] The scale of the longitudes is reversed by convention, so the East is on the left, and the West on the right.

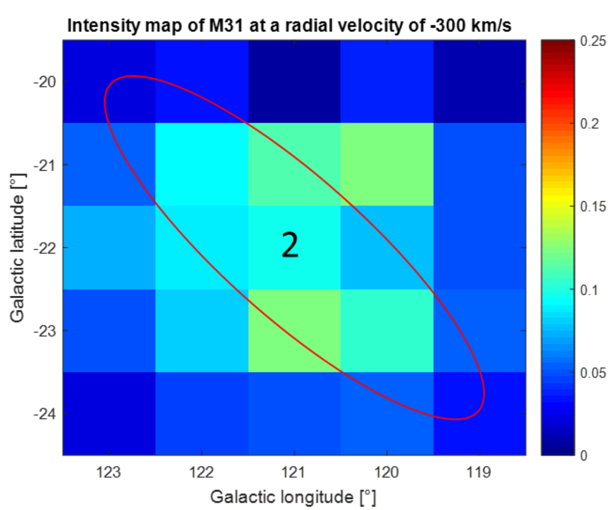
M31 - The Andromeda Galaxy

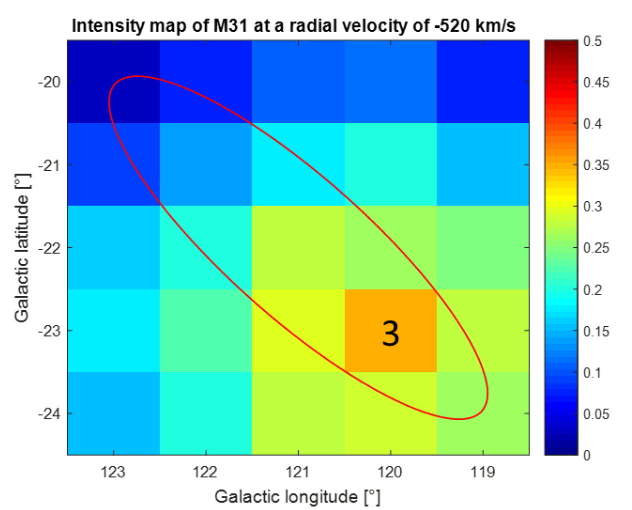
Below, 3 cuts at typical velocities corresponding to the 2 peaks of M31 and its central value (Vsys). For every cut, every pixel corresponds to a direction of antenna (Galactic Longitude / Latitude) and show its antenna temperature. These maps show that the peak at -60 km/s is in the NE[1] map (left) and those at -520 km/s is in the SW (right). The 2 pics (1&3) are symmetric to the center (2) with velocities near -300 km/s. This view also confirms the angular position of the major axis of the ring of M31..



If we refer to the figure above (from reference 3), this measurement result is correct. But the low angular resolution of the RT does not allow to extract a curve of rotation speed versus M31 radius.

