EMBRACE RECEIVER

(SKADS Task DS5-T1-WP4)

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Sommario

1 INTRODUCTION

The international radio-astronomy community is currently making detailed plans for the development of a new radio telescope known as the Square Kilometer Array (SKA). This instrument will be two orders of magnitude more sensitive and will have a much larger FoV than radio telescopes currently in use. It will operate in the 100 MHz to 25 GHz frequency range. Many institutes around the globe are considering the design of SKA antennas using parabolic and cylindrical reflectors as the collecting area, the properties of which are well known within the radio community. The novel antenna concept proposed by the Europeans for the SKA is the dense aperture array, in which elementary antennas are densely-packed and connected together with beam-forming circuitry. This is the most innovative concept under investigation for the SKA, and it offers unique features and potential opportunities for future growth in radio astronomy.

2 EMBRACE ARCHITECTURE

This demonstrator is denoted as the Electronic Multi-Beam Radio Astronomy ConcEpt (EMBRACE) which is planned as about 300 square metre aperture array with multiple large independent Field of View (FoV) capabilities.

EMBRACE is the technology demonstrator for the European SKA concept. It consists of a 300m^2 aperture array at Westerbork and a 100m^2 aperture array at Nancay.

The main objectives of EMBRACE are to demonstrate the technical and scientific potential of the aperture array concept using a low cost phased array station with the essential Square Kilometre Array (SKA) functionality. It will operate in the frequency band 0.4 - 1.6 GHz and will have at least two independent and steerable beams. An array of such a size can function as a radio astronomy instrument whose sensitivity is reasonably close to that of a standard 20-m diameter parabolic dish. The collecting area also represents a significant percentage (~8%) area of a final individual SKA ''station'' when based on the aperture array concept.

2.1 EMBRACE SYSTEM CONCEPT

The EMBRACE system will be built on similar principles as used for THEA (Thousands Elements Array) . A large number of antenna tiles, each of area around 1 m^2, will form the collecting area. The signals from the integrated elementary radiating elements from each tile will be amplified and initial RF (i.e. analogue) beam forming will be applied. Here a trade-off between FoV and required receivers per square metre is a fundamental issue. This property plays an important role in the optimization of the design for cost. A tile may be split into quadrants, due to the limitations imposed by the use of phase shift control with large instantaneous bandwidth requirements. The outputs of these quadrants are then combined with time-delay units. Digital beam forming will not be integrated at tile level but this digital processing takes place at a central place near the station.

A system level block diagram is shown in Figure 1, indicating the formation of two independent fields-of-view at the tile level and at the aperture array “station” level. Channel selection, digitization and remaining digital station processing is done at a central back-end. The tile beam signals are transported to a central station back-end using analogue RF links. For the analogue link we are pursuing an RF-on-fibre approach where the RF signal modulates a laser directly.

In the current EMBRACE system architecture the approach is to use distributed units with only just the essential functionality and integrating the more complex functions at a central (non distributed) facility. The approach with central receivers and digitisation, has the advantage that the local oscillator and clock signals have to be distributed inside the station back-end cabinet only. For EMBRACE, a low IF receiver architecture has been adopted. After frequency conversion, digitisation takes place at low IF. Next, the filter bank divides the signals in narrow band channels with a bandwidth suitable for the digital beam former given the size of the array. The resulting station output beam signals are transported using digital fibre optics towards a central correlator. The EMBRACE beams will be correlated against the Westerbork Synthesis Radio Telescope (WSRT) signals using the WSRT correlator.

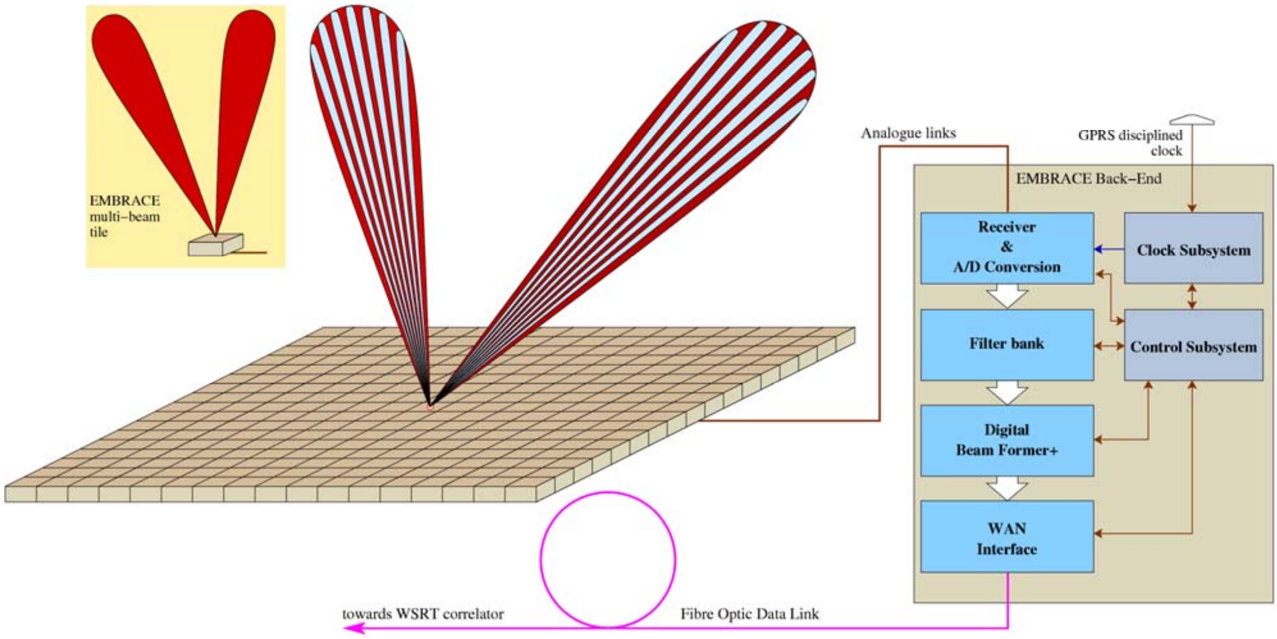


Figure 1: A system level block diagram of EMBRACE showing the formation of independent multiple fields-of-view at both the tile and station level, with processing at the back-end.

2.2 EMBRACE SPECIFICATION

In Table 1 the specifications for the key parameters of the EMBRACE system are given. From the collecting area and a $\lambda_0/2$ spacing at a suitable frequency, it is estimated that in the order of 20,000 antenna elements will be required. The final element spacing should be determined in order to optimize the array performance over the frequency range. The system will be built with tiles approximately of 1x1 metre size although larger building blocks will also be considered.

