
The Medicina IRA-SKA Engineering Group
The Northern Cross as
a very promising SKA test bed
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Abstract.

We propose in this paper a global upgrade of the Northern Cross radiotelescope aimed to obtain a good test bed for the Square Kilometre Array (SKA) project. It could allow to gain useful experiences in the design of low cost receivers, analog and digital beam forming, multibeaming, RFIs mitigation and data transmission via optical fibre. Some proposal to install hundreds or thousands of receivers on both the N/S and E/W focal lines along with some already done technological activities are shown. The Northern Cross radiotelescope has a 1/33 of the SKA collecting area and host 5632 dipoles on its focal line. It is a very suitable SKA work bench that could allow the investigation of many crucial points of the project definition. In addition the upgrade would lead the Northern Cross to an operative working level presently unique in the low frequency radioastronomy observation. Since SKA is planned to give very important answers of the today and tomorrow astrophysic, we think that this Cross upgrade activity should be carried out by the widest possible collaboration with other international astrophysical research institutions. Different possible architectures will be presented and discussed here along with the working plans and costs.

1.0 Introduction.

The Northern Cross T-shaped radiotelescope (Figure 1.1), one of the largest transit instrument of the northern hemisphere, is composed by two arms: the E/W and the N/S one. The E/W (35 x 564 m) contains 1536 dipoles. The N/S array is composed by 64 (24 x 7.5 m) cylindrical reflectors with 64 dipoles each (8 dipoles x 8 blocks) a total of 4096 dipoles. A substantial upgrade is planned in order to transform such an instrument in one of the most flexible, sensitive and important transit UHF radiotelescope of the northern hemisphere. After the upgrade it could be considered as a unique SKA "reduced scale" precursor and work bench. Considered as a SKA test bed, large amount of beamforming, multibeamming, RFIs mitigation algorithms and correlation techniques could be developed and tested on it. The very high sensitivity reached with the upgrade along with the multibeaming operation possibility, could make the instrument role unique in the UHF radioastronomy activities. The upgrade is a relative low cost operation and it is distributable over a couple of years. By installing new low cost / low noise front ends, the system temperature could be drastically reduced opening up many potential applications in the low frequency radioastronomy field, in addition to the mentioned experiences for SKA definition and realisation. The key science driver of such a renewed instrument, are surveys of radio transient phenomena (e.g. Pulsar), low frequency spectroscopy (e.g. Carbon C252α sky survey) and sky survey in the continuous. In this paper we will discuss some different solutions that could be implemented on such an antenna oriented to SKA, exploiting the big amount of dipoles already installed on the focal lines. We describe the present configuration of the radiotelescope and some possible different upgrade of both the N/S and E/W arms.

Figure 1.1: Aerial view of the Medicina station with Northern Cross telescope and the VLBI dish

2.0 The Northern Cross radiotelscope.

2.0.1 Present configuration: overview.

The present configuration is characterised by 8 receivers in the N/S arm and 6 receivers in the E/W one. The instrument is one of the largest collecting area in the northern hemisphere and it is well known having produced accurate sky survey (B1, B2 and B3) at λ=73.3 cm (408 MHz). This T shaped array is presently essentially a transit radiotelescope. The total number of dipoles installed on the antenna is 5632. The main present characteristics are here summarised:

- **Working Frequency** — **408 MHz (λ=0.735 m)**
- **Band-Pass** — **2.7 MHz and 5 MHz (only E/W)**
- **Angular Resolution** — **2'.6 (EW) x 4'.8 sec θ (NS)**
  (θ= Zenith Angle = 90^o + dec. - lat) Lat=44^o.5
  (interferometry mode)
- **Angular Resolution** — **4' x 110' (EW) Total Power**
  96'x 3.6' sec θ (NS) Total Power
- **E/W number of beams** — **5 (2' separation)**
- **E/W Antenna Gain** — **2.7 K / Jy**
- **N/S number of beams** — **5 (2' separation)**
- **N/S Antenna Gain** — **1. 7 K/ Jy**
- **E/W System Equivalent Flux** — **60 Jy**
- **N/S System Equivalent Flux** — **230 Jy**
- **Geometrical Collecting Area** — **31.020 sq mt**
- **Effective Collecting area** — **~20.000 sq. mt**
- **Synthesis of 0^o.5 strip of sky in a single scan.**
- **R.M.S. noise of 10 mJy in a single scan**
- **Number of channels** — **6 (E/W), 8 (N/S)**
- **Number of dipoles installed** — **1.536 (E/W)**
  4.096 (N/S)

In the present configuration the transmission line in front of the receivers have 0.7 dB losses in the E/W and 1.2 dB in the N/S one. The N/S and E/W antenna sections are analogically summed with a proper phase gradient in order to obtain respectively 5 total power fan beams in N/S and 3 in E/W. The E/W beams are multiplied with each of the 3 E/W beams to produce a matrix of 15 pencil beams obtained with analog correlators (FET). With this system a strip of sky about 10 arcmin wide can be mapped in a single scan. As an alternative more flexible system, a bank of 48 complex correlators (FET), is also present. It performs the correlation between the 8 N/S receivers with the 6 E/W ones. The image is reconstructed by Fourier inversion performed with an off line computer. The whole primary beam of a single antenna section is thus sampled: In the N/S direction it allows observation of a 30 arcmin strip of sky every single scan. In the E/W direction the main advantage is transferred to a longer integration time, because, as mentioned before, the radiotelescope is a transit instrument. When using this system, the telescope doesn't need accurate amplitude and phase calibration before the observation because any error can be numerically corrected at the post processing level. The reflecting mirrors (E/W and N/S arms) are compose by many metallic wires with 0.5 mm diameter for a total length of about 2000 Km. The wires are visible in Figure 1.2, a black and white artistic winter time picture, because they are covered by snow .

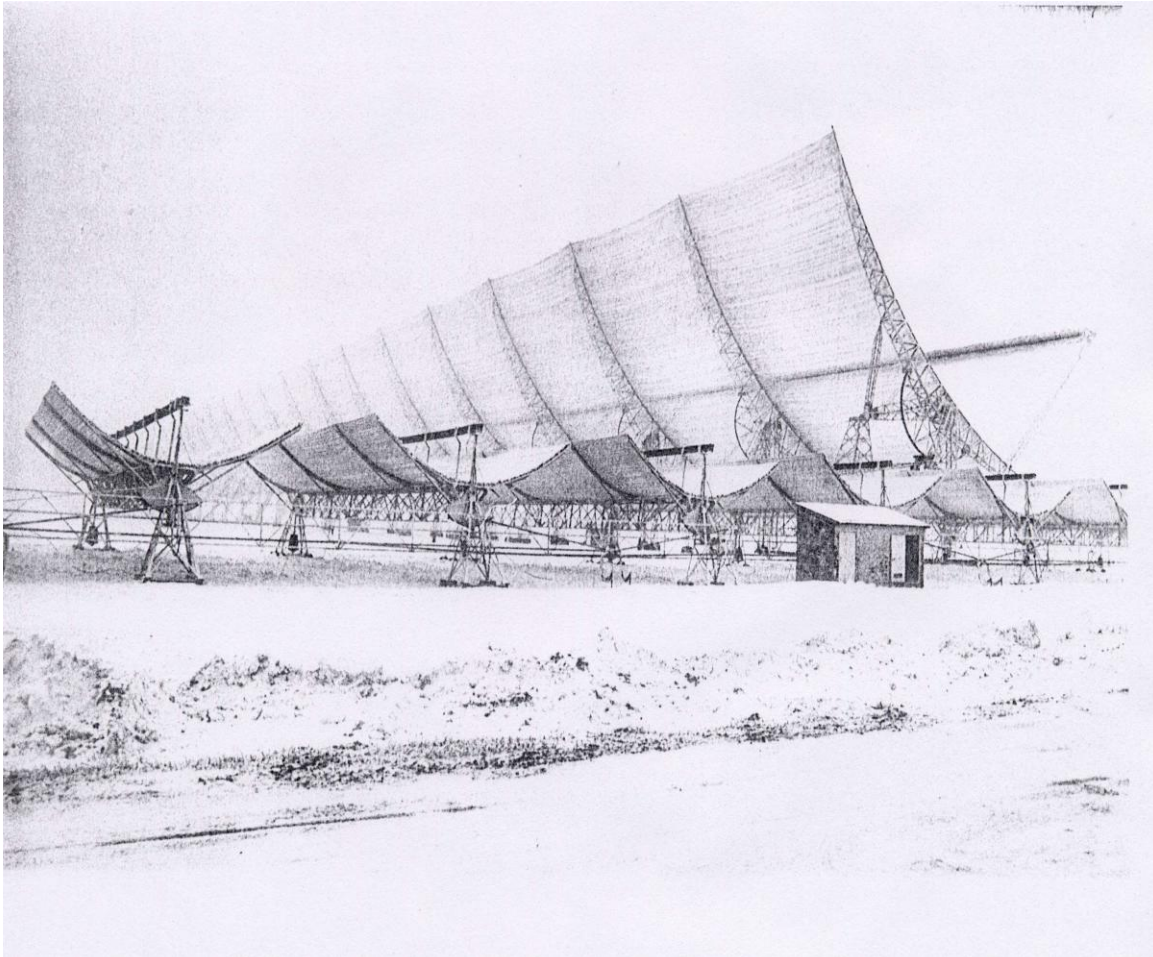


Figure 1.2: An artistic black and white picture of a part of the Cross in winter time

2.0.2 The antennas.

The N/S and E/W arms (Figure 2.0) are horizontal-axis cylindrical reflector antennas, in particular:

- The single N/S antenna is a symmetrical reflector with feed on 1.84 m support frames (512 blocks of 8 dipoles each)
- The E/W arm is an offset-reflector with feed mounted on 21 m support frames (1536 dipoles).

In the N/S the short frames supporting the linear feeds simplify the upgrade and maintenance because the reflector structures are accessible with a standard ladder or a small *moving platform.* If a new printed focal line (printed antennas) will be designed, the on-field test is relatively simple because the focal line is quite near the ground. The Declination range of this arm is limited from 0^o to 90^o due to mechanical reasons. At present this arm is the more suitable one to start some SKA-oriented upgrading activities. The E/W arm is an offset-feed reflector (564 x 34 m) with the focal lines mounted (as already mentioned) at about 21 m from the parabolic cylinder.

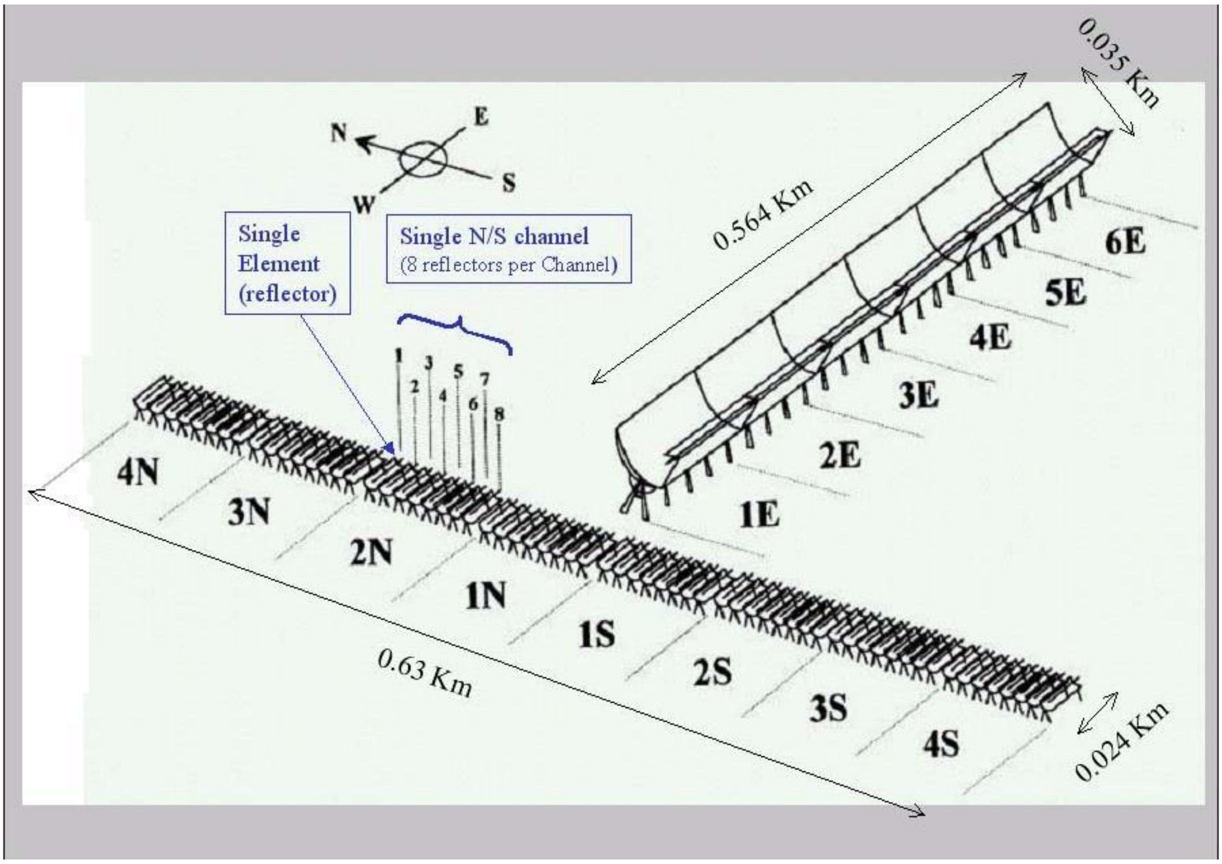


Figure 2.0: Sketch of the Northern Cross radiotelescope

The offset design allows the E/W antenna points any region in the sky having a Declination between -30° and +110° (i.e.> +70° in inferior culmination). This arm is very large and, possible E/W focal line upgrade activities would present many more problems than the N/S arm.

2.0.3 The N/S arm.

The N/S arm is composed of 64 cylindrical reflectors aligned in the N/S direction, as visible in Figure 2.1. This antenna is very suitable for the tests oriented to gain experience for SKA, due to its electrical capabilities and its mechanical structure. It will be very easy to operate to install the new front and also new printed wide band antennas. The focal lines are at less than 6 m from the ground.

Figure 2.1: Overall view of the N/S arm

At present 8 cylinders are grouped to form a single N/S channel. This is implemented by means of a gradient of phase introduced by 64 kerosene dielectric phase shifters. The kerosene phase shifters system is a rudimentary "beam former" in declination (Figure 2.2). The field of view of a single cylinder is about 5°.

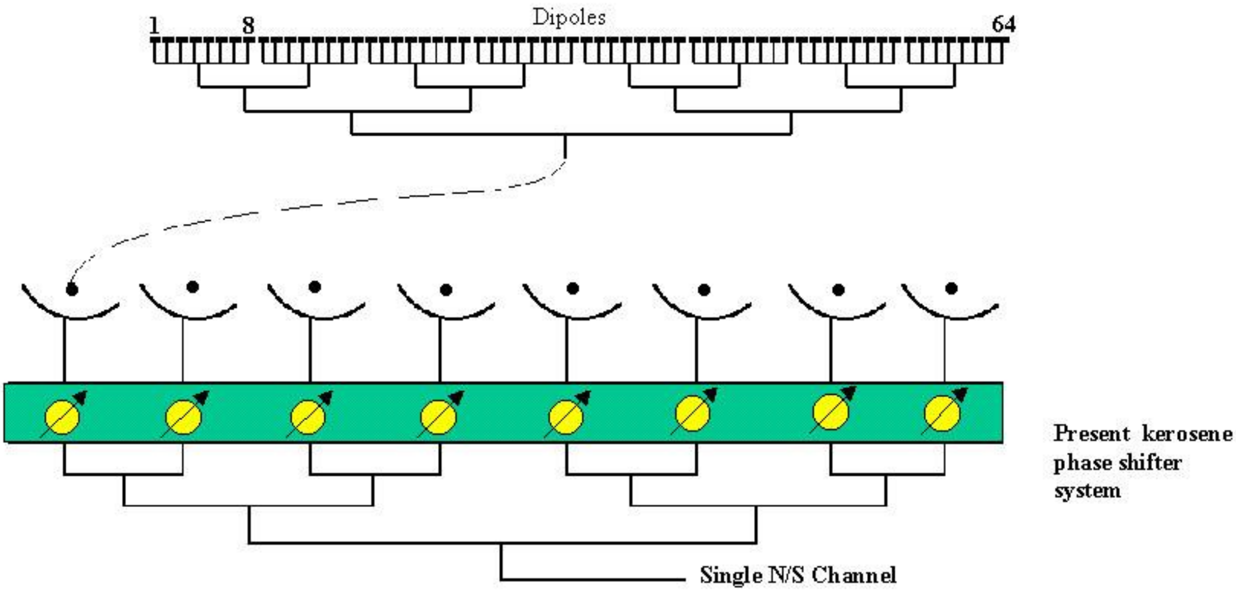


Figure 2.2:Schematic diagram of the N/S single channel architecture

2.0.4 The E/W antenna.

The E/W antenna is the largest arm of the Northern Cross telescope (Figure 2.3). This arm is an offset-reflector (parabolic-shaped) cylindrical antenna where each channel is obtained by summing 256 "λ/2 dipoles" placed in the focal line, by a christmas tree transmission line as reported in Figure 2.4.

Figure 2.3: The E/W antenna is the largest arm of the Cross telescope

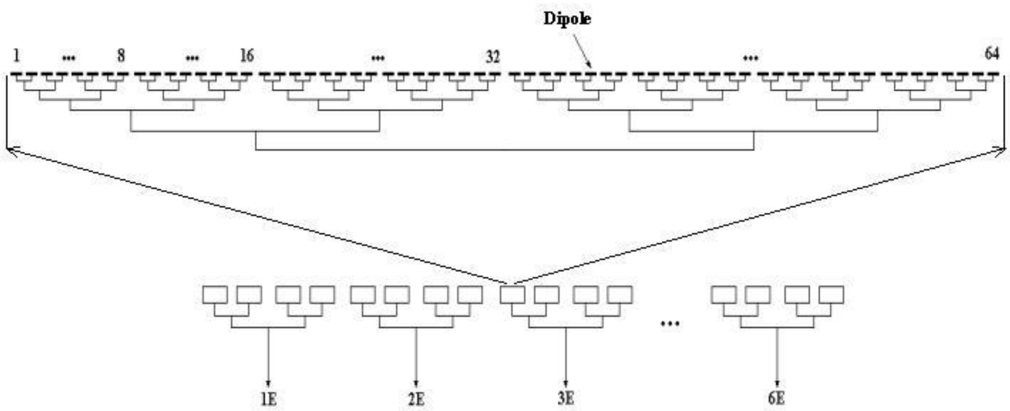


Figure 2.4: the E/W antenna single channel composition

At present each 128 dipoles are summed together before to enter in the front end (two front end per channels) as visible in Figure 2.5

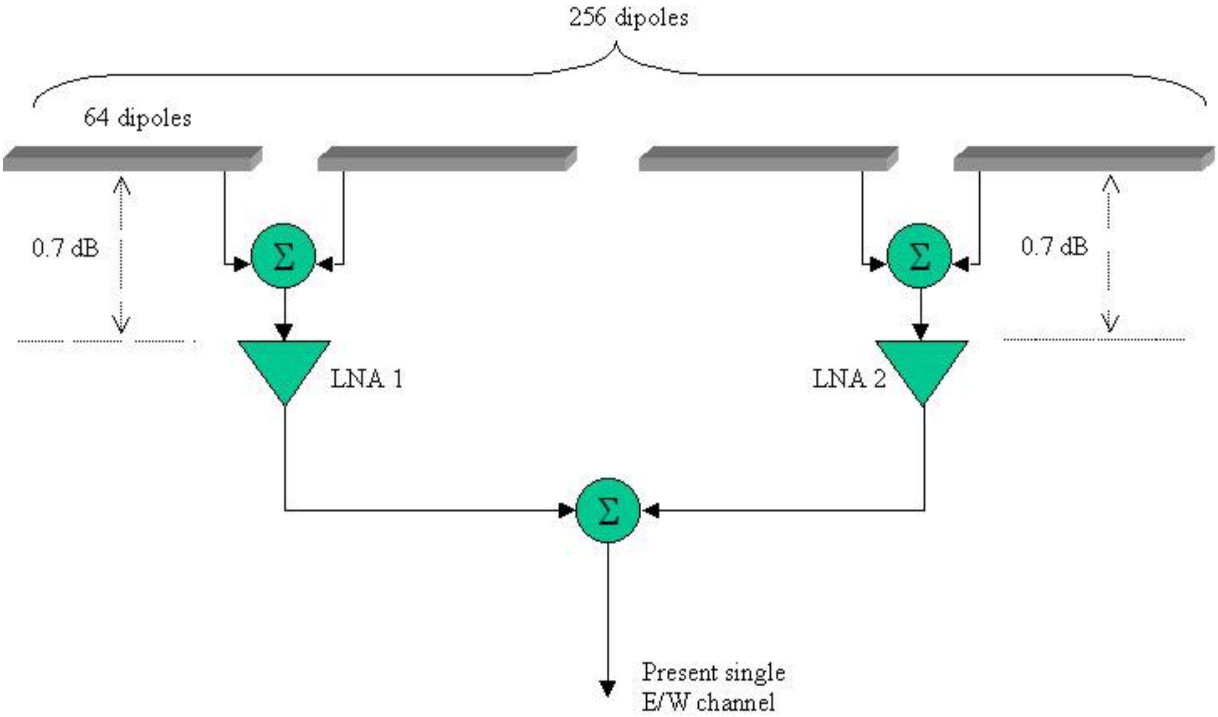


Figure 2.5: Block diagram of present E/W single channel front end

3.0 The Cross global upgrade plan.

The present plan is to start to implement several hundred receivers only on the N/S array. As a second step, N (to be decided) receivers will be installed on the focal line of the large E/W arm.
The implementation of several hundreds of receivers on the Cross will be aimed to achieve experience on the following topics:

- Beam forming (analog and digital)
- Multibeaming
- RFIs mitigation (null beam steering)
- New low-cost, low-noise high dynamic range receivers
- Data transmission via low-cost optical fibre
- Calibrations

We briefly discuss now some points involved in the Cross upgrade.