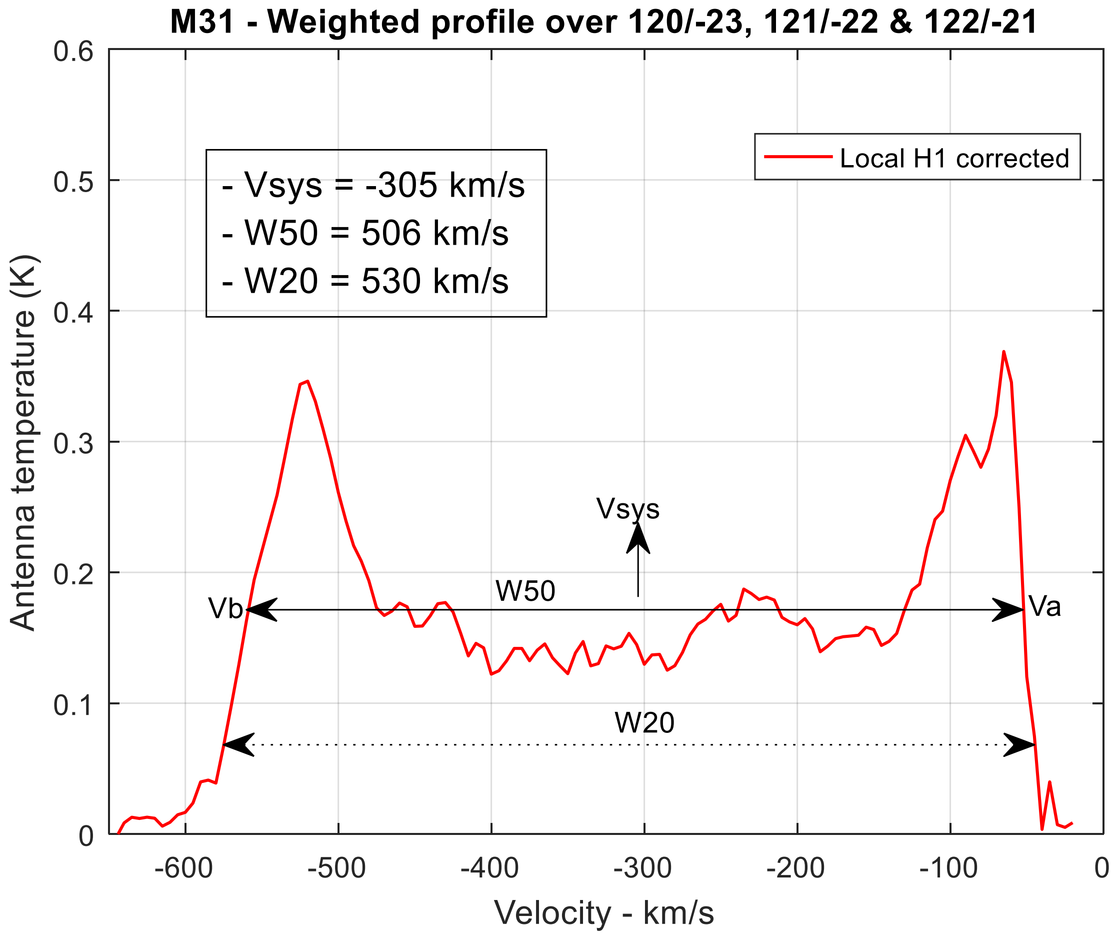






M31 - The Andromeda Galaxy

The figure below shows the weighted profile spectrum gotten from the 3 spectra at positions 1, 2 & 3 (see previous slide). It is not an integrated spectrum because this calculation is limited by the RT angular resolution. So the curve is computed to respect the amplitude of both peaks by applying a symmetrical weighting law.



- ✓ Va = -52km/s
- ✓ Vb= -558km/s
- ✓ W50 = 506 km/s
- ✓ W20 = 530 km/s
- ✓ Vsys = -305 km/s

  Vsys = mean(Va,Vb)
- ✓ Vr = 265 km/s

  Vr = W20/2

M31 - The Andromeda Galaxy

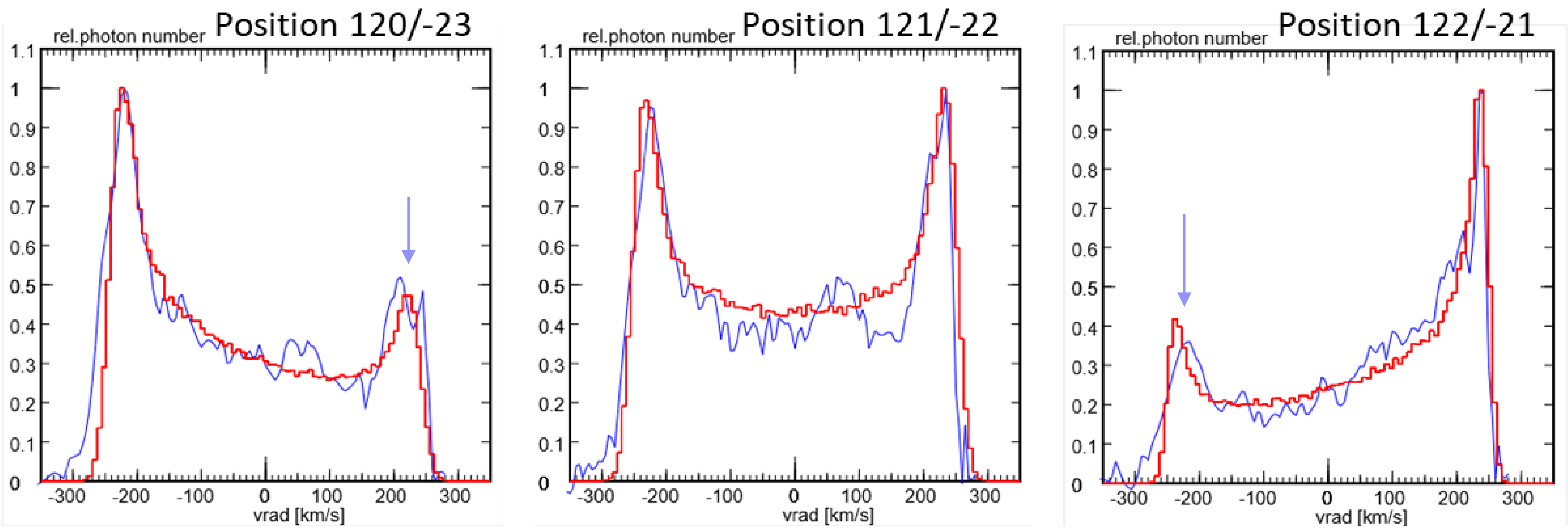
The figure below shows 3 simulations done with the tool (reference 5) for the positions 1, 2 & 3 (see previous slide).