Frequency range of receiver chain:	400 MHz - 1600 MHz.
Polarisation:	Single polarisation
Physical collecting area	≈ 300 m^2
Aperture efficiency:	>0.80
Electronic scan range:	Full hemispherical
Tsys:	<100 K @ 1GHz (aim for 50 K)
Antenna element phase control accuracy:	3 or 4 bit
Instantaneous bandwidth:	40 MHz
Dynamic range A/D converter:	60 dB
Number of independently tuned FOVs (RF beams):	2
Number of digital beams:	8, of 20 MHz per FoV

Table 1: EMBRACE Specifications

2.3 LOW COST ARRAY DESIGN

The effort regarding the array design shall focus on the selection and optimisation of a suitable antenna element, balancing electromagnetic behaviour, mechanical manufacturability and cost. Cost is an important parameter. A suitable element, known as the Vivaldi radiator has already been identified. Much work on this element has already been completed at ASTRON. The work will therefore concentrate on the integration of Vivaldi elements with LNAs, phase shifters and other components to produce a design which will give low noise and low cost design for the array.

The signal transport distance between element and amplifier has to be small such that resulting loss shall not dominate the noise performance. Therefore, a low noise amplifier has to be placed behind each element, close to element excitation. This implies distribution of amplifiers, so high scale integration is not a suitable technique for the first amplifier in each signal path.

However, low cost design implies the use of high scale Integrated Circuit techniques as soon as possible in the signal path. Therefore, the gain of the first amplifier shall be just big enough to define the system temperature and after the LNA the signals have to be transported to a central place in a tile where Integrated Circuits can be deployed.

A fundamental problem is related to these distributed amplifiers. The gain of an LNA cannot be too big. Too much gain can lead to instability, since the antenna with feed structure connected to the LNA may resemble a perfect resonator at out of band frequencies. Furthermore distortion has to be taken into account. As soon as the received signals are transported to a central place within a tile, high scale integrated circuit technology shall be applied.

2.4 BEAM FORMER HIERARCHY

The ultimate all sky beam former requires the highest density of digital receivers with corresponding demand on digital signal processing and signal transport. By means of RF analogue beam forming the required density of digital receivers can be reduced and therefore balancing costs and FOV. In EMBRACE, RF analogue beam forming is used to reduce the cost while demonstrating flexibility in balancing cost and FOV. Beam forming takes place at different levels in the system. An overview of the terminology used for the beam forming hierarchy is:
Intra tile beam former: The first level of analogue RF beam forming combining elements in a tile;
Inter tile beam former: The second level of analogue RF beam forming combining the beam signals of several tiles;
Digital station beam former: The third level of beam forming. After digitisation, the analogue beam signals are combined into digital station beams.

One of the key aspects of EMBRACE will be the ability to form multiple simultaneous beams. A generic architecture has been identified which will allow the formation of multiple beams. Only two beams are considered for realisation, without loss of any generality, i.e. more beams can be integrated in a tile by scaling the beam former. It may be convenient to combine tile beams at RF level at a second level of beam forming. Inter tile beam formers may be used to further reduce the number of required digital receivers.

The electronic steering and beam-forming creates the possibility of generating multiple independent fields-of-view, which makes the dense aperture array antenna a multi-user instrument, a very important aspect for a radio astronomy instrument of the size and cost of the SKA. The effective observing time therefore can now be expended without the loss of sensitivity simply by providing more electronics and computing power to create more beams.

2.5 EMBRACE TILE ARCHITECTURE

The tile provides the physical area to receive the incident electromagnetic waves in the required frequency range with a single polarisation. It consists of the receiving elements, low noise amplifiers and phase shifters as well as the power combiner/splitter. Figure 2 shows how the 4-elemental radiators are combined with 1:2 way RF power splitter, two phase shifters per radiator and further 4:1 power combiners to produce a 2 beam configuration.