3.1.1 Analog and digital Beamforming

Beamforming is a particular combination of signals coming from a set of small antennas to create a large directional antenna. In beamforming, both phase and amplitude of each antenna element need to be properly controlled. Moreover, controlling phase and amplitude in a proper way, it is possible to adjust the side lobes levels and steer nulls for RFIs mitigation, much better than if combining only the phase. In both the N/S and E/W cases we can form a directional beam that can be electronically pointed, within the single element beam width, at a given mechanic pointing of the reflectors. Beamforming can be implemented in different ways and levels, mainly it is implemented by means of:

1. Analog phase shifters (RF- IF stage level)
2. Digital mode (Base Band level)

1- Generally, the analog phase shifters are introduced at the front end level (sometime at the IF level) if the bandwidth and/or size of the resulting antenna are not too large. The normalised gain (g=1 → max gain) tells us when it is necessary to start recovering the delays as well as the phase, according to the dimensions and the operational bandwidth of the resulting antenna:

$$g = \frac{\sin(\pi B \Delta t)}{\pi B \Delta t}$$

where B= Bandwith

Δt= Delay of the arrival time of the front wave on the different points of the antenna macro elements.

2- Beamforming can also be implemented in digital mode by introducing, at a computation level, complex weights on the signal from each element of the array. If $S_k(t)$ is the signal (Base band) coming from the k[th] element of the array, we can modify its phase and amplitude by multiplying it by a complex weight

$$W_k = a_k e^{j\phi_k} = a_k(\cos\phi_k + j\sin\phi_k)$$
$$S_k(t) = x(t) + jy(t)$$
$$S_k(t)W_k = a_k[x_k(t)\cos\phi - Y_k(t)\sin\phi_k] + ja_k[x_k(t)\sin\phi_k + Y_k(t)\cos\phi_k]$$

The Figure 3.0 shows the block diagram of the above mentioned task while the Figure 3.1. shows the digital beamformer block diagram in deeper detail [1].

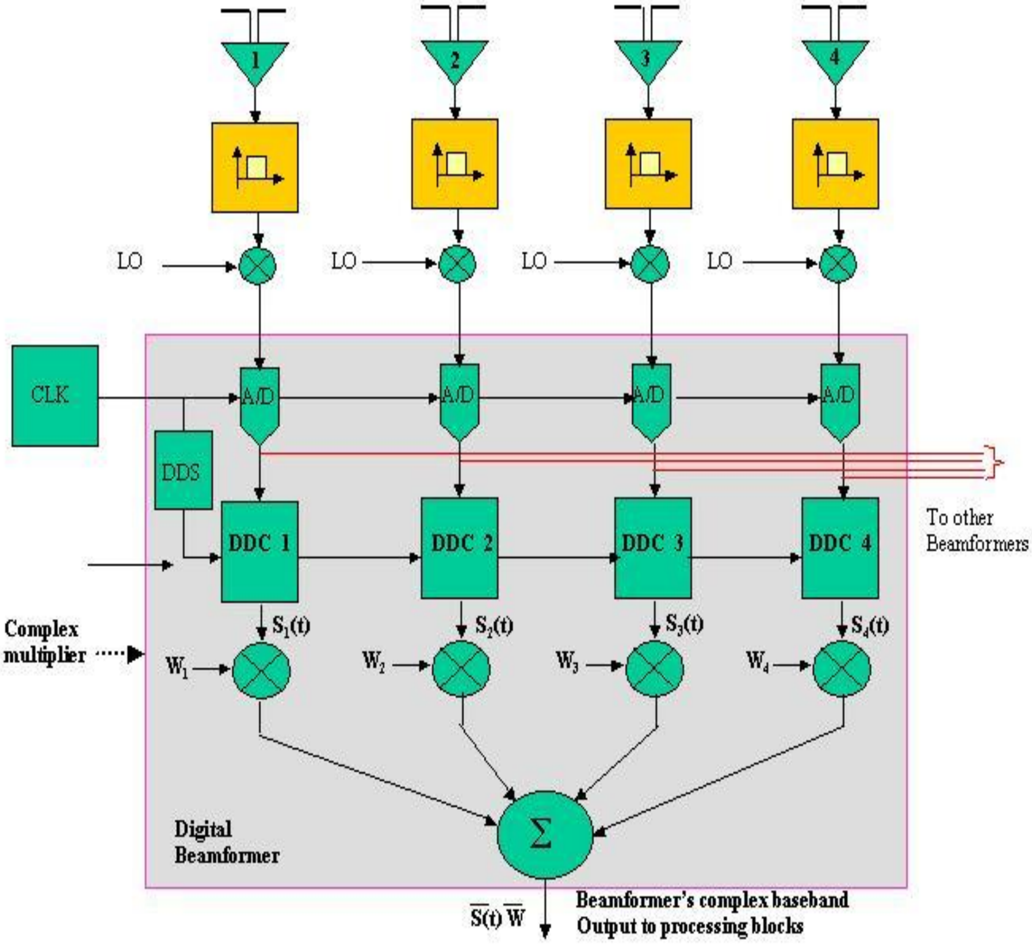


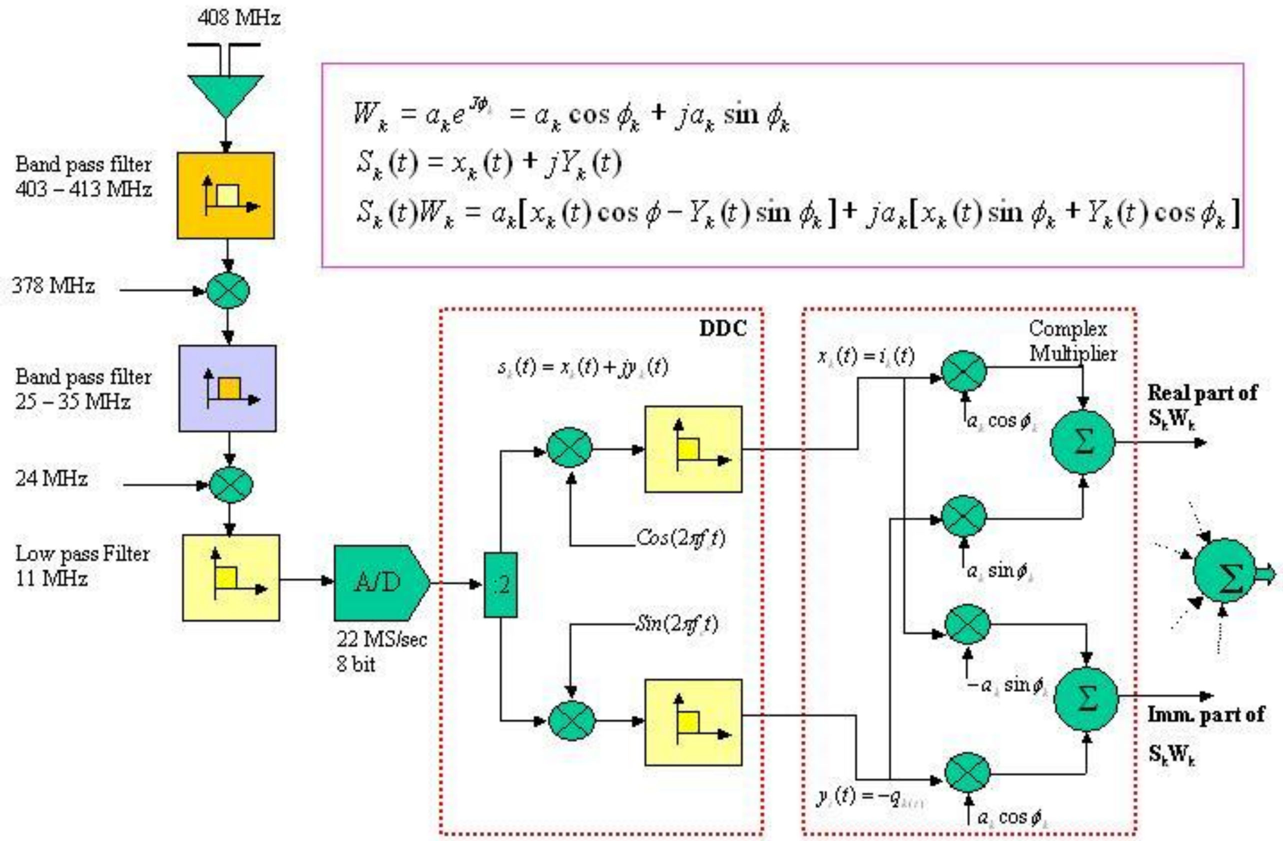
Figure 3.0: Fully digital beamforming working principle (4 elements)

In order to have the peaks and nulls in the radiation pattern in the desired positions, Adaptive Beam forming is requested. This may be obtained in different ways, depending on the conditions [2]:

1. ***Minimum Mean Square Error***: When the shape of the received signal is known *a priori*, the complex weights are adjusted to minimise the mean square error between the beamformer output and the expected signal

2. ***Maximum S/RFIs:*** This method adjusts the complex weigth to maximise the ratio of the desired signal (S) and an interfering signal.

3. ***Minimum variance***: This method is used when the shape and direction of the signal are well known. Weights are selected to minimise the noise at the output of the beamformer.



$$W_k = a_k e^{j\phi_k} = a_k \cos\phi_k + ja_k \sin\phi_k$$
$$S_k(t) = x_k(t) + jY_k(t)$$
$$S_k(t)W_k = a_k[x_k(t)\cos\phi - Y_k(t)\sin\phi_k] + ja_k[x_k(t)\sin\phi_k + Y_k(t)\cos\phi_k]$$

Figure 3.1: More detailed digital beamformer block diagram

In practical applications beamforming is generally performed in a mixed way [2]: analog and digital.

- The first analog beamforming step is implemented at the RF level to create a first "tile" or "macro-element" of the final antenna (since the macro elements are generally limited in size, delays are not compensated in case of small operation bandwidth).
- The second level of beamforming is done digitally at the base band side. In this case the tiles or macro cells are summed to obtain the total beam. At this level, delays need to be compensated very carefully.

3.1.2 Multibeam

The cylindrical reflectors of the Medicina Cross allow to form a certain amount of beams. The number of independent beams will depend from both the available number of receivers and number of beamforming blocks (Figure 3.2). The multibeaming way to operate is very important and offers the following capabilities:

- Efficiency: different and independent beams allow to investigate simultaneously different targets (by different users) within the FOV.

- Response: after a couple of minutes (worst case) taken by the cylindrical reflector mechanical pointing , the different beams can switch in a very short time (hundreds of microseconds) within the Field Of View (FOV).
- Sensitivity: for instance, with 8 separate beams it is possible to average 8 different measures, so increasing the sensitivity by a factor of $8^{1/2} = 2.8$, or the surveying speed by a factor of 8.

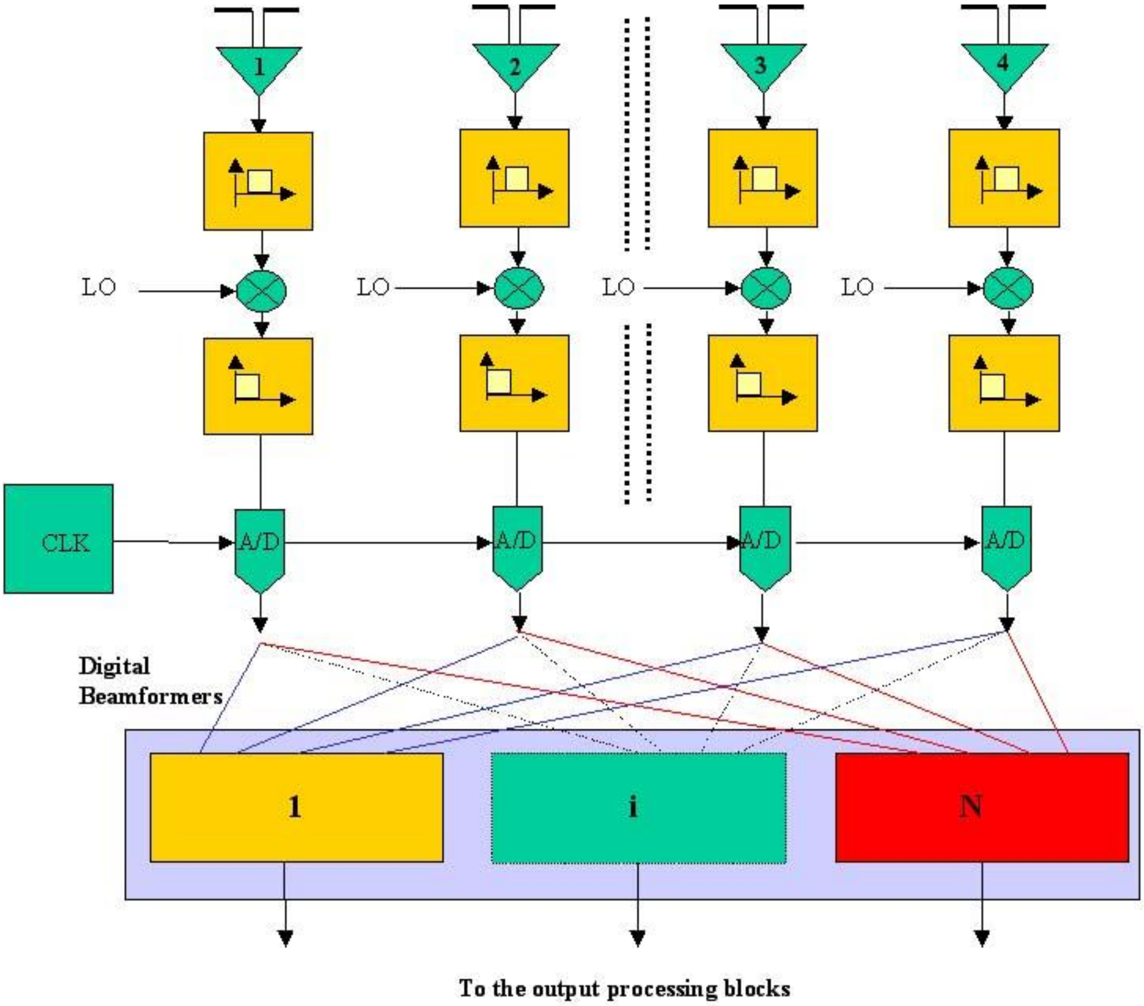


Figure 3.2: Principle diagram of the multibeam forming

4.0 NORTHERN CROSS UPGRADE PLAN

We start the description of the Cross telescope upgrade (N/S and E/W) plan followed by the description of the present SKA oriented technological activities at the Medicina labs.

4.1 N/S arm possible configurations,

We will mainly discuss two solutions: 8 receivers grouped by two (4 blocks) and eight single receivers, both installed on the focal line of each cylindrical reflector. Of course, installing 4 blocks of 2 receivers or 8 single receivers, means to install 4 or 8 coaxial 45 m long cables (to carry the amplified radio signal at 408 MHz from the focal lines down to the cabins) and the double of optical links from the cabin to the processing room.

4.1.1 Four groups of two receivers on each reflector

The first concept is to introduce 4 groups of two receivers on each single N/S element, as visible in Figure 4.1 The four groups of receivers are planned to be installed on the focal line at the output of the first 8 single dipoles sum. In this condition the number of receivers installed on the N/S would be **256** groups of two receivers (**512** total receivers). It has to be noted that in this configuration the integration time can be increased of about a factor of two, by moving the four beams inside the beam of the single receiver by means of the Vector Modulator (VM).

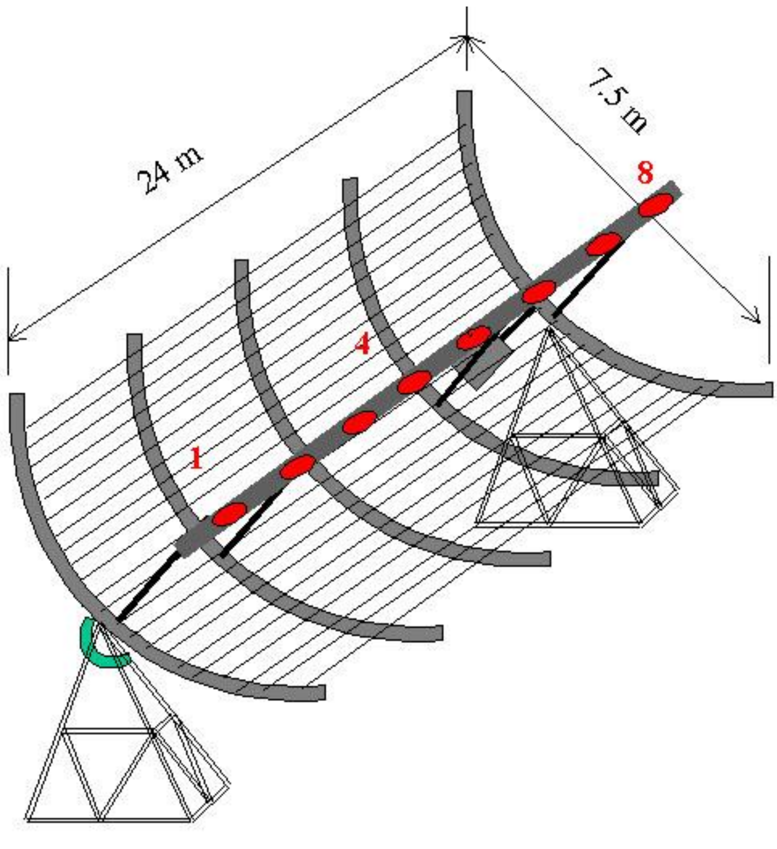


Figure 4.1: Sketch of one of the 64 single N/S element with the eight single receivers position on the focal line

The block diagram for this option is drawn in Figure 4.2. This is just a diagram of principle, that doesn't consider the signal levels, of the number of amplifiers needed to reach the correct level along the different points of the diagram. From the same diagram we see that a Vector Modulator is requested, after the front end, to create the single channels that will be used later in the digital beamformer. The same VM also performs a down conversion to the first IF (30 MHz ±10 MHz). After the sum with the proper phase and amplitude of two receivers, the resulting signal is converted down to the video band (1-11 MHz), digitised with 256 levels (48 dB of dynamic range), translated in the optical field and sent to the processing room via low-cost optical links. At this level the digital signal is converted with a DDC to a complex signal, ready to be processed by the digital beam former. In Figure 4.3 is reported a pictorial view of the system of 4 blocks from the focal line up to the summing point and down in the cabin housing the hardware of the already existing N/S channels. In Figure 4.4 a more detailed block diagram is reported. The signal coming from the 8 parallel dipoles is fed to the low-cost LNA, filtered (BW=10 MHz) by a cost-effective multipole ceramic filter, 18 dB amplified and both filtered and 18dB amplified again. The signal then passes through a wide band new Vector Modulator (10 dB insertion loss). In this stage, beside to be phase shifted, the signal is equalised in amplitude and down converted to the IF frequency value (30 MHz, BW=10 MHz). The signal is then strongly band-shaped by the exploitation of the impressive characteristics of the state-of-the-art SAW filter technology. As already mentioned, the digital signal is converted with a DDC to a complex signal, ready to be processed by the digital beamformer.