By slightly tuning the parameters of the simulation as Vsys, the antenna HPBW, the dispersion, we see that the simulations give results similar to the measurements. Here the HPBW antenna has an impact because, as already noted, the measurements are not completely independent (because of the angular resolution) and the amplitude of the lowest peak (arrows) is related to the angular resolution of RT.

These results confirm the inclination of M31 at 77 ° (parameter of this simulation).

With i = 77°, Vr = W20/2 = 265 km/s, the max rotation speed of M31 is Vr/sin(i)

=> v = 272 km/s.



M31 - The Andromeda Galaxy

Regarding the reference 6, with v = 272 km/s, we can estimate the M31 mass.
$M = 2.3 * 10^5 * v^2 * r$ solar mass $M_\odot$ => M = 6.4 10^{11} $M_\odot$ (for r = 38 kpc from reference 3)
With the same reference, we can estimate the neutral hydrogen mass M(HI) with taking account the integrated flux on W20 interval (dv) => S(v)*dv = 30475 Jy.Km/s (coming from 530 km/s * 0.184 K/3.2 mK/Jy).

$M(HI) = 2.36 * 10^5 * D^2 * \int S(v) * dv$ => M(HI) = 4.49 10^9 $M_\odot$ with D = 0.785 Mpc.

The chart below shows the main results of this M31 observation compared to reference 3.

Paramètres	Résultats de l'observation	Résultats référence [3]
Position M31 (centre)	Long. Gal. : 121 / Lat. Gal : -22	RA 00h42m44.4s / Dec 41°16'08"
Vitesse système (héliocentrique)	-305 km/sec	-300 +/- 4 km/sec
Distance	--	0.785 Mpc
Inclinaison	77° (estimés par simulation)	75°
Position angulaire (axe majeur)	45° (estimés d'après datacube)	38°
W50 Largeur spectrale H I à 50%	506 km/sec	509 km/s
W20 Largeur spectrale H I à 20%	530 km/s	533 km/s
Vitesse de rotation maximum Vrot	272 km/s	275 km/s
Masse dynamique (r = 38 kpc)	6.4 10^{11} $M_\odot$	4.7 10^{11} $M_\odot$
Masse H I – M(HI)	4.49 10^9 $M_\odot$	4.23 10^9 $M_\odot$

M31&M33 survey @21cm - Conclusions

The adaptations made on the RT have allowed to observe new objects such as M33 and M31 very rarely accessible to the small amateur RT. The quality of the measurements and high integration time made it possible by partially compensate the small antenna diameter.
Even with this small antenna size, it was possible to reveal details of M31 and highlight its direction and axis of rotation.
With precise spectral measurements, the figures obtained for the masses of these galaxies, their H I contents, the inclination and their rotational velocities are close to the scientific origin values obtained with RT 10 to 30 times larger like the one used for the reference M31 [7]. This note includes numerous measurements and spectra according to the line of sight towards M31 => A real extragalactic voyage.

I invite you to read in detail the results obtained and presented by the references [3] and [4]. The details revealed by interferometry techniques are impressive and show how great the gap between amateurs and scientists remains. These notes are also very important for amateurs because radio astronomy is a beautiful hobby but of extreme complexity and I had the chance to use their formulas which I already have difficulty imagining all relations and complex astrophysical dimensions. I was also fortunate to be able to exchange with Joachim Köppen, astrophysicist, radio amateur and simulator author [5] who has this scientific knowledge and abilities and patience to simply explain these things. Other simulators are available on its very rich site for radio astronomy enthusiasts.

Once again I have developed all my tools and I am sorry for not being able to give references other than the quoted notes. This is what allows me to better understand my experiences and customize them by adapting them to my RT.
This activity was spread over a period of more than 4 years (2013 – 2017) and was only possible thanks to the detailed scientific information in the references below.

References

Contact : jjm_f1ehn@wanadoo.fr

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