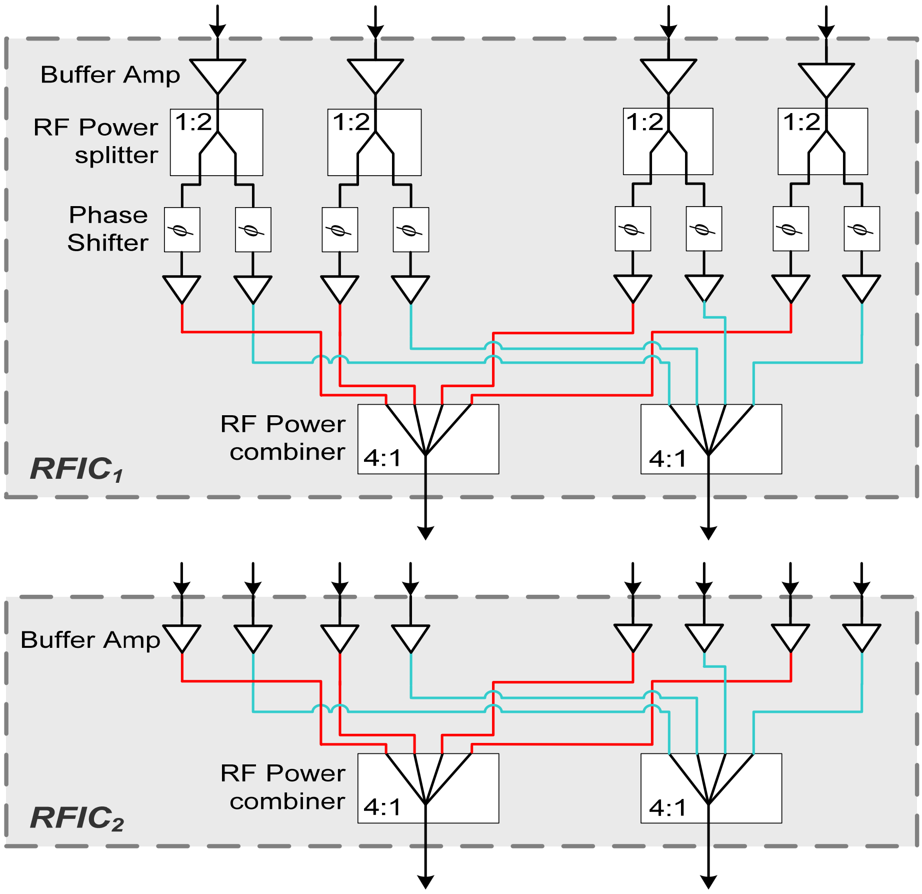


Figure 2: 4-radiator configuration for producing two RF beams

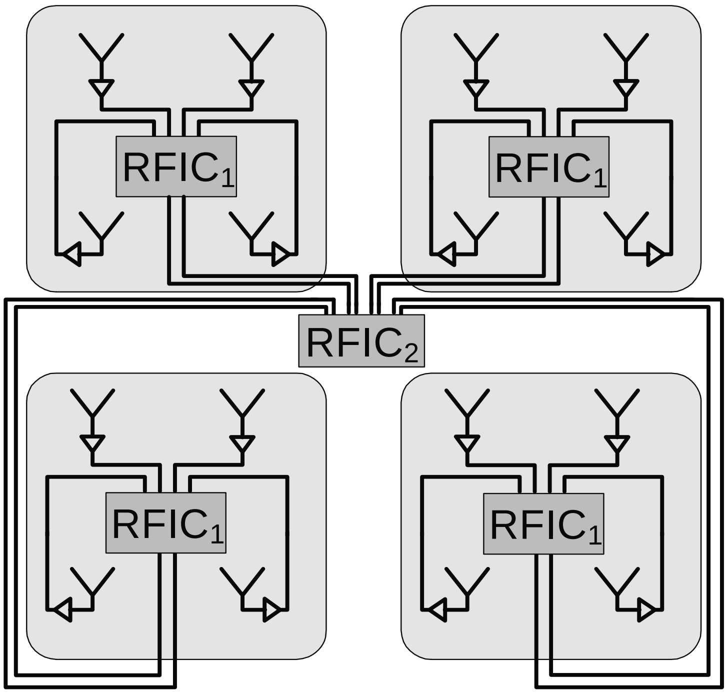


Figure 3: Four of the 4-radiator configuration

The 4-radiator configuration shown above now forms a building block for combining rest of the radiators within the tile. The four of the 4-radiator configurations are now used with a further 4:1 combiner and amplifiers, combine 16-elemet within the tile as shown in Figure 3.

The sixteen-element arrangement is then further combined to connect all the 64 radiators within a tile as shown in Figure 4. producing two RF beams. There is no loss of generality in producing only 2 RF beams as the concept can be easily be extended to produce 4 or more beams.

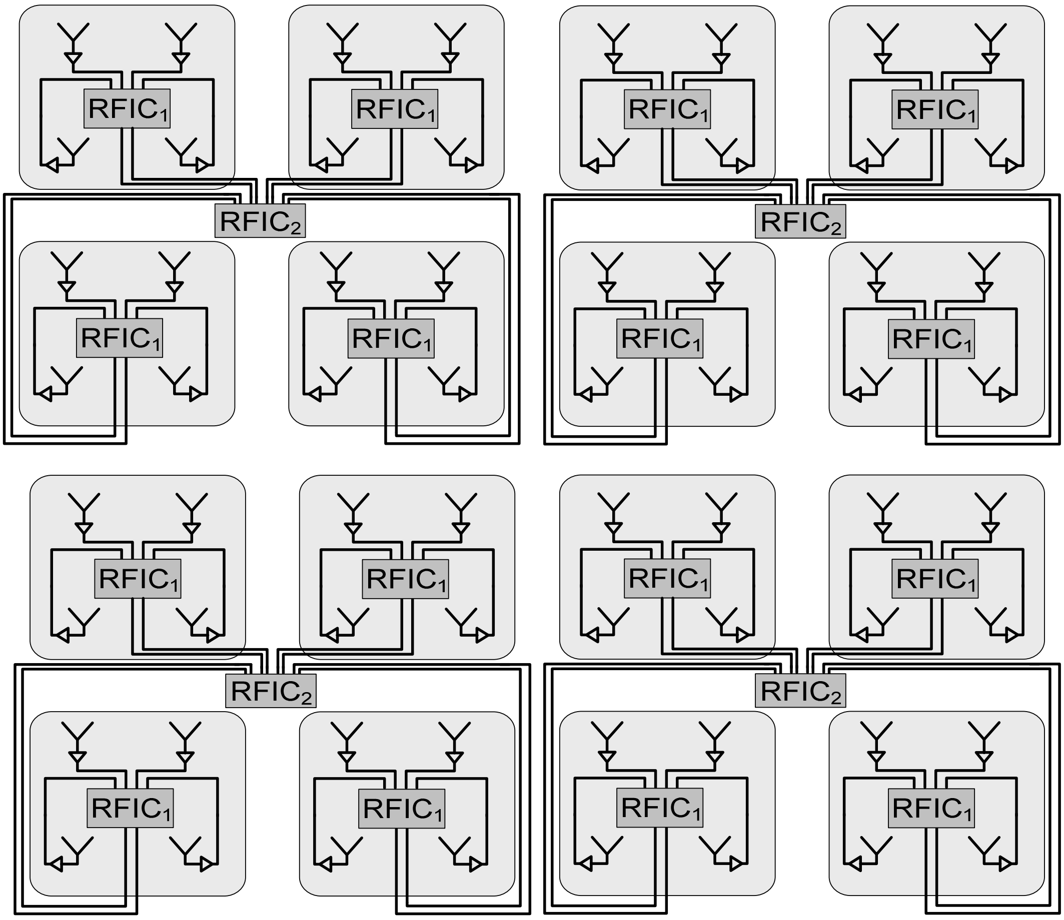


Figure 4: Four of the sixteen-element radiator configuration

In Figure 5 a functional block diagram of the EMBRACE architecture which focuses on the data flow from the tiles up to and including the remote station processing boards is provided. Tiles at the left hand side are denoted as the front end subsystem. A tile provides two RF beams at its output denoted respectively A and B beam. These RF signals are transported over coaxial cables towards the back end subsystem situated at a central place at each station. From RF architectural point of view, it is preferable to have a setup with separated back ends, for beam A and the beam B respectively. The digital processing system will be tailored to this requirement resulting in a resilient configuration providing two independent digital beam processing sub systems, as shown in Figure 5.