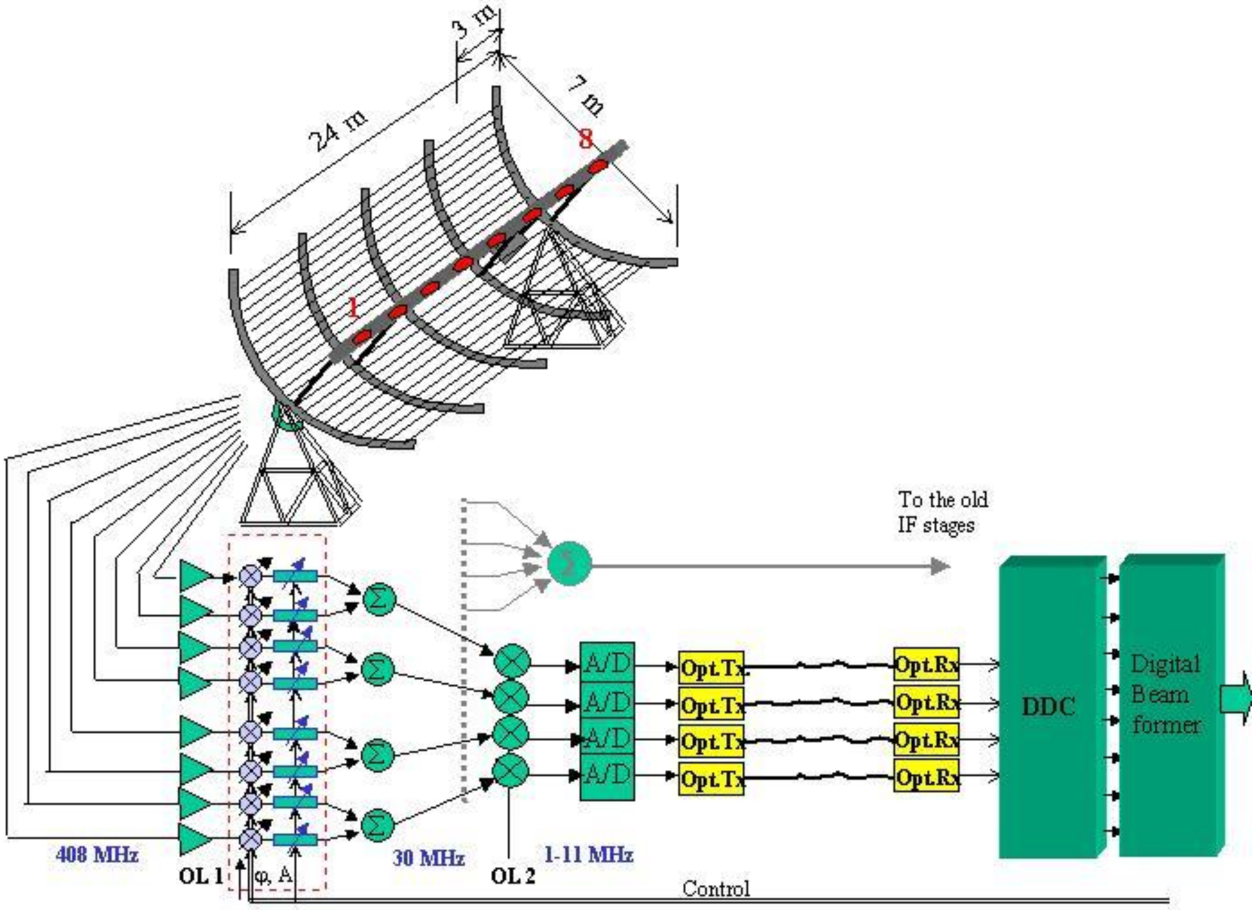


Figure 4.2: Block diagram of the 4 block –2 receivers on each reflector

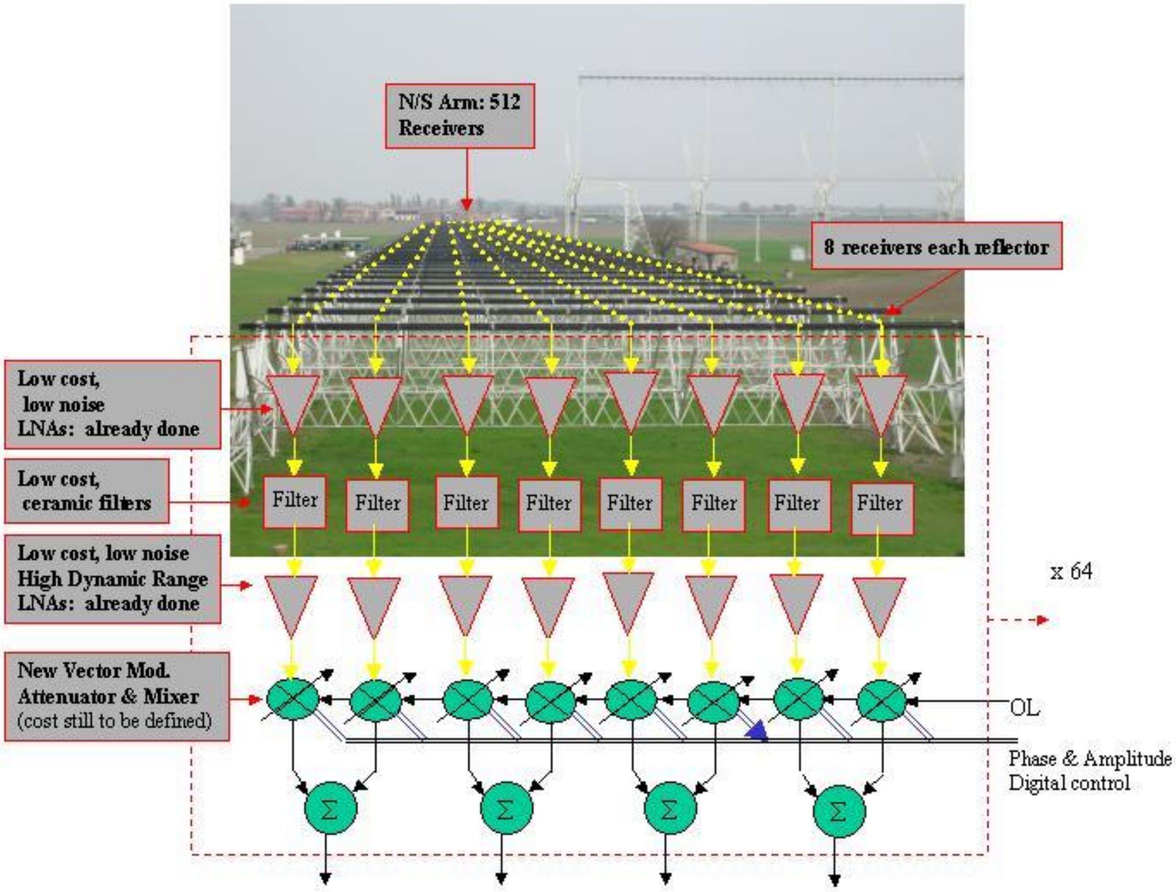


Figure 4.3: Pictorial view of the case of 4 blocks of 2 receivers on the N/S single reflector.

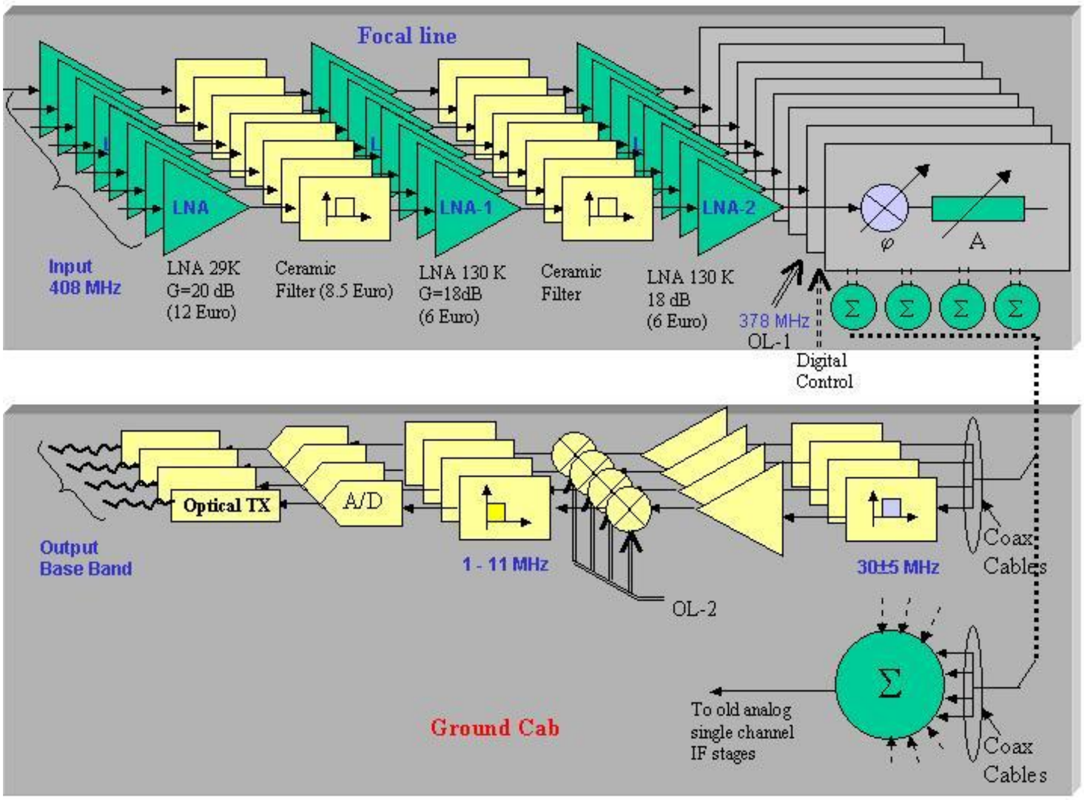


Figure 4.4: More detailed block diagram of the 4 blocks / 2 receivers each

The band-limited signal is down converted to the video band, filtered again, digitised (8 bit), and sent, via a low-cost optical link, to the data processing room, distant about 900 m (worst case). A sum of every single receiver inside the single channels is sent to the already existing IF stages.

4.1.2 Eight single receivers on each reflector:

In this solution we consider 8 single receivers on each single cylindrical reflector. The number of receivers installed on the total N/S would be **512** as in the previous case. This is the maximum number of receivers installable on the N/S arm without changing the focal line design. Due to the mechanical structure of such an antenna, it should be very easy to change (if requested) the old dipoles with a new design low-cost wide-band printed sensors on the same focal line. In this case more than 4500 receivers could be installed. The block schematic diagram is visible in Figure 4.5. The Vector Modulator is not needed in this solution because each phase and amplitude can be numerically adjusted in the digital beamformer.

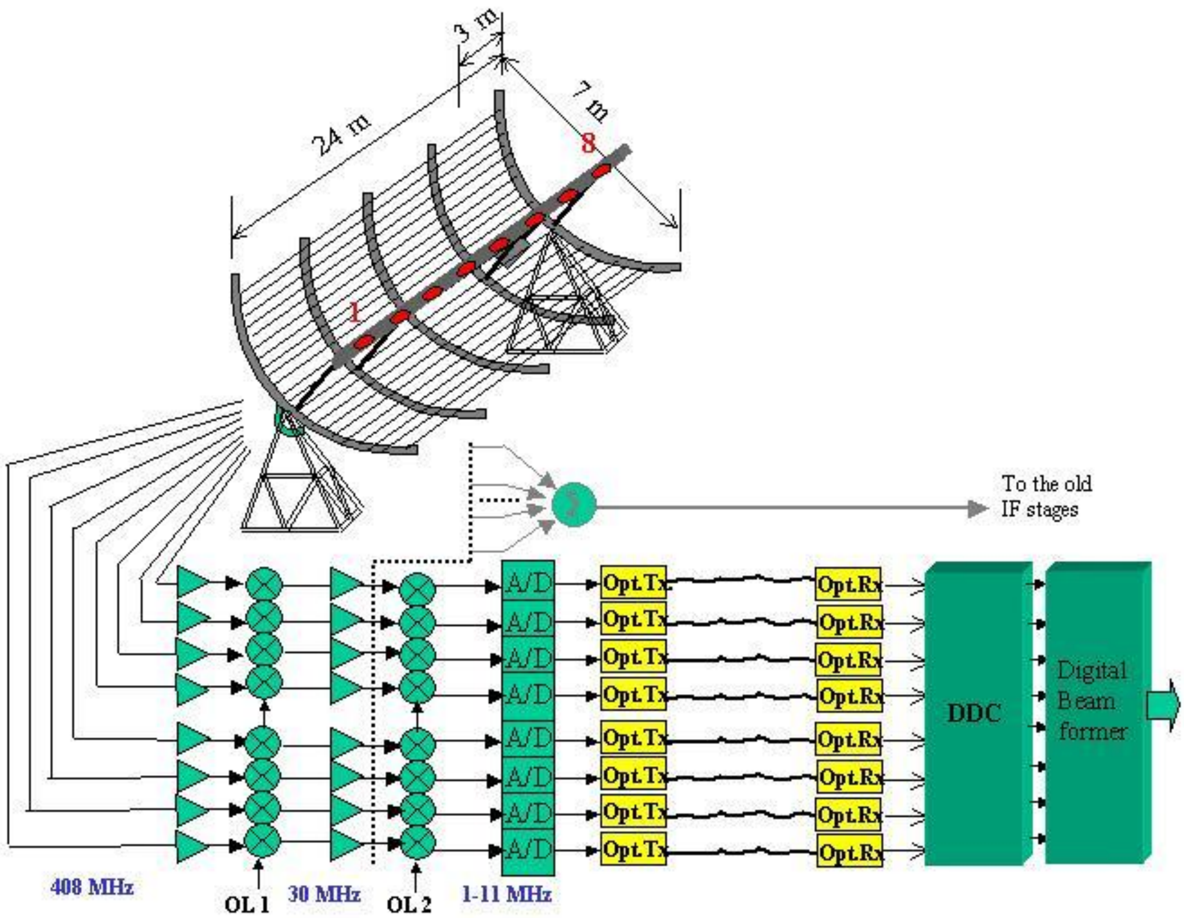


Figure 4.5: Bock diagram of the version with eight separate receivers.

In Figure 4.6 is reported a pictorial view of the 8 receivers, from the focal line down to the cabin housing the existing receivers. In Figure 4.7 a more detailed block diagram is shown. The Signal coming from the dipoles is fed to the LNA, filtered (BW=10 MHz) by a cost-effective multipole ceramic filter, amplified (18 dB) and filtered and amplified again. The signal is down converted to the IF frequency value (30 MHz, BW=10 MHz) and is strongly band-shaped by state-of-the-art filters. The band-limited signal is down converted to the video band (1 –11 MHz), filtered again and finally digitised and sent, via a low-cost optical link, to the data processing room. A sum of every receivers inside the single channel (composed of 8 reflectors →8x8=64 receivers) is sent to the existing analog IF stages. As visible in the same Figure 4.7, in this configuration the VM is not required because the beam forming is totally managed by the Digital beamforming block.

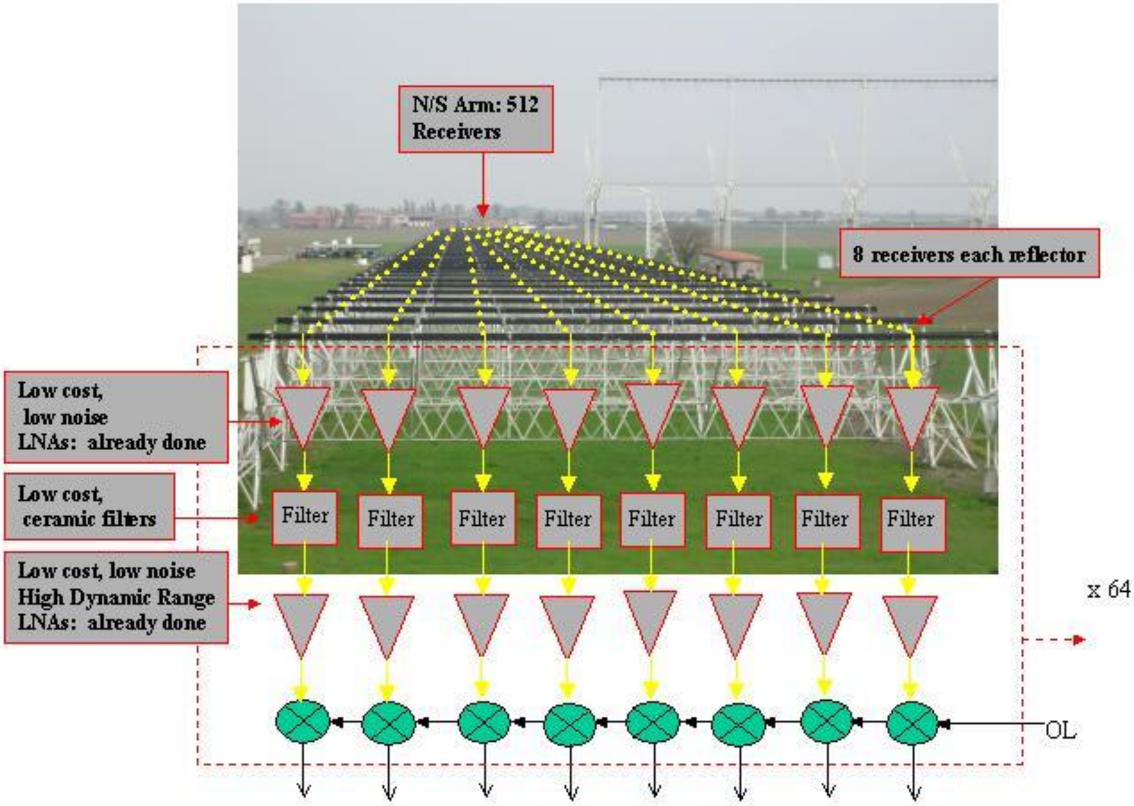


Figure 4.6: Pictorial view of the case of 8 single receivers on the N/S single reflector.

A comparison, in terms of devices requested by the different configurations (for each single reflector), is reported in TAB.1.