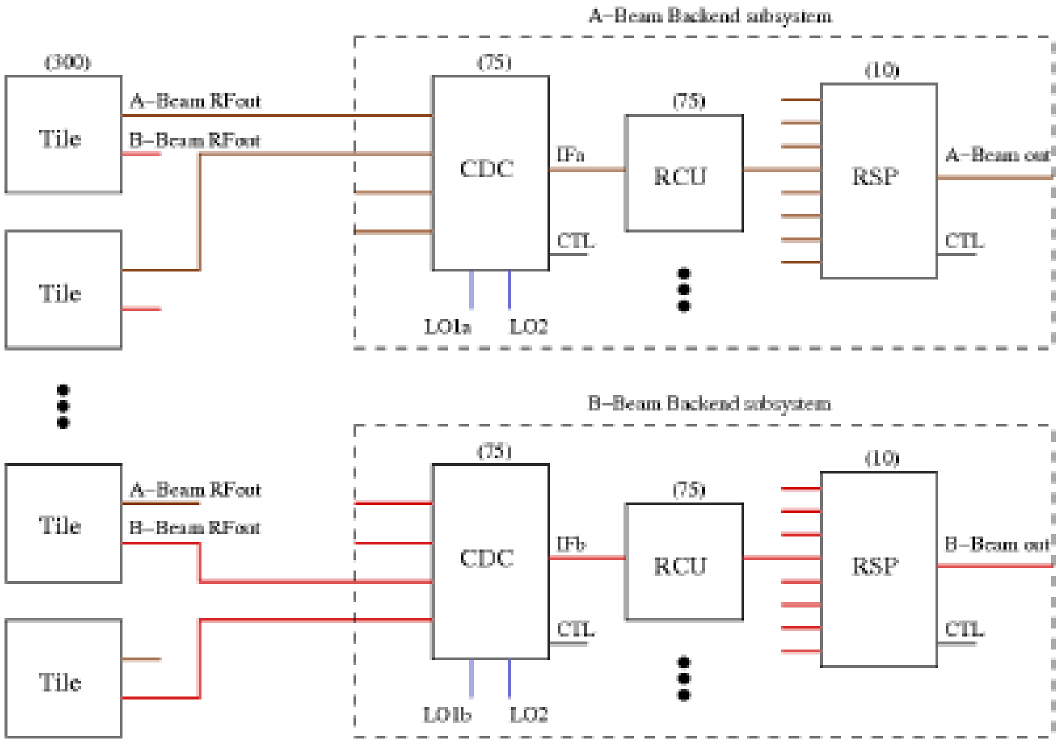


Figure 5: General EMBRACE schematic signal path

The Digital Processing will be based on the LOFAR station architecture, however adaptations will be required. The WAN system from the LOFAR station is reused as well for signal transport to the Interfacing unit. This unit will provide the interfacing between the EMBRACE system and the correlators at Westerbork and Nancay.

Besides the signal path, the station control system from LOFAR is reused as well, however adaptations are needed to support the new LO distribution system and the control of the antenna tiles. The Control system is a Linux based system running on a standard PC with a local maintenance interface. No interface to a higher level Operation and Maintenance system is planned at this time. The LO and Clock system consists of a 200MHz clock distribution system which is used by the AD converters on the Receivers and as a system clock for the Digitial Processing. The LO distribution is used to convert the EMBRACE receive band (500-1500MHz) to the 100-200MHz band, with an IF frequency around 3GHz.

2.6 EMBRACE cost/performance perspective

In the Figure 6 EMBRACE architecture is shown. From a cost/performance perspective, the main focus will be on the Tile Mechanics, Front End/Antenna and Receiver subsystems due to the sheer number of units in the system.

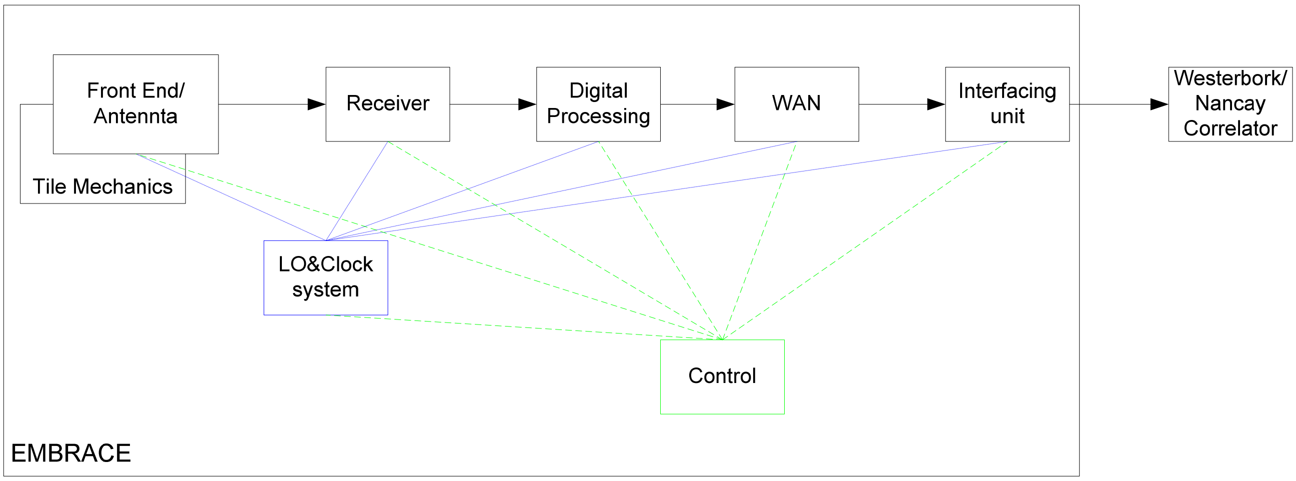


Figure 6: EMBRACE architecture overview

The Embrace Design Task consists of seven sub – systems work packages. They are:

1. Systems
2. Front End
3. Signal Transport
4. Receiver
5. Digital processing
6. Control
7. Mechanical

EMBRACE sub-system tasks are divided between the European partners, so the international flavour of the project is inherent. The main partners in this task are the OPAR, INAF(DS5-T1-WP4) and MPiFR, as well as ASTRON.

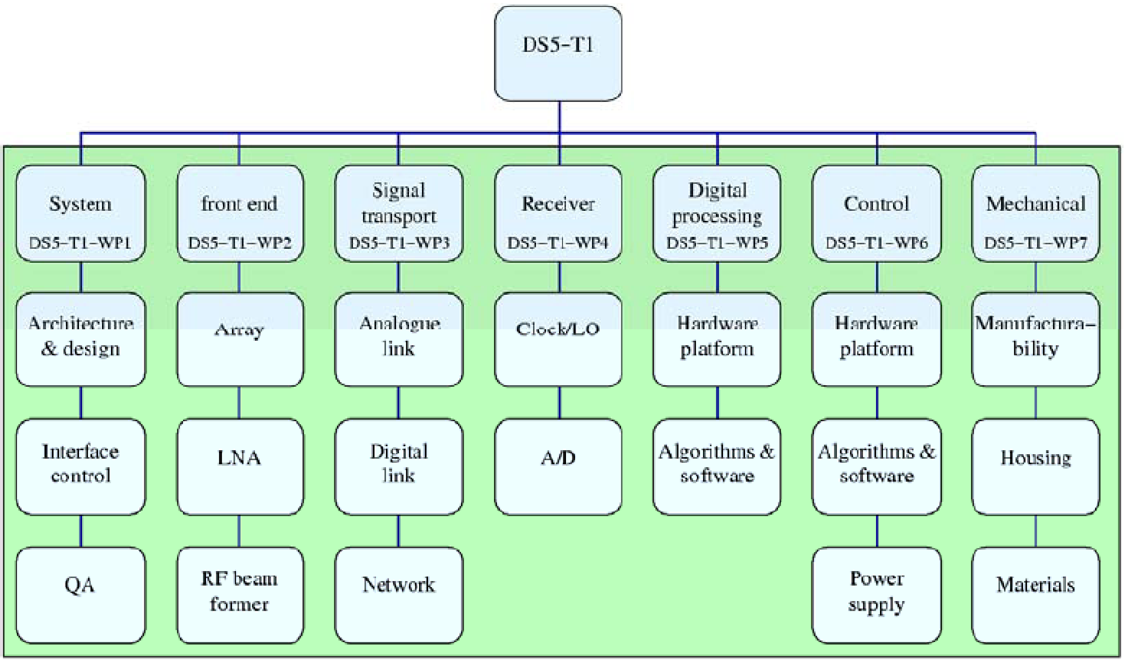


Figure 7: EMBRACE Tasks Design

3 General Description of INAF RECEIVER

The EMBRACE RECEIVER is a low cost, performing and reliable 400-1600MHz tunable double down conversion unit to 100-200MHz IF bandwidth. The architecture, LO frequencies and RF, IF amplifiers/ filters have been selected to provide optimal noise figure, intermodulation products, dynamic range and spurious free performance. Selectivity Filter bank is incorporated to avoid undesired interferences and increase the dynamic performances. To select the right filter a control signal TTL/Open collector/dip Switched must be provided. This receiver includes PAD attenuators and equalization stages to flat the received bandwidth as better as possible.

3.1 FUNCTIONAL BLOCK DIAGRAM

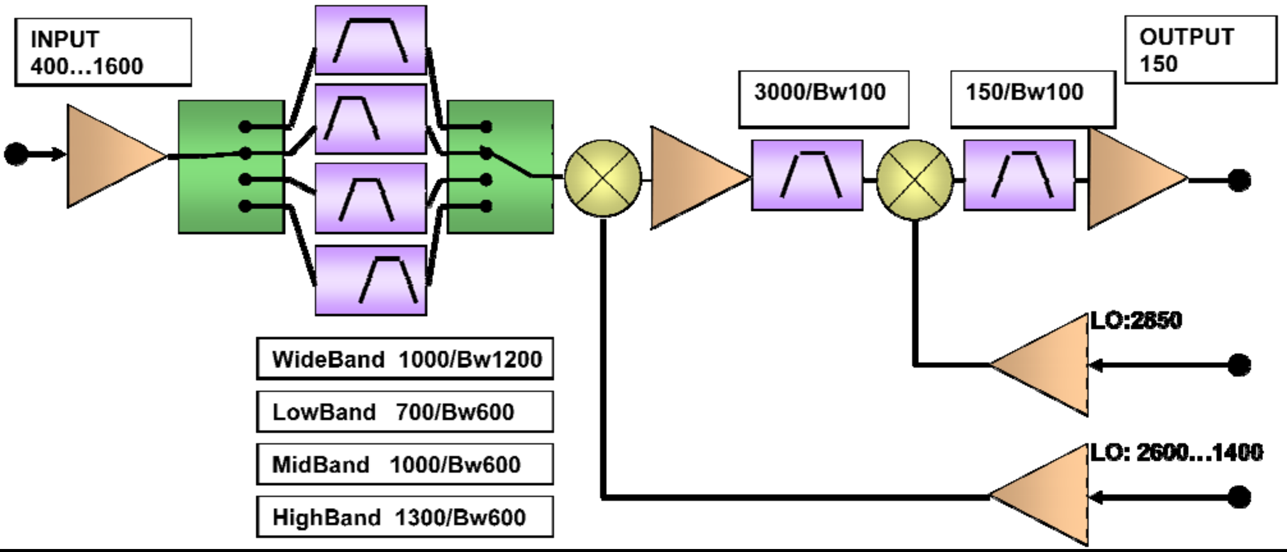


Figure 8: EMBRACE receiver general architecture

The frequencies of local oscillator and the architecture of conversion (Upper Conversion+ LSB Down Conversion) have been chosen to minimize the undesired spurs, harmonics and intermodulation products in each IF section of the receiver.
In the table below, we list the key specifications gave us from ASTRON colleagues to satisfy as goal at the end of the EMBRACE receiver project.

Key specifications

Frequency Range:	400-1600 MHz @3dB
Input noise density:	-151 dBm/Hz
Noise Figure:	< 10 dB
Input IP3:	> 8 dBm
Input IP2:	> 28 dBm
Input Damage Level:	> 10 dBm CW
Input Return Loss:	> 15 dB
Dynamic Range:	> 60 dB
Image Rejection:	> 80 dB

Table 2: EMBRACE Receiver goals

Considering the time schedule very short for designing the receiver we adopt a Rapid Prototyping technique. It consists as an iterations between simulation and measures to reach as soon as possible the goal. This approach permits to verify if any critical part has been designed correctly or are necessary any changing.
Several fixtures of the most critical subparts of the receiver have been done and measured.
From the original design this technique underline it is necessary to have a RF equalizer to compensate the mixer conversion losses and an equalized LO amplifier to drive with constant power the L port of mixer.