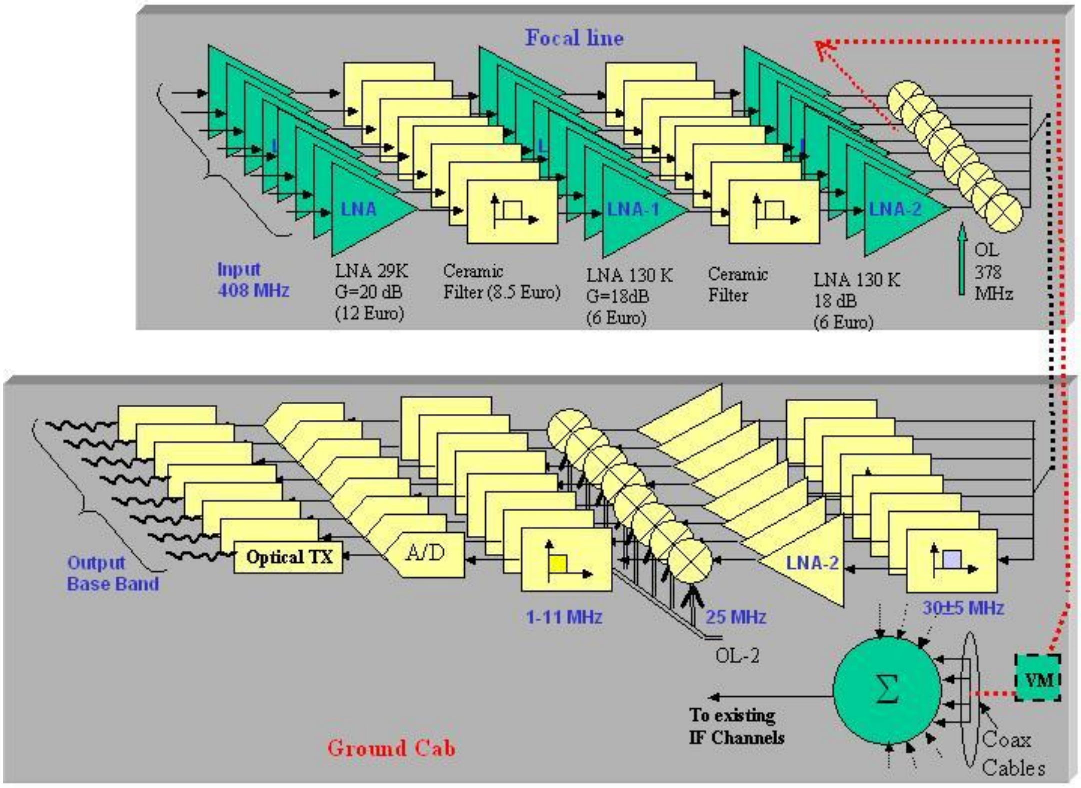


Figure 4.7: More detailed block diagram of the 8 receivers on each reflector configuration.

	8 Single antennas /refl.	4 Blk -> 2 rec. each
LNA installed	8	8
2^{nd} stages installed	8	8
3^{th} stages installed	8	8
RF interstage filters	16	16
Vector Modulator	0	8
Mixers	8 (408 → 30) 8 (30 →Base Band)	16 VM (408 → 30) 8 30 →Base Band
A/D	8	4
Opt ical links (TX+Fiber+RX)	8	4
Digital DDC inputs	8	4
FOV	81.8 square degrees	40.7 square degrees
Independent beams	**511**	**255**

TAB.1 Number of requested devices in the two configurations (each reflector)

It can be noted in this table that the number of independent beams in the N/S antenna could be 255 or 511, depending on the number of the installed receivers.

4.2 The E/W Upgrade

4.2.1 The plan

The upgrade plan is to install a certain number of receivers on the cylindrical reflector focal line (Figure 4.10)

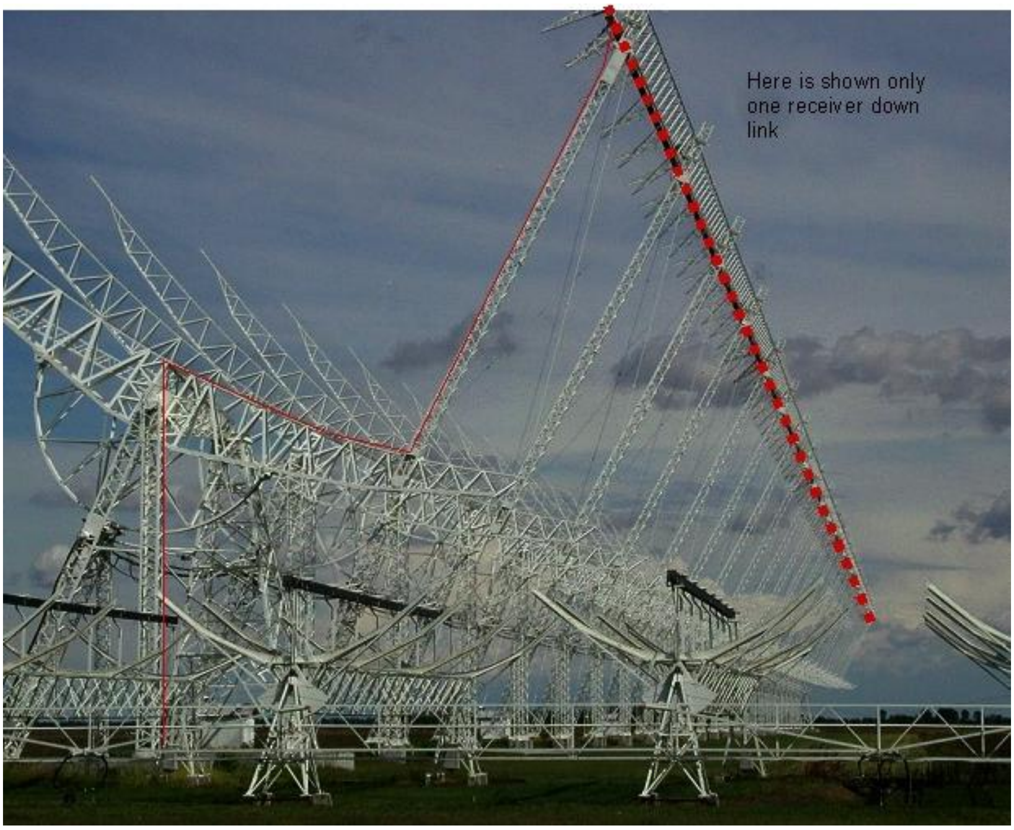


Figure 4.10: Pictorial view of the E/W antenna with the new receivers positions

In the present configuration (Figure 4.11) a 4 arcmin total power beam is obtained adding the 6 EW channels with a proper phase.

Different upgrade solutions may be considered:

1.	1 receiver for each 24 m focal line (64 dipoles / receiver)	24	receivers
2.	8 receivers for each focal line (8 dipoles / receiver)	192	receivers
3.	1536 receivers (1 dipole / receiver)	1532	receivers

Solution 1: As reported in Figure 4.12 – 4.13, we can increase the transit time up to 380 s (HPBW = 96') installing 24 receivers in the E/W present focal line (1 receiver / focal line segment)

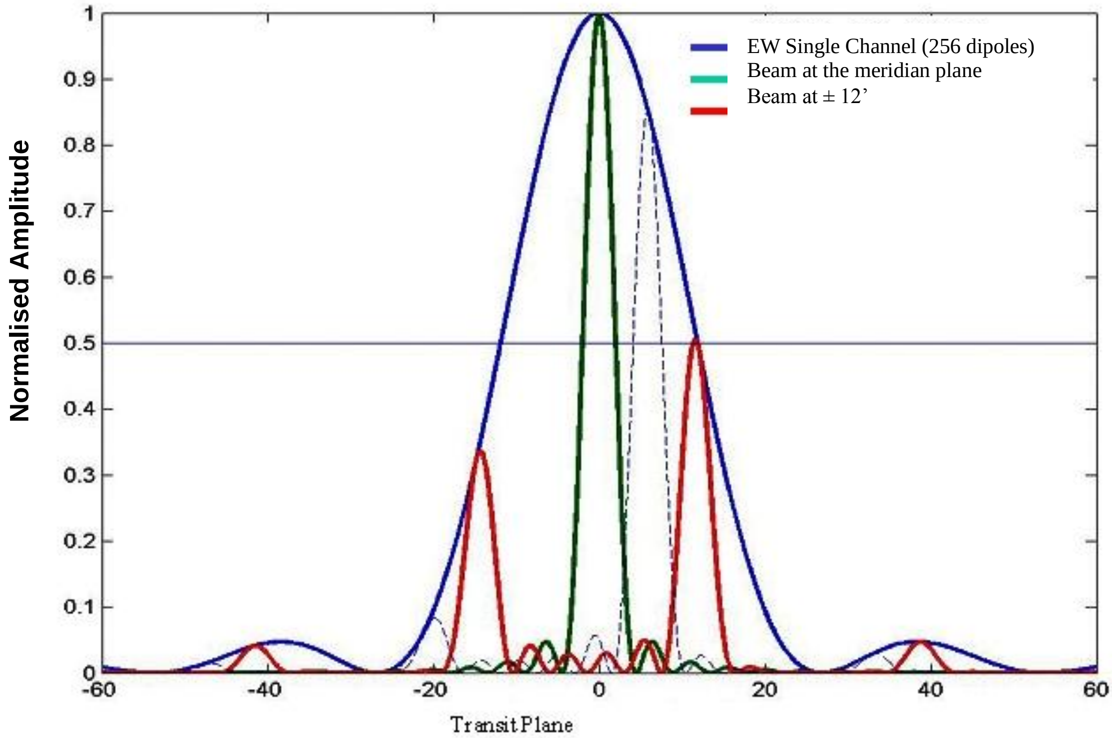


Figure 4.11: Present configuration: total beam normalised amplitude on the transit plane.

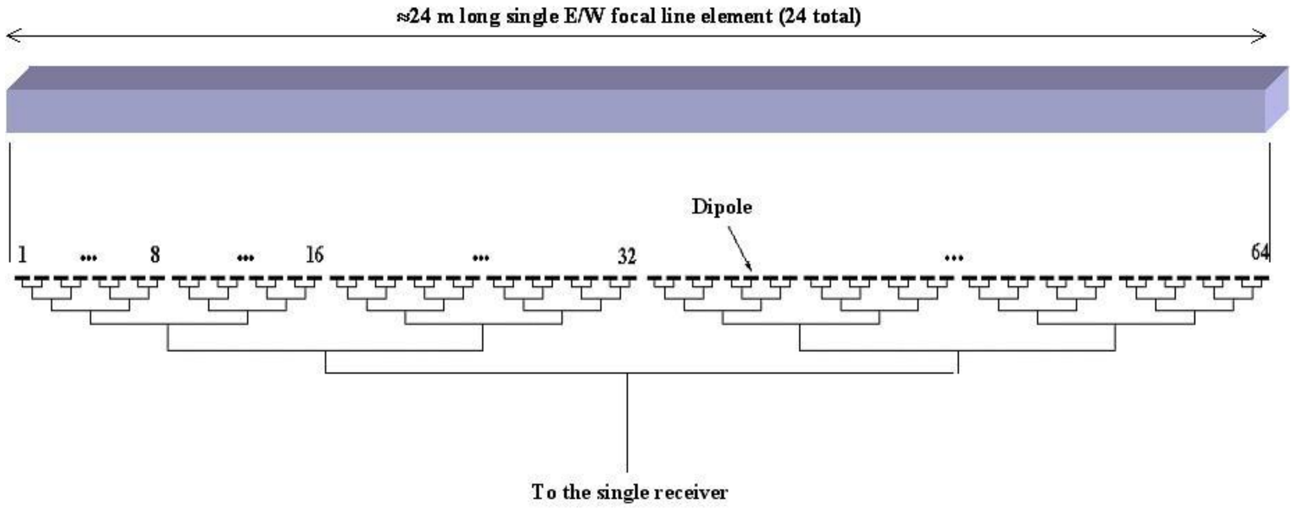


Figure 4.12: 1 receiver per focal line segment (24 receivers total)

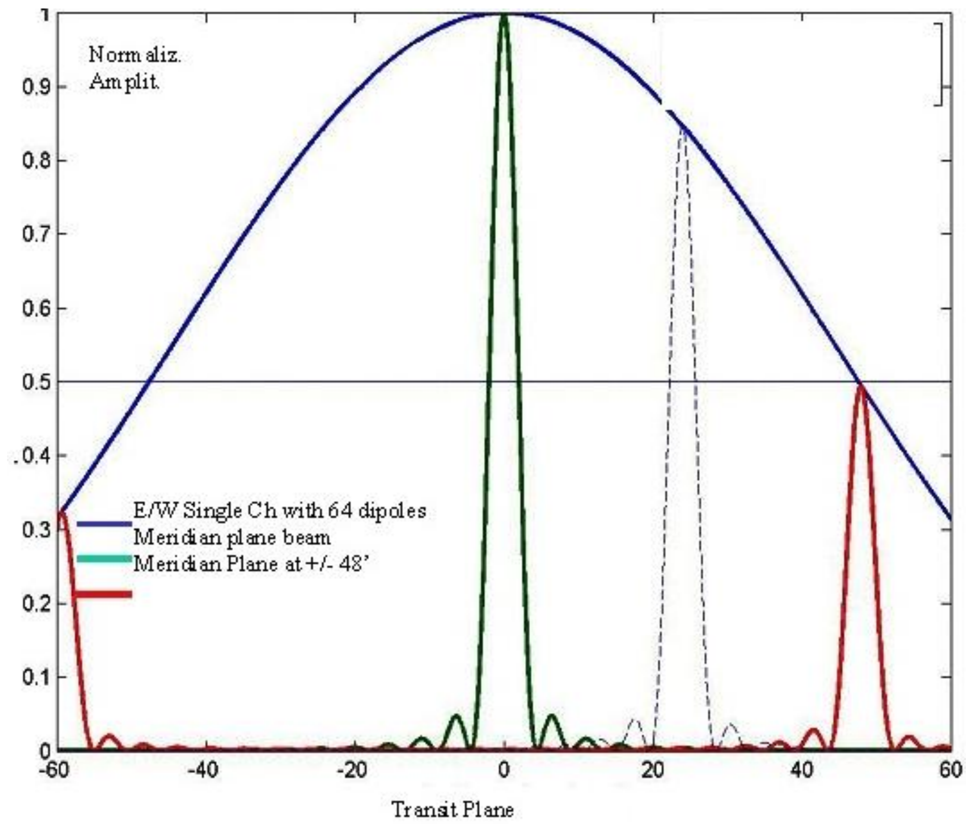


Figure 4.13: Total beam on the transit plane in the case of a 24 receivers solution

Solution 2: If we install a receiver on each block composed by 8 dipoles, as visible in Figure 4.14, we will have 192 receivers.

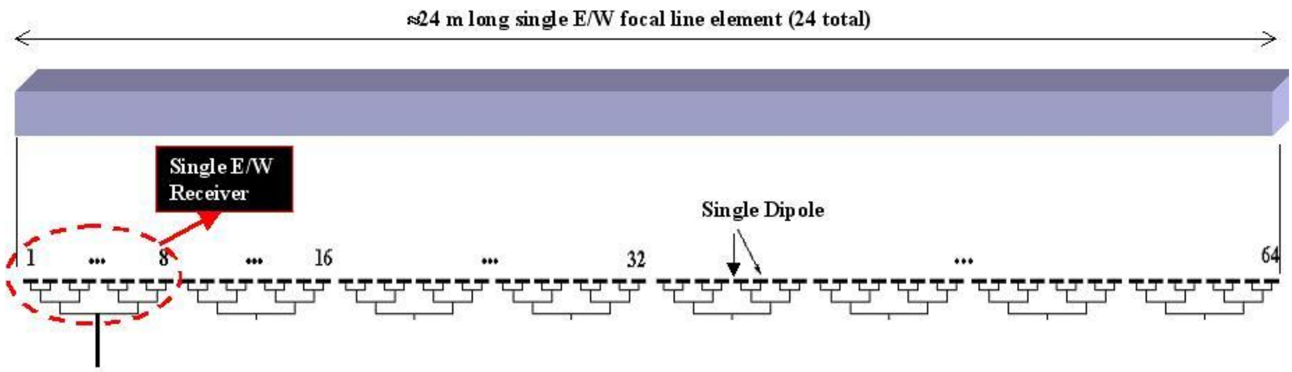


Figure 4.14: Position of each single receiver in the 192 single elements solution

Solutions 3: 1536 receivers (1 dipole / receiver, Figure 4.15). This represents the maximum expansion in terms of number of receivers on the E/W focal line. This configuration would allow the maximum FOV for the E/W antenna.

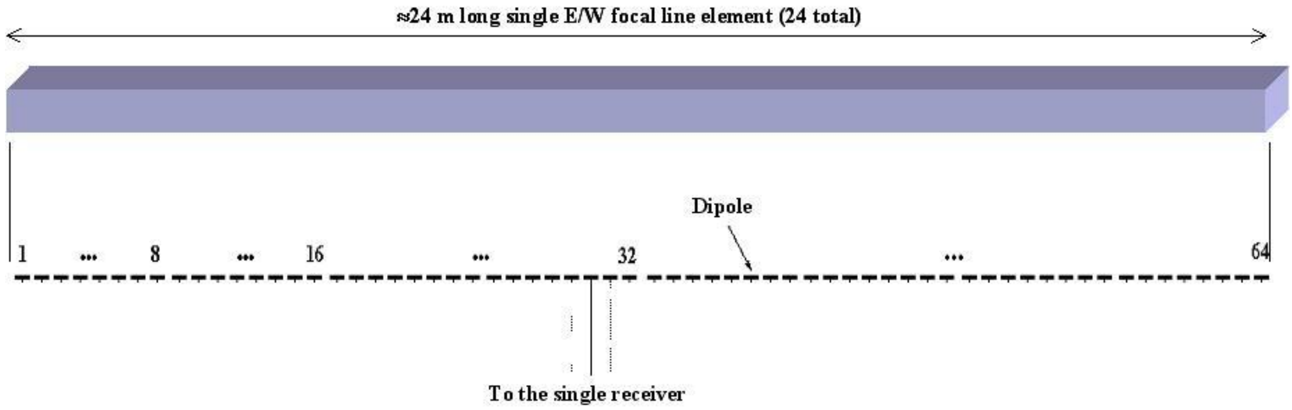


Figure 4.15: One receiver connected to every single dipole

In the E/W case the developed VM can be used to shift the phase and down convert the signal to form the 6 analog channels as in the present configuration. Intermediate solution in which we use the VM to form block of receivers (as in the considered N/S case) can be considered.

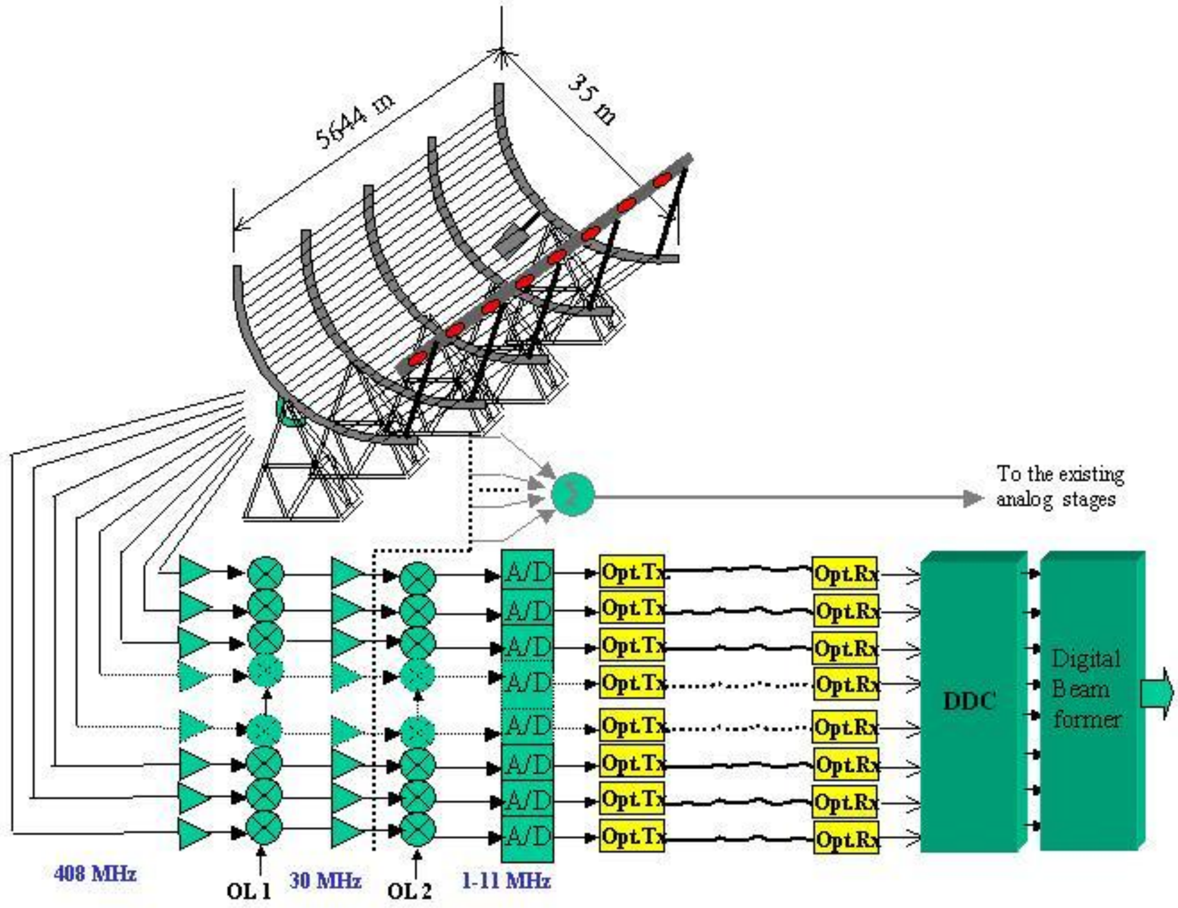


Figure 4.16 : Block diagram of the planned E/W upgrade configuration

4.3 FOV

We consider now the FOVs of both the N/S and E/W antennas different configurations.