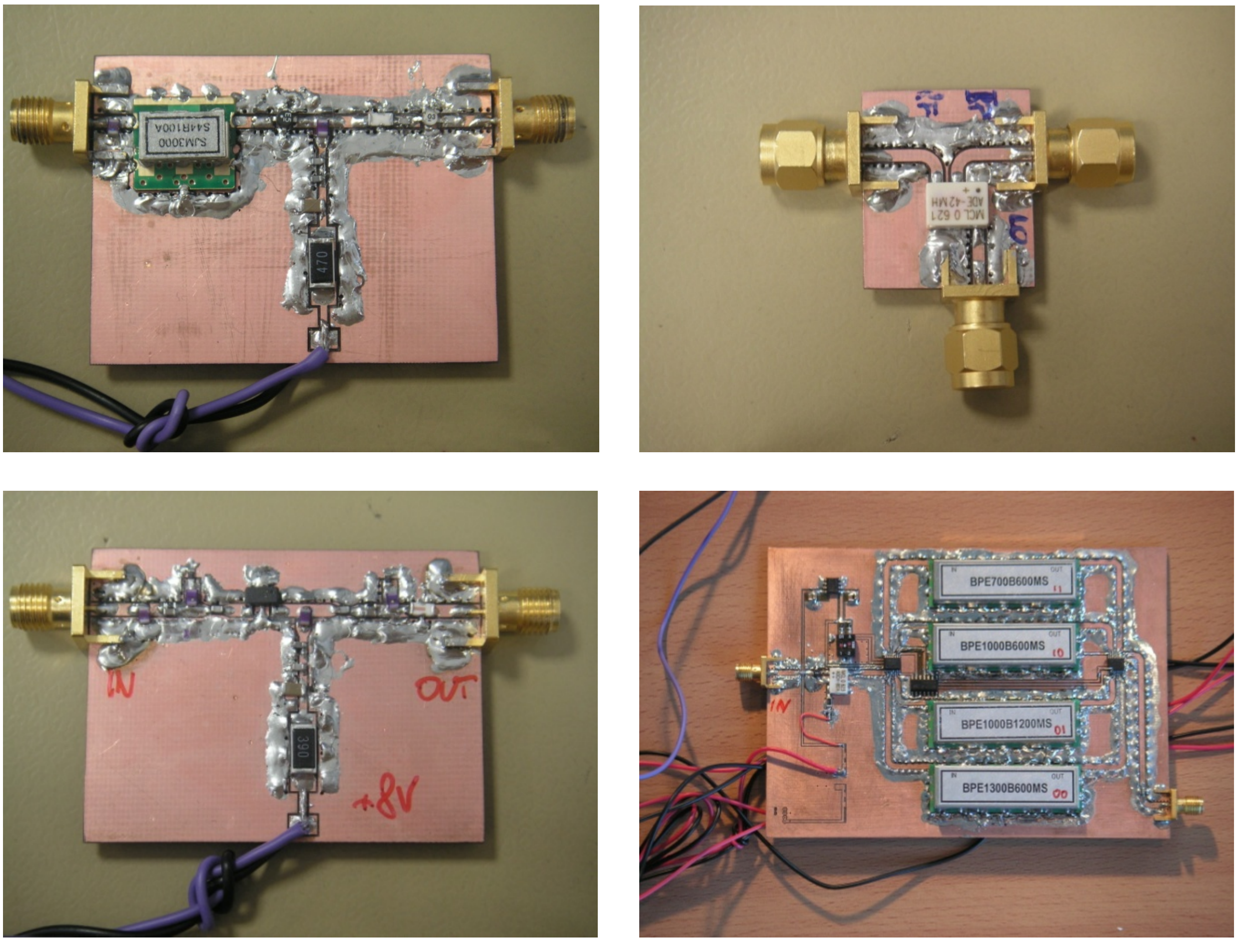
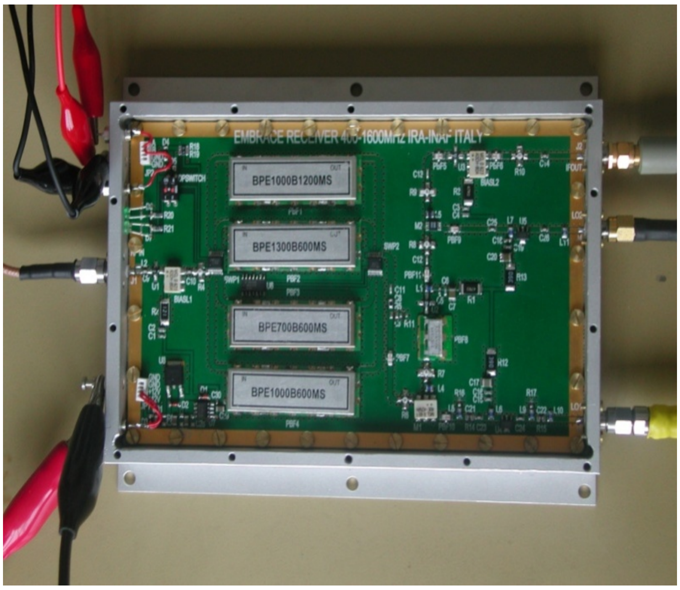


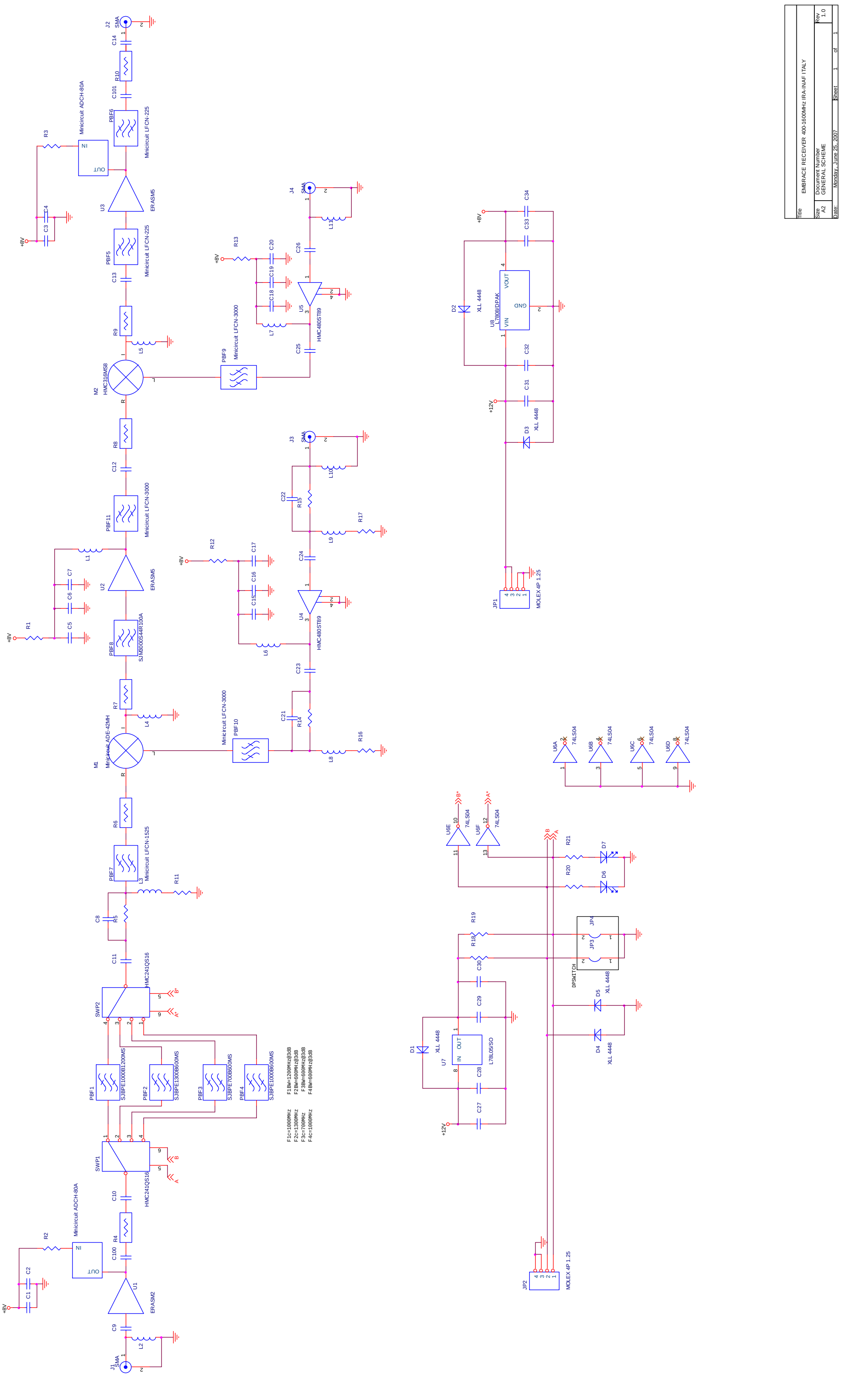
Figure 9: Some fixtures realized for EMBRACE receiver. From upper left; IF1-IF2 Section, MIXER UPC, Driver OL1, RF section

4 Main Feature



- RF 400-1600MHz
- IF 100-200MHz
- LO1 2600-1400MHz
- LO2 2850MHz
- Double Conversion
- Input ports ESD protected with inductor
- RF/IF equalizazion
- RF High Selectivity Filter bank
- TTL/OC/M controls
- Low Power for driving LO Typ 2dBm
- No Phase Noise degradation
- High Reliability
- Substrate FR4, 1.6mm, 1Oz. Cu
- Eurocard Standard Dimension (160x100)

5 Schematic of the receiver[1]



[1] The value of some PADs could be evaluate during test phase in order to tune better the performances of the whole receiver

6 *Bill of Material*[2]

Item	Quantity	Reference	Part
1	2	BIASL1,BIASL2	Minicircuit ADCH-80A
2	11	C1,C3,C9,C10,C11,C12,C13, C14,C20,C100,C101	Murata 150pF GRM1885C1H151JA01
3	2	C2,C4	Murata 10nF GRM2195C1H103JA01
4	3	C5,C17,C18	Murata 2.2uF GRM32RR71E225KA01
5	3	C6,C16,C19	Murata 1nF GRM1885C1H102JA01
6	2	C15,C7	Murata 10pF GRM1885C1H101JA01
7	3	C8,C21,C22	Murata 3pF GRM1885C1H3R0CZ01
8	4	C23,C24,C25,C26	Murata 100pF GRM1885C1H101JA01
9	4	C27,C29,C31,C33	Murata 1uF 25V GRM31MR71E105KA01
10	4	C28,C30,C32,C34	Murata 100nF GRM188F51E104ZA01B
11	5	D1,D2,D3,D4,D5	XLL 4448
12	2	D6,D7	OSRAM SFH 421
13	2	JP1,JP2	MOLEX 4P 1.25
14	2	JP3,JP4	JUMPER2
15	4	J1,J2,J3,J4	SMA
16	3	L1,L4,L6	COILCRAFT 0805CS220XJB
17	1	L2	COILCRAFT 0805CS180XJB
18	3	L3,L8,L9	COILCRAFT 0805CS150XJB
19	1	L5	COILCRAFT 0805CS221XJB
20	1	L7	COILCRAF 0805CS100XJB
21	1	L10	COILCRAFT 0805CS330XJB
22	1	L11	COILCRAFT 0805CS390XJB
23	1	M1	Minicircuit ADE-42MH
24	1	M2	HMC316MS8
25	1	PBF1	SJBPE1000B1200MS
26	1	PBF2	SJBPE1300B600MS
27	1	PBF3	SJBPE700B600MS
28	1	PBF4	SJBPE1000B600MS
29	2	PBF5,PBF6	Minicircuit LFCN-225
30	1	PBF7	Minicircuit LFCN-1525
31	1	PBF8	SJM3000S44R100A
32	3	PBF9,PBF10,PBF11	Minicircuit LFCN-3000
33	2	R3,R1	R47 2512
34	1	R2	R120 2512
35	6	R4,R6,R7,R8,R9,R10	ATTENUATOR
36	6	R5,R11,R14,R15,R16,R17	R47 0603
37	2	R12,R13	R39 2512
38	2	R19,R18	R100 0805
39	1	R20	R75 2512

2 C100 and C101 are bugs fixed in the prototype, so they aren't present on this layout board.

40	1	R21	R75 0805
41	2	SWP1,SWP2	HMC241QS16
42	1	U1	ERASM2
43	2	U2,U3	ERASM5
44	2	U5,U4	HMC480ST89
45	1	U6	74LS04
46	1	U7	L78L05/SO
47	1	U8	L7808/DPAK

7 RECEIVER General SPECIFICATIONS

INPUT/OUTPUT PORTS SPECIFICATIONS

Parameters	***Units***	***Minimum***	***Typical***	***Maximum***
RF Frequency	MHz		500-1500	400-1600
Input noise density	dBm/Hz		-151	
RF Return Loss	dB	11	15	
LO1 Frequencies	MHz		1500-2500	2600-1400
LO1 Return loss	dB	9	15	
LO1 Drive Power	dBm	0	+2	+5
LO2 Frequency	MHz		2850	
LO2 Return Loss	dB		14	
LO2 Drive Power	dBm	0	+2	+6

DC BIAS

Parameters	***Units***	***Minimum***	***Typical***	***Maximum***
Vcc	V	10	12	15
I	mA	370		450
Ripple Rejection@50Hz	dB	59	75	

RECEIVER RF SPECIFICATIONS

Parameters	***Units***	***Minimum***	***Typical***	***Maximum***
Gain	dB	24	25	27
Ripple	dB		±1	
NF	dB	8	9	10
IIP_3	dBm		-1@550MHz 0@850MHz 3@1450MHz	
Output 1 dB Compression Point	dBm		16@550MHz 17@850MHz 17.5@1450MHz	
Image Rejection	dB		>80dB[3]	

FILTER BANK[4]