4.3.1 FOV of the N/S in the different solutions

It is interesting to compare at this level the different Fields Of View in both configurations (the FOV is the instantaneous and contiguous solid angle area of the sky that can be imaged, in practice the angle in which we can place N independent beams at the same time) . In the case of a cylindrical reflector, as in the N/S and E/W (*L x d)* rectangular apertures, it is given by [3]:

FOV @ f $= (\lambda^2 / L\, d) \times (57.2)^2$ **deg.**^{2}

Where **f** and λ are the operating frequency and wavelength respectively.

Considering that in both configurations 8 receivers are installed at about 3 m each from the other one, the FOV becomes:

4 blk / two receivers each: **FOV @ 408 MHz** $=[0.54 / (6 \times 7.5)]\,(57.2)^2 \approx 40$ **deg** ^{2}
(Figure 4.8)
8 single receivers: **FOV @ 408 MHz** $=[0.54 / (3 \times 7.5)]\,(57.2)^2 \approx 80$ **deg** ^{2}
(Figure 4.9)

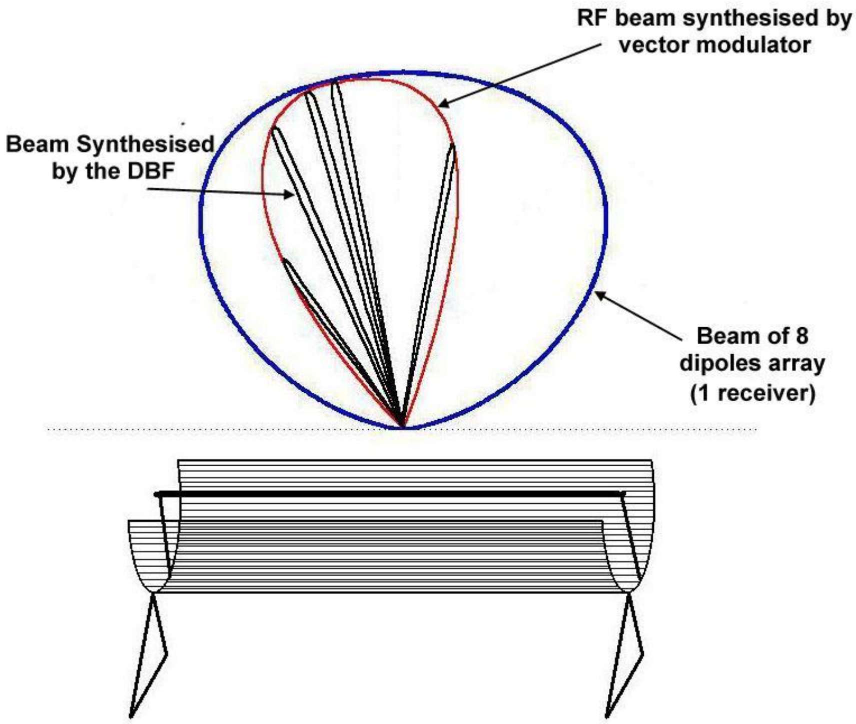


Figure 4.8: Beams, on the transit plane, on the 4 blk / 2 rec. configuration (drawn not in scale). The RF-beam can be moved in the beam of 1 receiver to increase the integration time (DBF → Digital Beam Former).

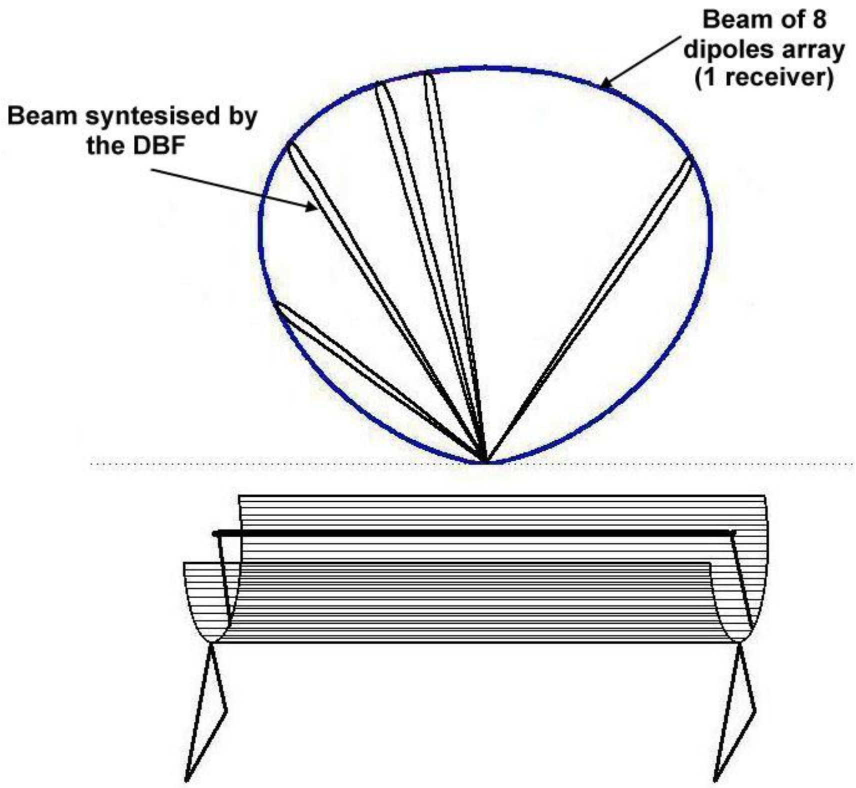


Figure 4.9: Beams, on the transit plane, in the 8 single receiver /reflector configuration

4.3.2 FOV of the E/W in the different solutions

We now estimate the FOV in the different considered solutions, by applying the same formula used in the N/S case:

FOV @ f = **(λ^2/ L d) x (57.2)^2 deg.^{2}**

Independently from the number of receivers that will be installed, the schematic diagram, reported in Figure 4.16, remains the same for all the solutions. As in the previously considered N/S case, we need to develop very low-cost receivers, optical links and digital beamformers. In the following table, an additional 768 receivers configuration is also considered.

Number of receivers	Beam dimensions (deg)	FOV (deg ^{2})	Total beam solid angle (deg ^{2})	Number of E/W independent Beams
24	**(1.75 x 2)**	**3.5**	**0.26**	**23**
192	**(14.3 x 2)**	**28.6**	**0.26**	**191**
768	**(56 x 2)**	**112.0**	**0.26**	**767**
1536	**(112 x 2)**	**224.0**	**0.26**	**1535**

4.3.3 Note on the tracking time

The tracking time of each E/W and N/S cylindrical reflector, as sketched in Figure 4.17, depends on the number of receivers installed, in other words from the beamwidth in the transit plane.
Considering that the earth rotates **15^o/h** (15 arcsec / sec) at δ=0, for a given right ascension plane beamwidth corresponds a tracking time:

$$Tr_{time} = \left(\frac{57.3}{L_{xx\lambda}}\right)\frac{60}{0.25\cos\delta} = \frac{13.752}{\cos\delta L_{xx}} \quad \text{sec.}$$

Where L_{xx} is the length in units of λ (in the E/W direction) of the considered arm.

4.3.3.1 N/S arm

In the case of 8 single receivers, the tracking time at δ=0 (worst case) is given by:

$$Tr_{time} = \left(\frac{57.3}{4.08}\right)\frac{60}{0.25} = \frac{13.752}{4.08} = 56.18 \quad \text{minutes}$$

while is 79 minutes at δ=45^o and about 164 minutes at δ=70^o. As already mentioned this tracking time may be considerably increased by adding receivers and mechanically move the reflector, during tracking, with a computer controlled power inverter.

4.3.3.2 E/W arm

For the sake of simplicity, we consider 192 receivers. In this case one receiver is 3 m far away from the other one as in the N/S case, so the tracking time is the same (56.18 minutes).

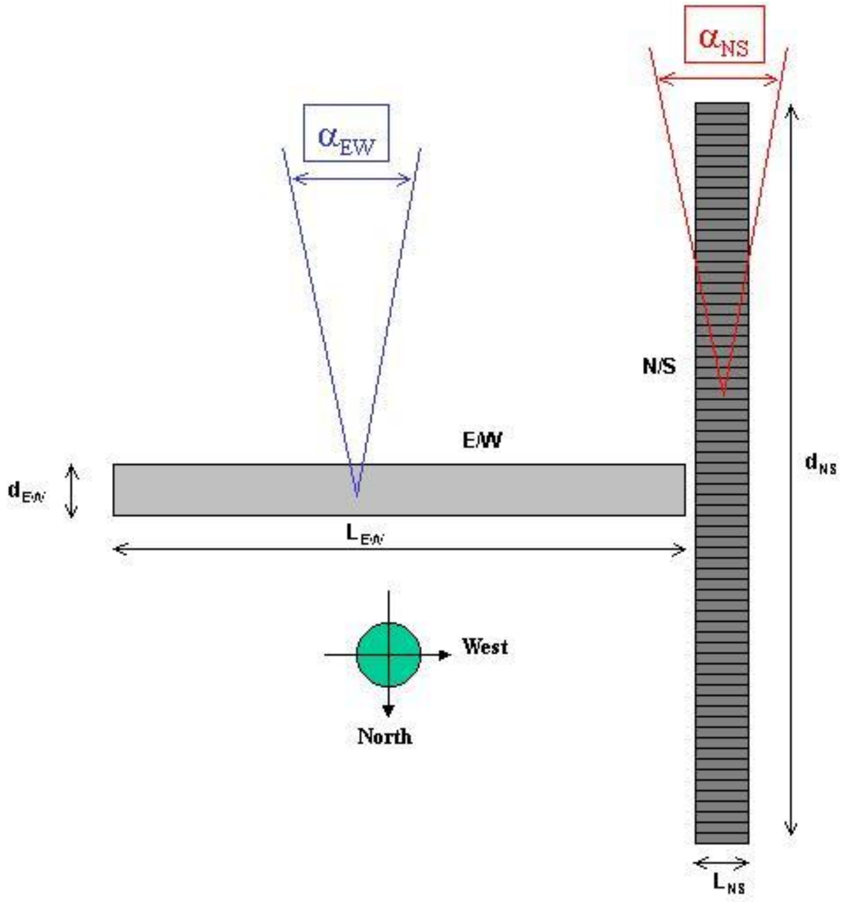


Figure 4.17: Sketch of the E/W and N/S single channel transit plane.

As in the previous N/S case we have 79 minutes at $\delta=45^o$ and about 164 minutes at $\delta=70^o$ This tracking time may be considerably increased by adding receivers and mechanically move the reflector during tracking. During this tracking time no mechanical pointing of the two arms are requested.

4.4 Number of independent beams

Taking in consideration the grating lobes in the situation of equispaced antennas as in the Northern Cross, the independent pencil beams we can obtain are:

N/S (10 m spaced 64 single reflectors):

1- 4 blocks of 2 rec. on each reflector **(64-1) x (4-1) = 189**

2- 8 receivers on each reflector **(64-1) x (8-1) = 441**

E/W:

1- 24 receivers	**(24-1) = 23**
2- 1536 receivers	**(1536-1) = 1535**

Just before concluding the paragraph, let us to underline the main characteristics of the instrument after the above discussed possible upgrades:

➢ **Aeff/Tsys**	**~ 10^2 m^2/K**
➢ **E/W Antenna Gain**	**Unchanged**
➢ **N/S Antenna Gain**	**Unchanged**
➢ **E/W System Equivalent Flux**	**~ 35 Jy**
➢ **N/S System Equivalent Flux**	**~ 50 Jy**
➢ **Angular Resolution**	**Unchanged**
➢ **Band-Pass**	**10 (20) MHz**
➢ **FOV (NS)**	**≈ 40 (80) deg^2**
➢ **FOV (EW)**	**≈ 3.5 – 224 deg^2**
➢ **Sky Coverage**	**0 ÷+90 deg (N/S arm)**
	- 30 ÷+90 deg (E/W arm)
	0 –+90 deg (Cross)
➢ **Number of possible simultaneous indipendent beams (N/S)**	**189 – 441 (depending on the adopted solution)**
➢ **Number of possible simultaneous indipendent beams (E/W)**	**23 –1535 (depending on the adopted solution)**
➢ **Sky Pixeling**	**(N/S Ind. beams N.)x(E/W Ind. Beams N.)**
	(min. 4347 – max 676.940)
➢ **Maximum beam spacing**	**14 deg (on the transit plane)**
➢ **Tracking time with no mech. moving (receivers 3 mt spaced)**	**N/S 56 minutes, E/W –30 /38 deg**
	50 / 90 deg.

5.0 Data transmission and processing

In both the N/S and E/W antennas upgrading cases, every single signal will be digitised (the present plan is to use 8 bit) inside the 14 already existing cabins (or may be at the focal line level) just below the two arms. Digital data have then to be sent to the main receiver room. This will be done via a low-cost bidirectional optical link under design as visible in Figure 5.1. Our present idea is that the “bidirectionality” is a little more expensive, but it could allow more flexibility for future requirements or upgrade. The analog signal are sent to the same processing room via the existing underground coaxial cables. A very simple block diagram is reported in Figure 5.2. In this figure it is shown how the optical signal is sent to both the new digital beamformer and correlators and to the already existing analog IF channels, phase shifters and complex correlators. It is very important to maintain the old existing blocks because they immediately give the results in the analogic domain, which is very useful during the evaluation, tests and calibration activities.

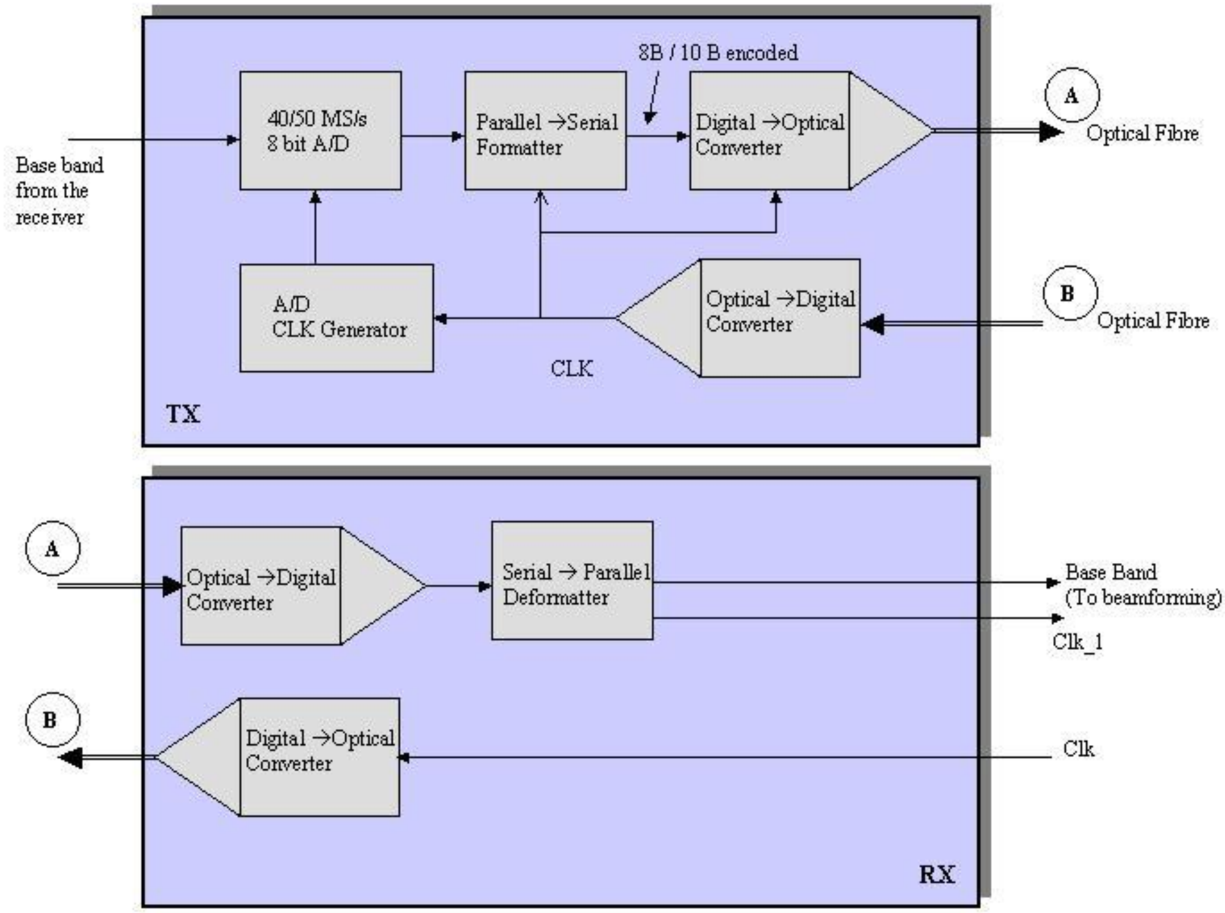


Figure 5.1: Basic plan for the optical TX /RX (bidirectional)

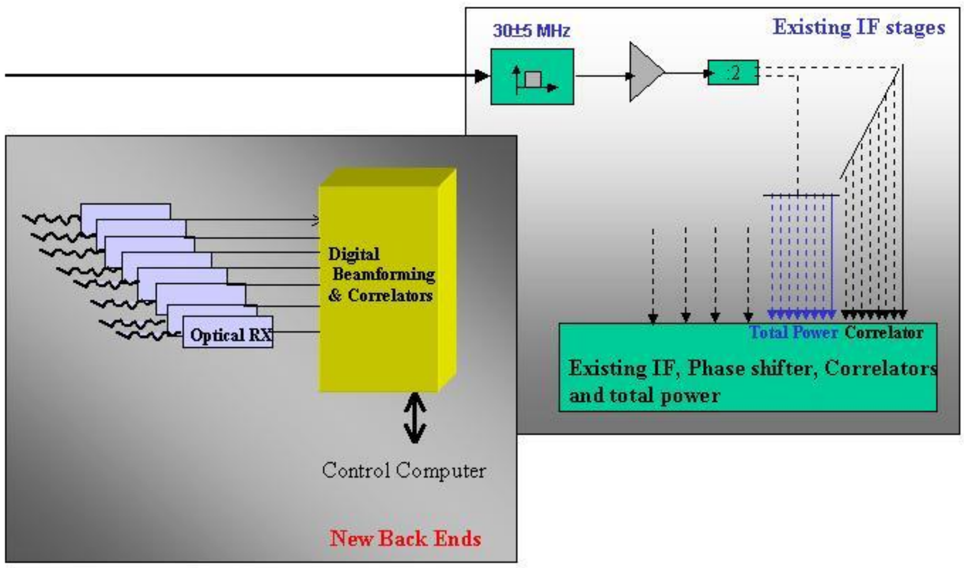


Figure 5.2: Sketch of the digital and analog processing room

At the preparation time of this paper, the Beamformer / correlators designa have not faced yet. May be that a FFT beamformer [4] will result more suitable in our case. The continuous increasing of computation power and the decreasing cost of the modern DSP, the plan to investigate the possible use of these devices represents a good starting point for near future discussions and developments within an international cooperation.

6.0 Upgrade Technological Activities

In the first 6 months of upgrade activities (SKA consortium oriented), a low-cost high-performance front end and a very low-cost high-dynamic-range second stage have been developed. Two receiver versions are considered: the first one equipped with a Vector Modulator (for tile or antenna macroelement formation at the RF level) and the second one without Vector Modulator (single receiver solution). The receiver basic block diagram (with VM) is visible in Figure 6.1. The final version could be composed by 3 amplifier stages as reported at the end of this paragraph.

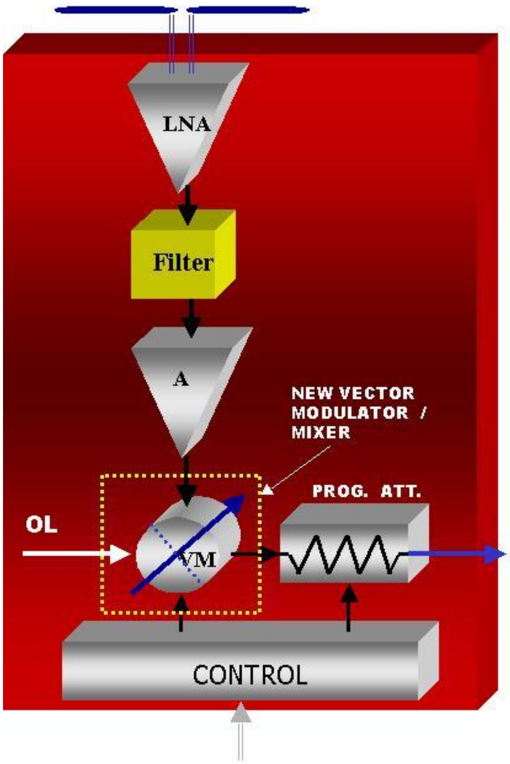


Figure 6.1: Schematic block diagram of the front end.

The Front End is composed by several stages:

The first stage (LNA): Since its detailed description will be the subject of future reports, we give here a brief summary of the main measured characteristics. In Figure 6.2 and 6.3 the electrical diagram and the prototype layout are visible.

- Tsys= 29 K,
- OIP3 =+24.5 dBm
- **Cost 12 Euro** (connectors not included)
- Single power supply

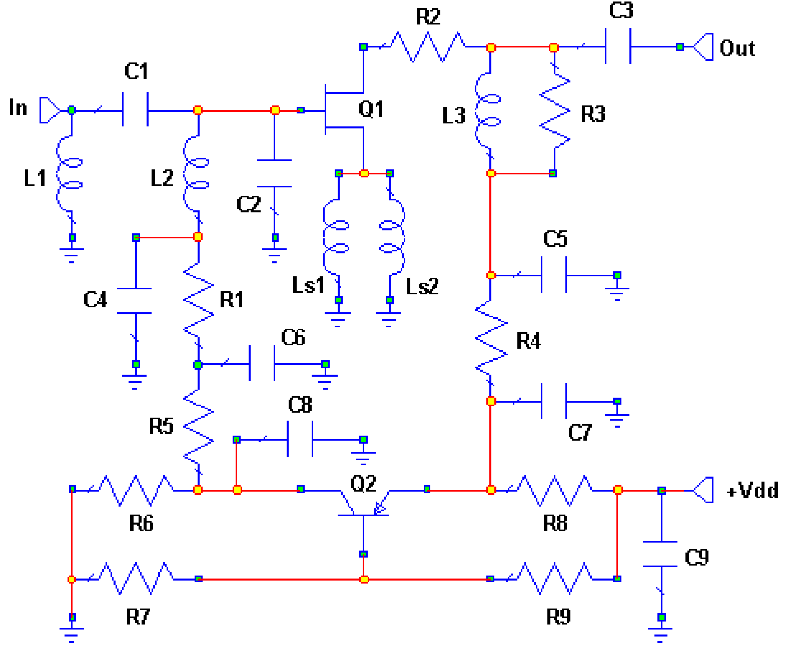


Figura 6.2: Electrical diagram of the front end

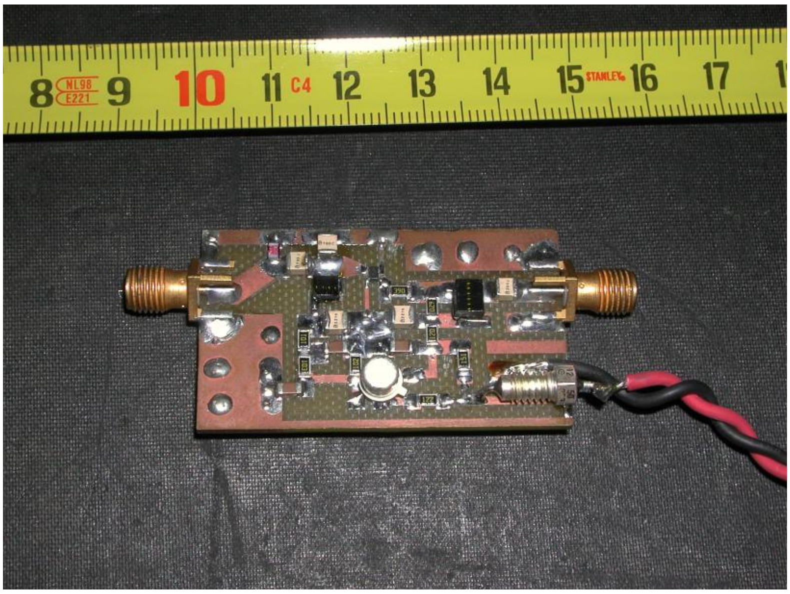


Figure 6.3: Picture of the front end prototype

IRA-SKA LNA Prototype *(measured @ 408 MHz)*	
S11 = -9.94 dB	S21 = 19.87 dB
NF (system) = 0.65 dB	OIP3 = 24.5 dBm
P1dBin = -3.56 dBm	P1dBout = 15.31 dBm

The OIP3 is measured with 2 tones at 407.5 and 408.5 MHz at -24 dBm at the D.U.T. input

P1dBin = -3.83 dBm, S21 = 20.1 dB @ 405 MHz
P1dBin = -3.62 dBm, S21 = 19.8 dB @ 411 MHz

The obtained values are very similar to the ones of a much more expensive (about 464 € / unit without connector) commercial LNA (without any input filtering) produced by a very well known industry.

Commercial LNA *(measured @ 408 MHz)*	
S11 = -8.9 dB	S21 = 21.8 dB
NF (system) = 0.60 dB	OIP3 = 24.2 dBm
P1dBin = -3.64dBm	P1dBout = 17.16 dBm

The OIP3 is measured with 2 tones at 407.5 and 408.5 MHz at -24 dBm at the D.U.T. input

Figures 6.4 – 6.6 report some graphics of the main characteristics:

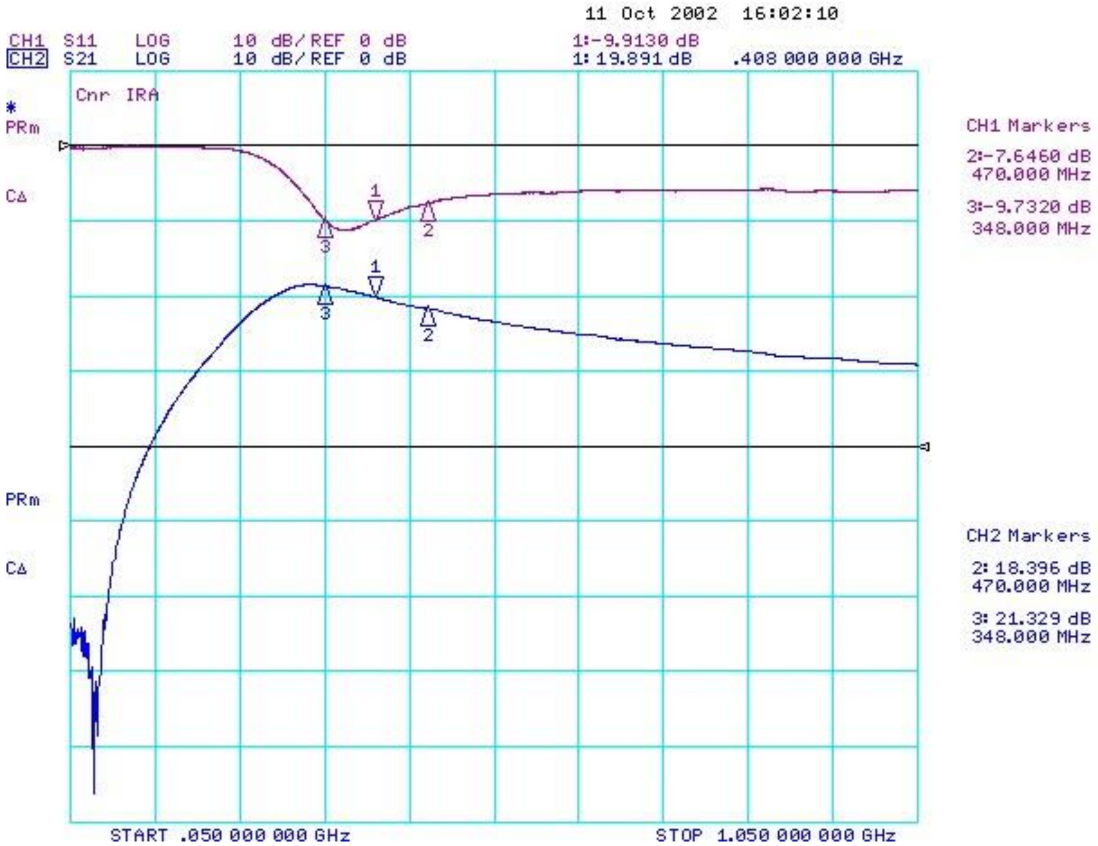


Figure 6.4: Measured S11 and S21 of the first stage prototype

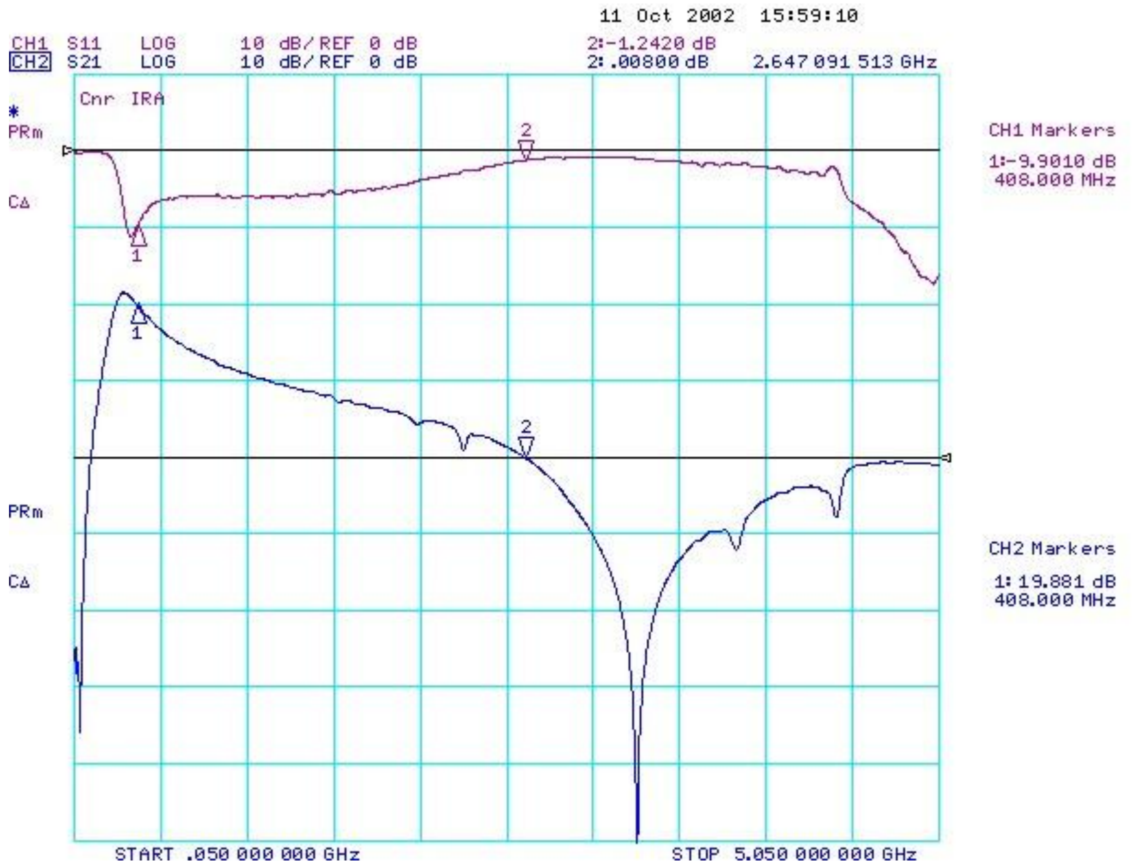


Figure 6.5: Measured S11 and S21 of the first stage prototype (wide band)

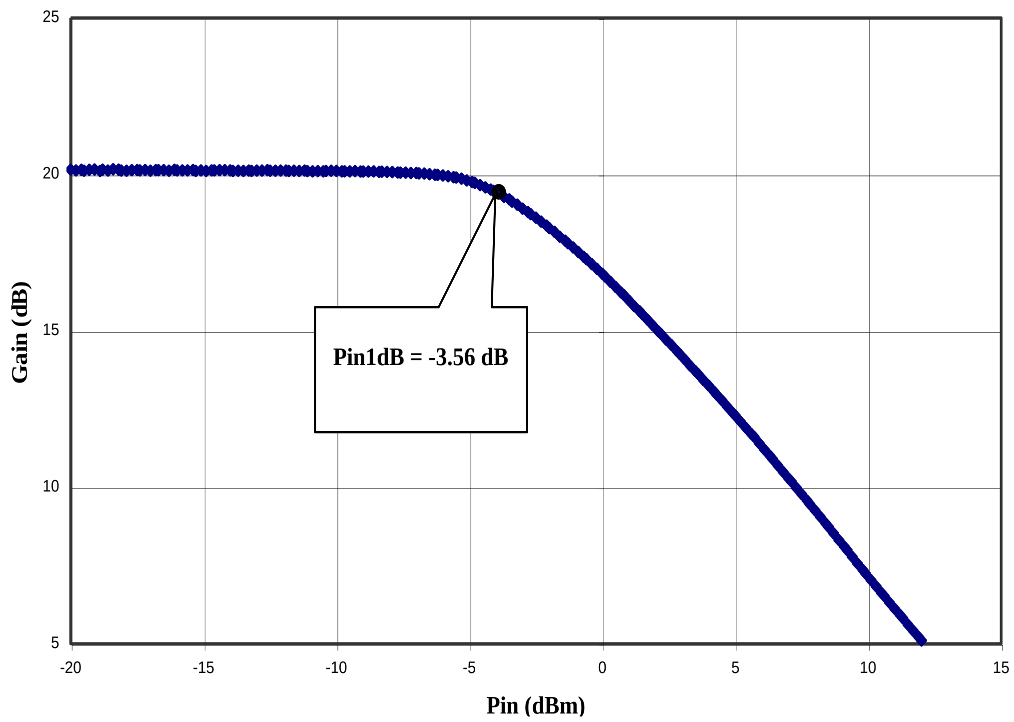


Figure 6.6: Measured input power @ 1 dB compression (408 MHz, T = 25 °C)

Between the front end and the second stage a new low-cost (8.5 Euro) ceramic pass-band filter is used. If a third stage is used, another identical ceramic filter will be inserted (between the second and third stage) to obtain a better channel shape and RFIs rejection. The insertion loss of such a filter is 3.5 dB.

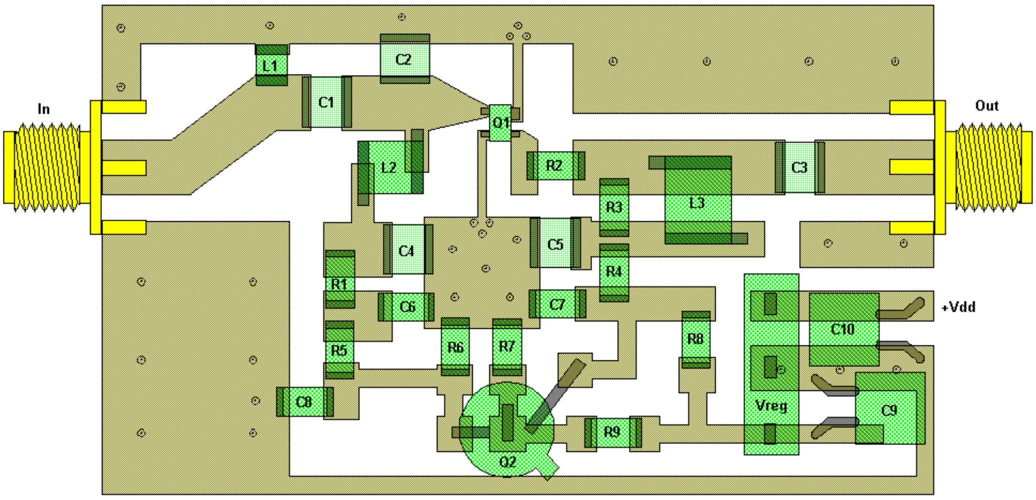


Figure 6.7: First stage prototype sketch

<u>**The second stage**</u> main characteristics are:

- Tsys=121 K,
- OIP3=+29 dBM
- **Cost 6 Euro** (connectors not included)
- Single power supply

Its detailed description will be presented in future reports. We show here a brief summary of the main measured characteristics This is a very robust amplifier that exploits the extremely good characteristics of the Agilent MGA-53543 IC (Figure 6.8 – 6.10)

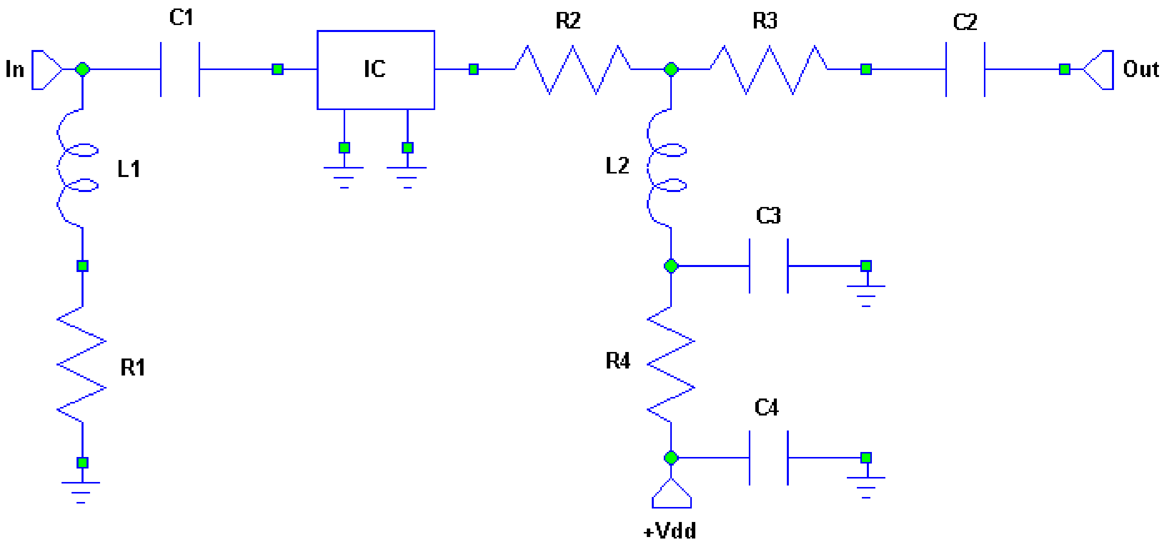


Figure 6.8: Second stage electrical diagram

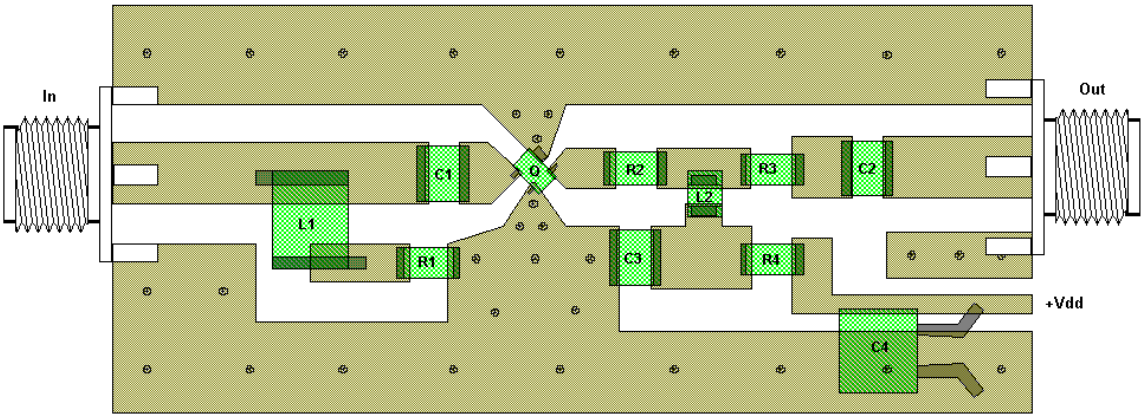


Figure 6.9 : Second stage layout sketch

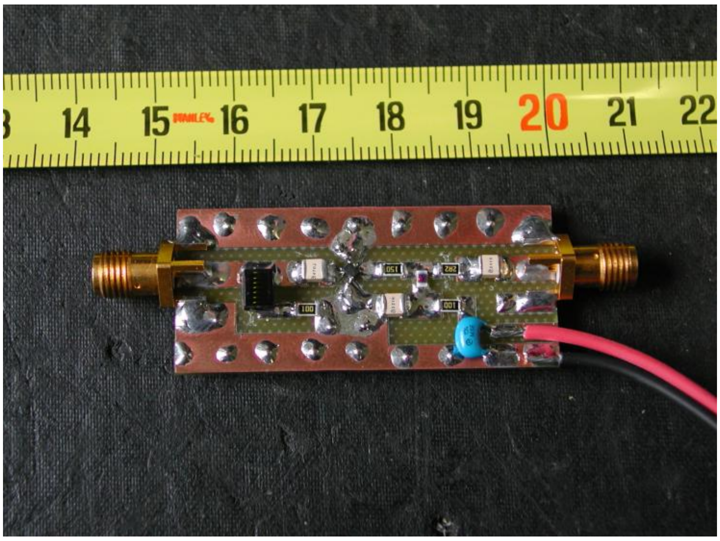


Figure 6.10: Picture of the second stage prototype

The S11 (matching) and S21 parameters are here reported:

S11 = -8.4 dB	S21 = 17.2 dB
NF (system) = 1.45 dB	OIP3 = 29.0 dBm
P1dBin = 3.6 dBm	P1dBout = 19.8 dBm

measured @ 408 MHz

The OIP3 is measured with 2 tones at 407.5 and 408.5 MHz at -19 dBm at the D.U.T. input.

P1dBin = 3.54 dBm, S21 = 17.4 dB @ 405 MHz
P1dBin = 3.67 dBm, S21 = 17.2 dB @ 411 MHz

Figure 6.11 – 6.12 show some graphs with the main characteristics;

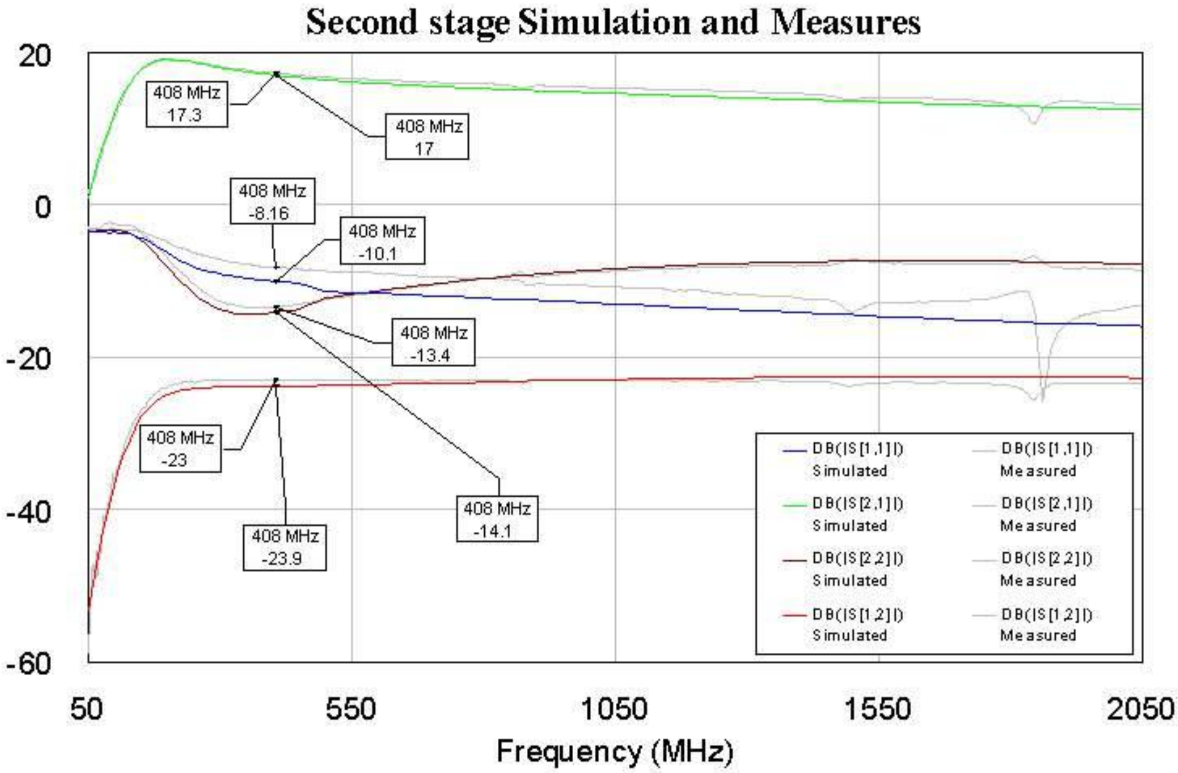


Figure 6.11: Simulation and measure comparison

Figure 6.12: Measured S11 and S21 of the second stage prototype

First Test: In order to test qualitatively the dynamic range of the two stages, they have been cascaded and installed on a N/S reflector without any inter-stage filtering (Figure 6.13 – 6.14)

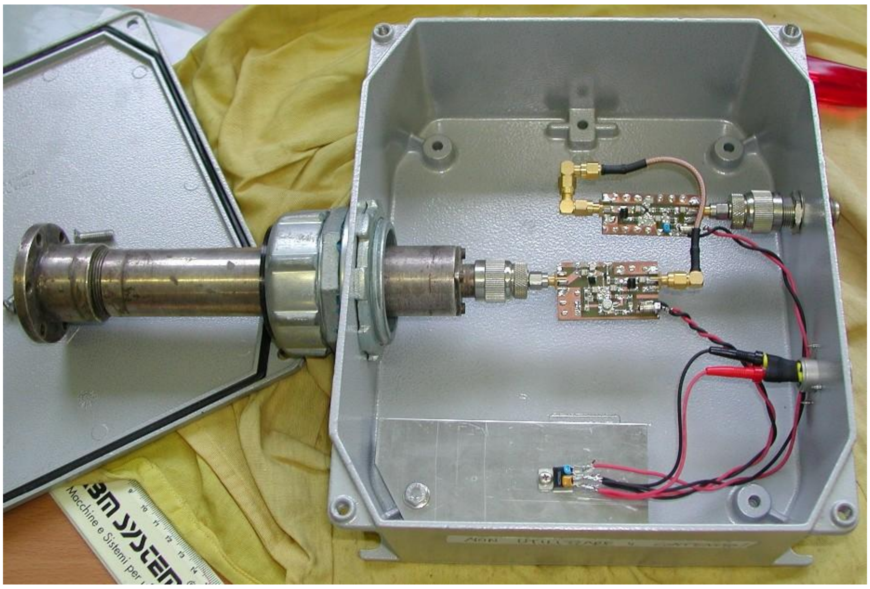


Figure 6.13: View of the two stage prototype without inter-stage filter

Figure 6.14: The under test system installed at the present focal line output

No problems of intermodulation, related to the presence of strong RFIs in the wide band of operation (see Figure 6.15), were found.

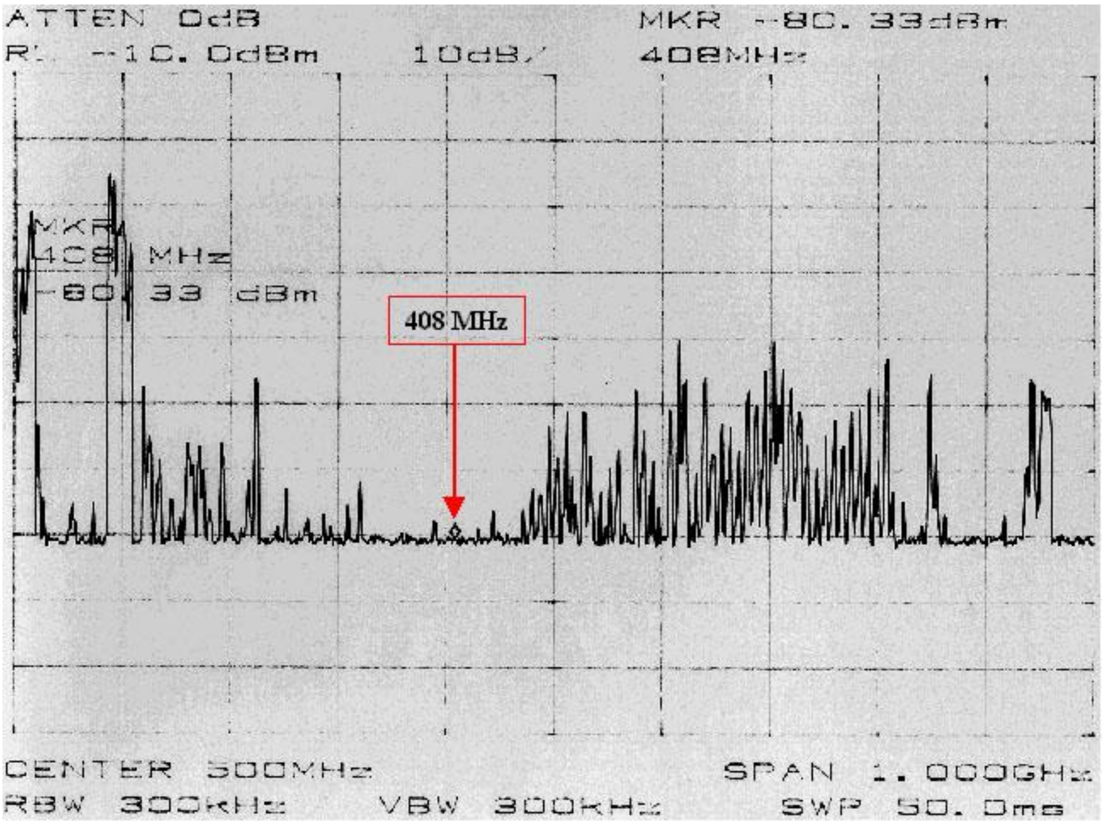


Figure 6.15: spectrum at the input of the above mentioned double stage under evaluation (only one reflector)

This is a very severe test for the dynamic range evaluation. In practice, in order to reduce the intermodulation, an interstage very shaped band pass filter (6 MHz BW centered at 408 MHz) is requested. Since, normally, such filters are very expensive our efforts were devoted to find the cheapest one fitting our requirements. The selected filters (Figure 6.16) for the first evaluation test were the ceramic models SGC S8P - 3A6 – 408, which are low-cost (about 8 Euro) and well shaped.

Center Frequency	408 MHz
Pole	3
3dB Bandwidht (BW)	10MHz
Insertion Loss	5.0 dB MAX
VSWR in BW	1.5 MAX
Ripple in BW	0.5 dB MAX
Attenuation	30 dB min @ 348 MHz and 30 dB Min @ 470 MHz

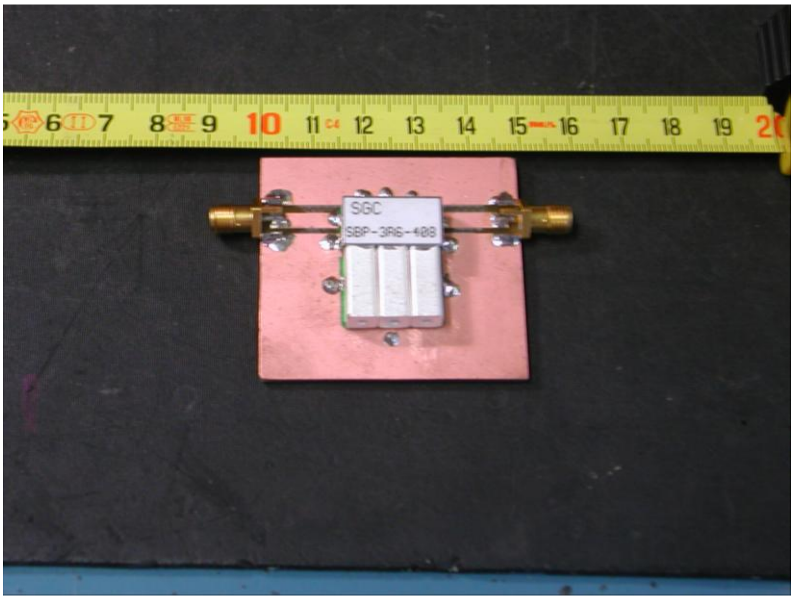


Figure 6.16: Filter evaluation test board

Some measurements were performed with the a Network Analyzer as visible in the following figures.

In a further step we plan to also evaluate low cost SAW filters. Making use of these filters at the RF level, we could have less band shaping problems in the IF or base band stages.

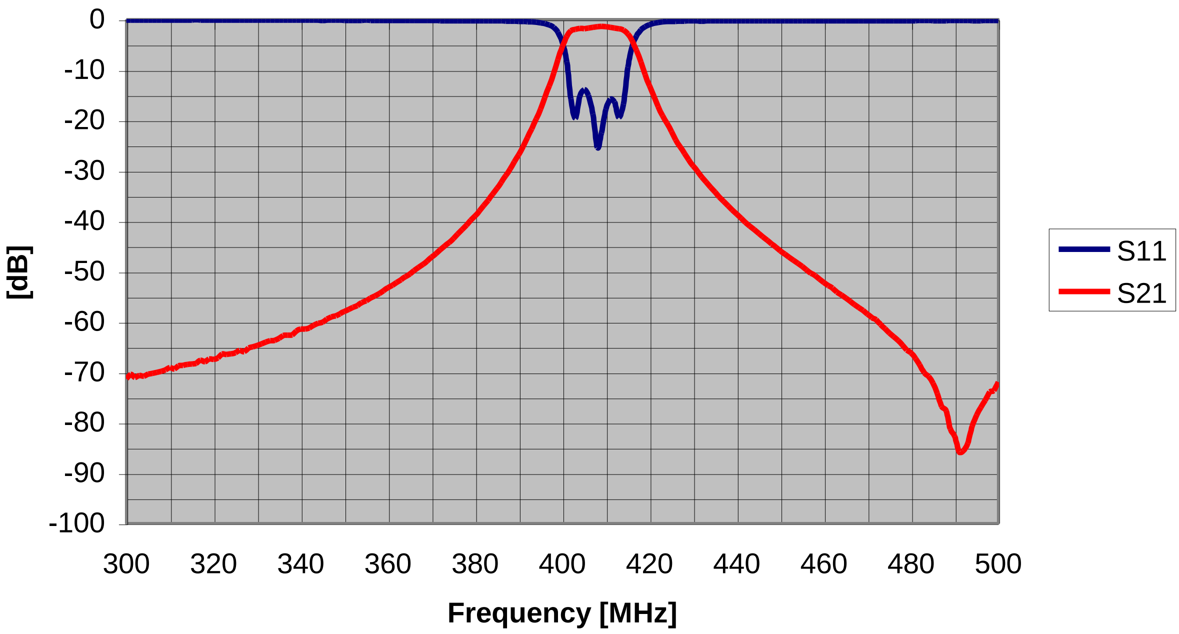


Figure 6.17: Filter Measured S parameters.

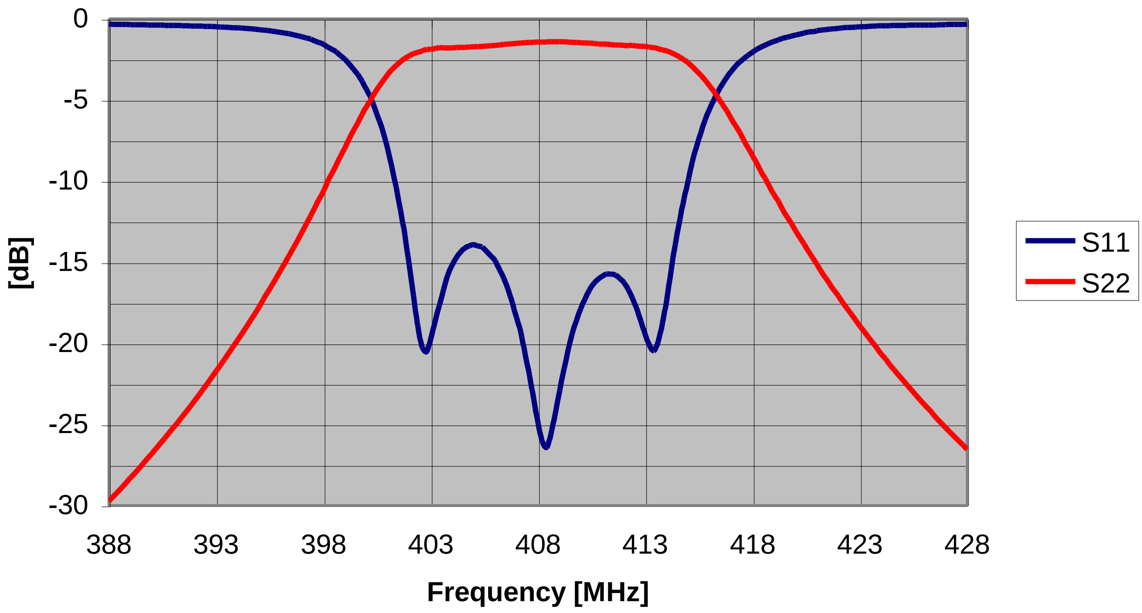


Figure 6.18: Measured S parameters of the filter: zoom at 408 MHz.

The block diagram of the final front end including the inter-stage filters, is reported in Figure 6.19

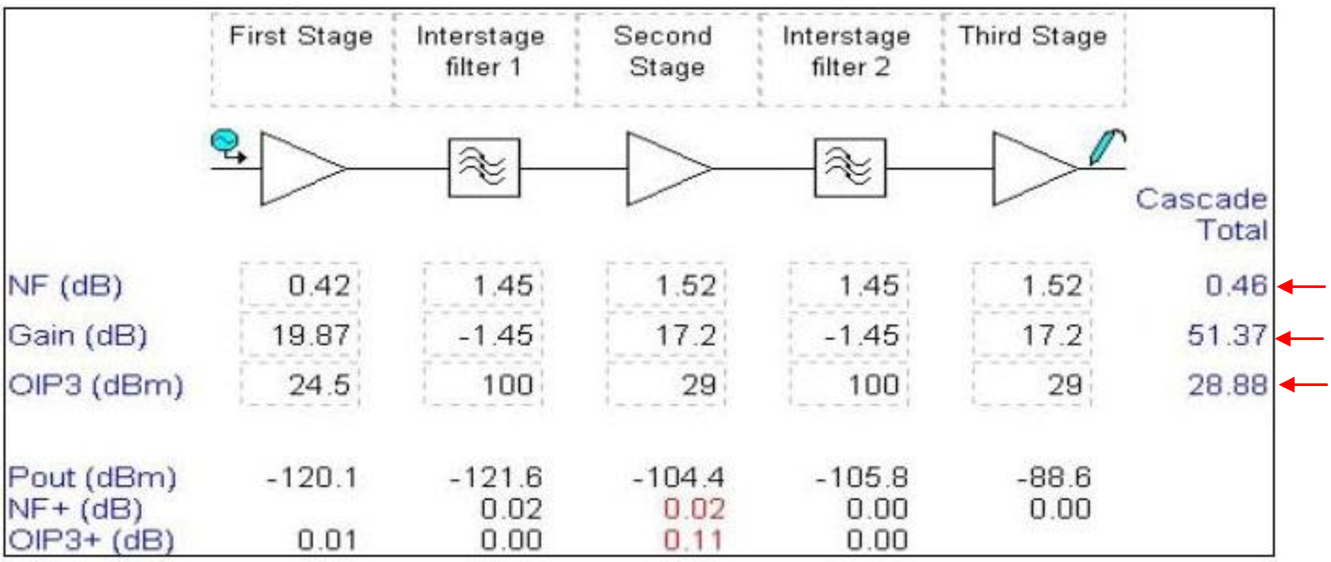


Figure 6.19: Possible front end final version block diagram.

Since the front end performances seems to be very promising, this could represent a standard front end for both the N/S and E/W arms.

The here presented prototypes can be optimized to work on broader band and/or different frequencies. The cost can be greatly reduced by mass production and/or using hybrid solutions.

The Vector Modulator

At present the most used analog phase shifters are the Vector Modulators (VM). A new kind of fully programmable and wide-band VM is under development at the Medicina labs. Its block diagram and the pictorial view of the board are visible in Figure 6.20 and 6.21.

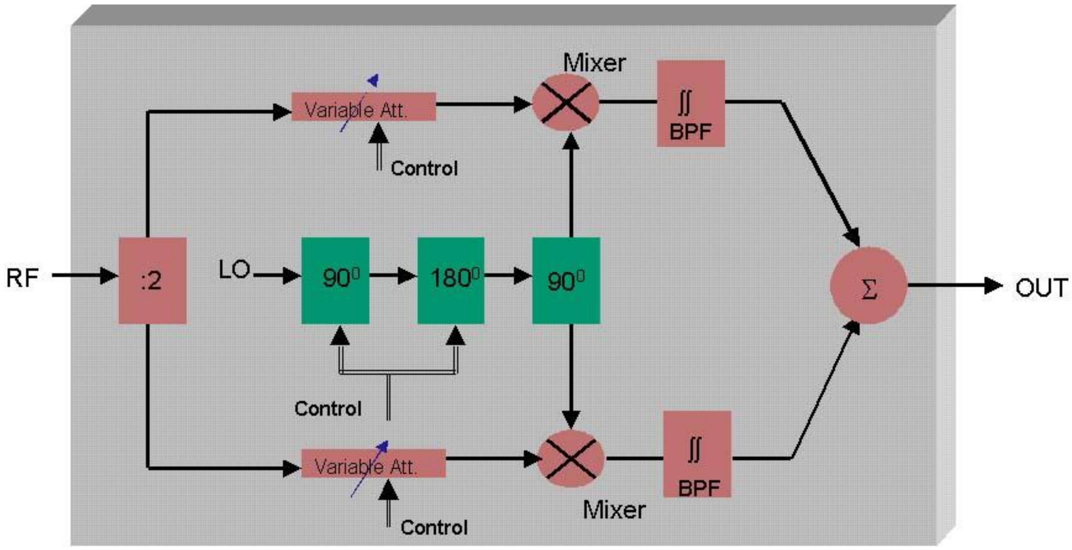


Figure 6.20: Block diagram of the new wide band Vector Modulator

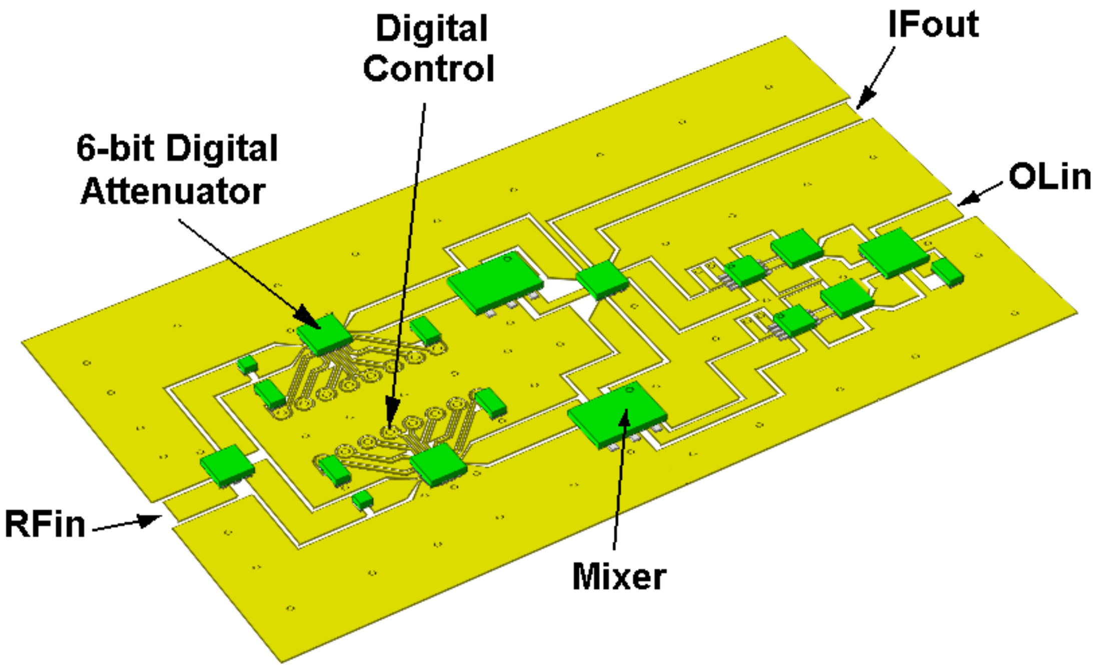


Figure 6.21: Pictorial view of the layout of the VM

In this Vector Modulator the RF signal flows only through attenuators which, being wide-band devices, do not affect the bandwidth. Attenuators programming determines the phase in the first quadrant while the quadrants selection is performed by handling the 90° and 180° steps on the Local Oscillator. In some designs these steps are introduced in the signal paths but, since they depend on the wavelength, they limit the operating bandwidth

7.0: Work plan.

The aim of this proposal is to design, construct, install and test 256 (or 512) receivers in the N/S and a certain number (to be defined) in the E/W one. This technological SKA oriented upgrade of the Northern Cross radiotelescope will be divided in the here described two parallel subprograms.

7.1: Subprogram N. 1, new receivers and related hardware

This subprogram can be implemented and tested using the existing Cross focal lines. It is composed by 4 phases:

- ***1^o Phase: test of 1 receiver on a single cylindrical-parabolic antenna element:*** In this phase a single receiver is installed at the antenna output connector. This allows to test:

- The dynamic range of the front end
- The Base Band Down–Conversion
- The Digitiser
- The Low-cost optical link

This is the first test on the front end performances. It is also useful to better understand the RFIs scenario seen by the antenna. The UHF band is very crowded by televisions (private and national), civil radio services, radio relays station and some meteorological radar.

- ***2^o Phase: test of 4 (or 8) receivers on a single cylindrical-parabolic N/S antenna element:*** In this phase 4 receivers are installed on the focal line (every 16 dipoles) of one single element composing the N/S channel (8 elements per channel). This will allow to test:

- The Vector Modulator / Mixer
- Base Band Down – Conversion
- The digitiser
- The low-cost Optical Link
- First test of beamforming

At this level it is possible to start trying simple algorithms to form and track the beam of a single N/S element on the transit plane in order to gain experience in this crucial aspect. It will be possible also to test the new kind of Vector Modulator/Mixer under development at the Medicina laboratories.

- ***3^o Phase: test of 32 (or 64) receivers on 8 single cylindrical-parabolic antennas (N/S channel):*** In this phase 4 receivers are installed on the focal line of each antenna element composing the single N/S channel (8 elements per channel).. This will allow to test:
- The Vector Modulator / Mixer
- Base Band Down – Conversion
- The RFIs rejection

- The digitiser
- First test of tracking algorithms (beam forming on the transit plane)
- First test of electrical pointing (beam forming on the delta plane)

At this point we would have a N/S channels complete of N receivers per each of the 8 single reflector, we would be able to track on the transit plane and, at the same time, electrically point the single channel on the vertical plane. In this conditions it would be also possible to start the design of algorithms aimed to the RFIs mitigation as the “null beam steering” method.

- ***4^o^ Phase: test of 256 (or 512) receivers on the 64 reflectors (grouped in 8 channels with 8 N/S element each) and installation of N receivers on the E/W arm, Beamforming:*** In this phase 8 receivers will be installed on the focal line of each reflector composing the single N/S channel and N receivers are installed on the E/W focal line. This will allow to test:

- (The Vector Modulator / Mixer)
- Base Band Down – Conversion
- The RFIs rejection
- Test of tracking algorithms
- Beamforming algorithms
- Mulfibeaming development hardware and software

This is the final configuration of the “SKA oriented” upgrade of both N/S and E/W arm.
It will allow to design and test the final beamforming version for the total N/S and E/W beam (beam forming for the transit plane and beam forming on the vertical plane) and RFIs mitigation. Exploiting the more than 20.000 square mt of effective collecting area, accurate tests will be performed.

In all the previous phases the receiver outputs will be base-band converted, digitised and sent to the post-processing room via a low-cost digital optical link under development.

7.2: Subprogram N. 2: New multi-band low-cost printed antennas

A more experiences for SKA could be obtained by introducing new low-cost printed multi-band dipoles installed on the same N/S antenna focal lines. This operation could allow to extend all the previous algorithms to wider operation bandwidth as specifically requested from the SKA consortium. After the Subprogram N.2 completion, receivers at 1420 MHz and 150-250 MHz (Upper side slice-band of the LOFAR) need to be installed. In a near future, the same upgrade could be planned for the E/W arm focal lines.

The Subprogram N.2 is composed by 4 phases:

1^o Phase: Development, simulation, characterisation and prototyping. This phase is developed with the collaboration of the Torino IRITI CNR Institute. It is aimed to the design of the 3 bands printed antennas (on a FR4 substrate) that will be mass produced later for the overall N/S antenna.

2^o Phase: test of the prototype line on a single N/S element. In this phase the prototype of the line is installed on a single cylindrical-parabolic element. It is intended to be tested with the new receivers (see subprogram N.1) and fully characterised.

3º Phase: mass production of the focal lines. This phase is aimed to the mass production of the 4096 multi band dipoles.

4º Phase: Installing the 4096 dipoles and final test. This is the final phase in which we plan to install the 4096 dipoles on the 64 N/S single element focal lines. In this way we will be able to check the overall system at the frequency (408 MHz) considered for the receivers of Subprogram N.1.

8.0: Costs estimation.

The costs estimated below are based on current commercial value of the used devices but they could significantly decrease in the future. We want also to underline that the here considered costs are valid in the case of use of discrete devices. In a future step, we could still reduce the costs with mass production and/or huge hybrid or integration approaches.

1- Cost of a complete single receiver: Since the plan is to construct thousands receivers, it is very important to evaluate the cost of each single receiver (see Figure 8.1).

Front end: the cost of the receiver front end (a 3 stages block labeled as LNA in Figure 81) can be considered to be less than 50 Euro in a discrete devices circuit assembling version. In the following table a more detailed evaluation of the front end single block costs are reported.

First stage	**Ceramic Filter 1**	**Second stage**	**Ceramic Filter 2**	**Third stage**
12	**8.5**	**6**	**8.5**	**6**

The cost of the complete receiver is shown in the same Figure 8.1

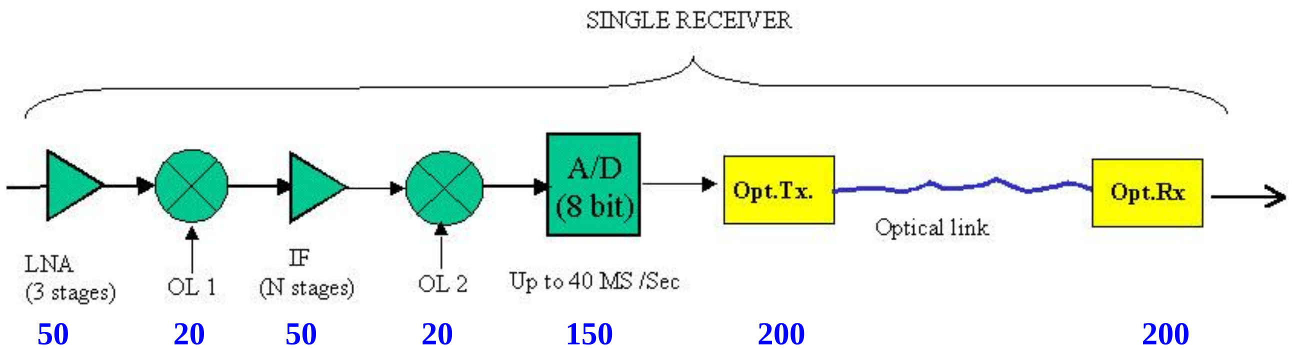


Figure 8.1 Block diagram of a single receiver chain and costs (Euro)

As visible in the figure, the most significant costs are primarily due to both the 8 bit, 50 MS/sec. A/D converter, parallel to serial /formatter, TX / RX digital /optical blocks and serial to parallel /deformatter. Lowering these costs will be the matter of future works and developments. At present the cost of the receiver is **690 Euro** each. The optical fibre links costs are considered apart later.

2- Cost of a single Vector Modulator / mixer (Figure 8.2): In the case we choose the solution in which the use of Vector Modulator /mixer is required at the RF chain level, we have to add its cost to that one of the single receiver. A rough estimation of VM under development at the Medicina labs gives a cost of about **100 Euro.** As in the previous receiver case, the here considered cost is valid in the case of use of discrete devices for a single piece. In a following step, we could still reduce the costs with mass production and/or huge integration approach.

8.1 Cost of Subprogram N.1

A rough estimation of the cost of the total N/S – E/W upgrade is given for 256 **(512)** receivers (N/S) and 768 (E/W). The amounts are expressed in Euro.

N/S *Action Item*	*Sub Total*
➢ 256 **(512)** Receivers	177 K **(354 K)**
➢ 256 x 50 mt Coax.Cable	65 K
➢ Optical link	171 K
➢ IF Hardware	98 K
➢ Computing (DSP, FPGA..)	86 K
➢ Personnel and overhead	481 K
Total	**1078 K (1255 K)**

E/W *Action Item*	*Sub Total*
➢ 768 Receivers	530 K
➢ 256 x 50 mt Coax.Cable	195 K
➢ Optical link	40 K
➢ IF Hardware	76 K
➢ Computing (DSP, FPGA..)	57 K
➢ Personnel and overhead	497 K
Total	**1395 K**

The cost of different solutions can be found by appropriately scaling the total costs.

8.2 Cost of Subprogram N.2

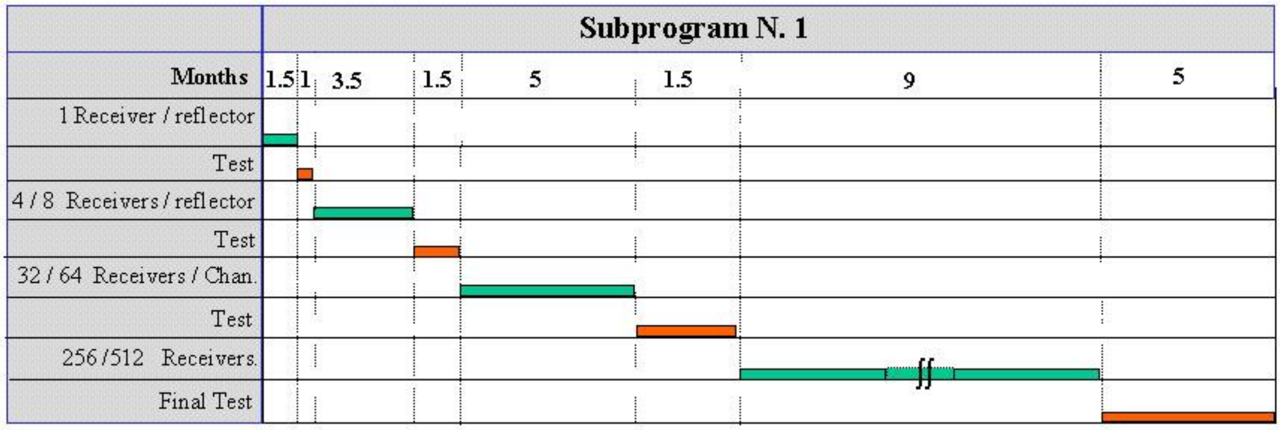
Here following the total costs for the implementation of the Subprogram (costs are given in Euro) are reported:

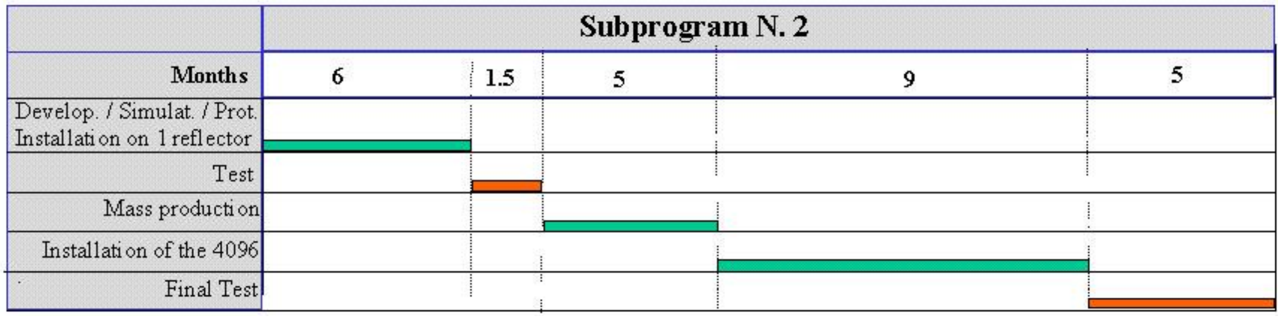
Action Item	*Sub Total*
➢ Developing, simulation Characterisation, Prototyping	140 K
➢ Printed antennas Mass production	159 K
➢ Man power: 4 persons hired & overhead	358 K
Total	**657 K**

Implementation of the 1420 MHz and 150-250 MHz receivers will be argument of future discussions, activities.

9.0 Time Schedule

Since at present we do not know exactly when the upgrade will begin, in the below reported time table we have estimated the number of months needed for each phase.





10. Conclusions:

Let us to summarize here the content of this paper: we consider the Northern Cross Telescope as an extremely good SKA test bed [3]. The use for this purpose of very large and cheap collecting areas (as the filled aperture instruments from the 60s) can appear today suitable due to their flexibility similar to other SKA concepts. The cost per m^2 of the Cross is much lower than the one relative to other kinds of antennas. In addition, the "classic" fan beam of a cylindrical antenna allows a much greater area per beam.

We have just started to investigate on the following topics:

1. A low noise, low-cost, high dynamic range LNA as a front end
2. A low noise, low-cost, high dynamic range LNA as a second and third stage
3. An excellent shaped inter-stage low cost, low insertion loss ceramic filter
4. A new low-cost Vector-Modulator-mixer
5. New low-cost digital optical link
6. Efficient beam forming with new RFIs mitigation algorithms
7. Low-cost multiband printed antennas simulations and design

Some of the above reported blocks have already been constructed and tested as reported in this paper. In our opinion, all of these blocks could be relevant for the SKA engineering group consideration / evaluation. The low cost along with their very good performances could make these stages suitable for mass production, as requested by the SKA project, for the N/S and E/W arms upgrades. Having these new low-cost receivers installed in the Cross telescopes arms would mean to have the possibility of both gaining experiences and developing new algorithms for crucial points as:

- Analog and /or digital beamforming
- Multibeaming
- Antennas array calibration
- RFIs mitigation
- Digital data transmission via low-cost Optical links
- Fast data acquisition
- On line Data Processing

Just a final consideration: the Cross upgrade could give back a great amount of experience in the more crucial and critical aspects constituting the SKA "adventure" along with the result to have still operative one of the few existing large radiotelescope in the UHF band. The so planned upgrade of the Cross antennas could made possible the use of them, separately or together.

✓ **The N/S arm**: it is equivalent to a parabolic 120 m diameter dish, G≈ **52.7** dB (λ=0.735 m)

✓ **The E/W arm**: it is equivalent to a parabolic 160 m diameter dish with, G≈ **54.5 dB**, B (λ=0.735 m)

✓ **The overall Cross (E/W +N/S):it is equivalent to 1/33th of SKA or a parabolic 200 m diameter dish. It has a directivity of about 70 dB and a gain of 56.7 dB**

In conclusion, the Northern Cross radiotelescope is an excellent SKA test bed and its upgrade activity could represent an extremely valuable task that is worthwhile to be faced by the scientific community, to get new experiences for the SKA.

References

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