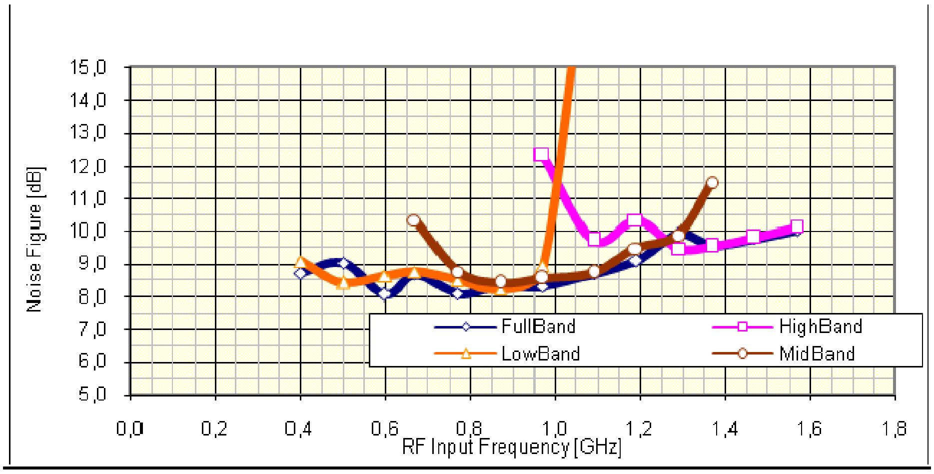
Central Frequency (MHz)	***Bandwidth@3dB (MHz)***	***Rejection@20dB***	***Digital control***	***Notes***
1000	1200	RF1c±750MHz	00	Full Band
1300	600	RF2c±400MHz	01	High Band
700	600	RF3c±400MHz	10	Low Band
1000	600	RF4c±400MHz	11	Mid Band

[3] Considering a Lofar-Like Filter in front of ADC

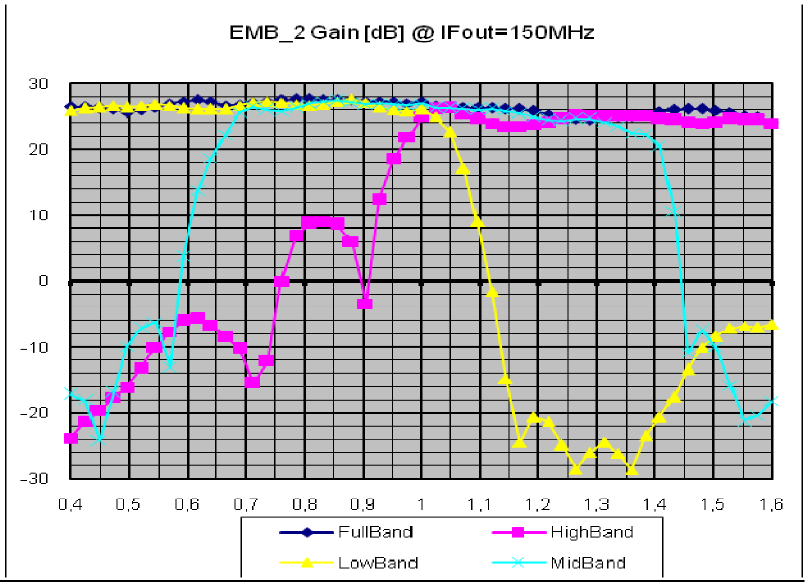
[4] To select the right channel control signals TTL/Open collector/dip Switched must be provided.
For TTL controlling, remove the dip-switch and the pull-up resistor and the Dip-Switch.
For Open collector controlling, remove or open the dip-switch.

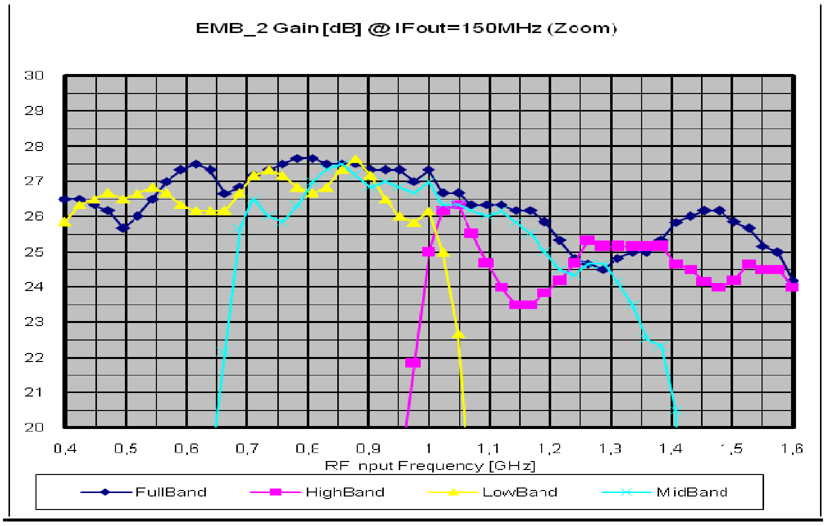
8 *Typical Electrical Performances*

Noise Figure

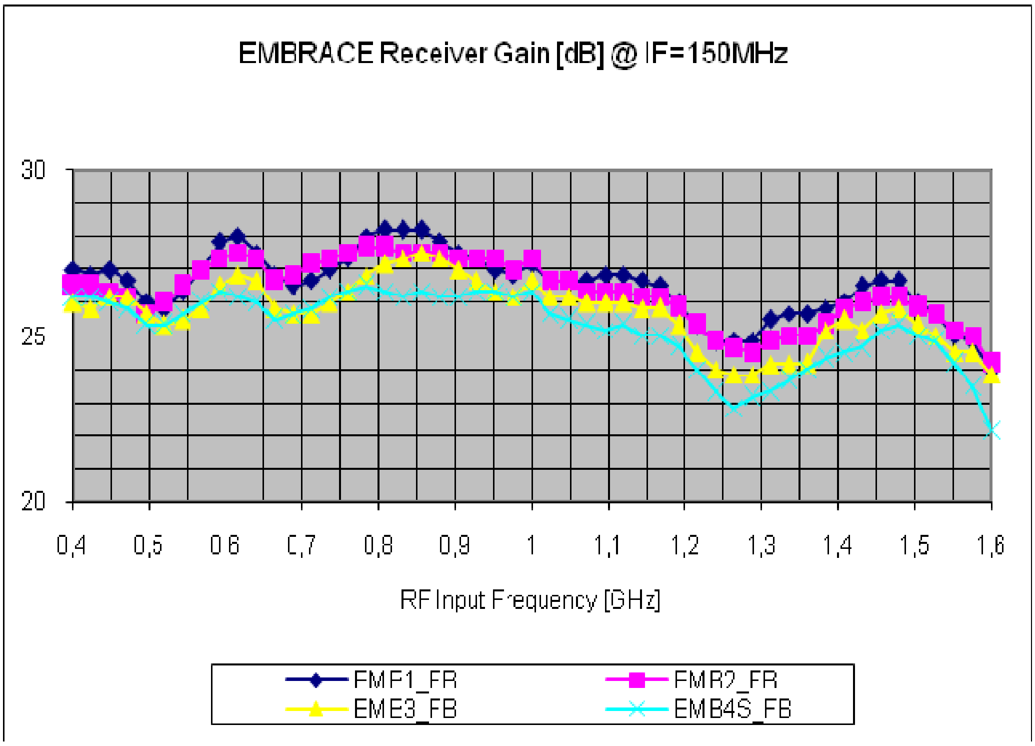


Gain Vs. Frequency

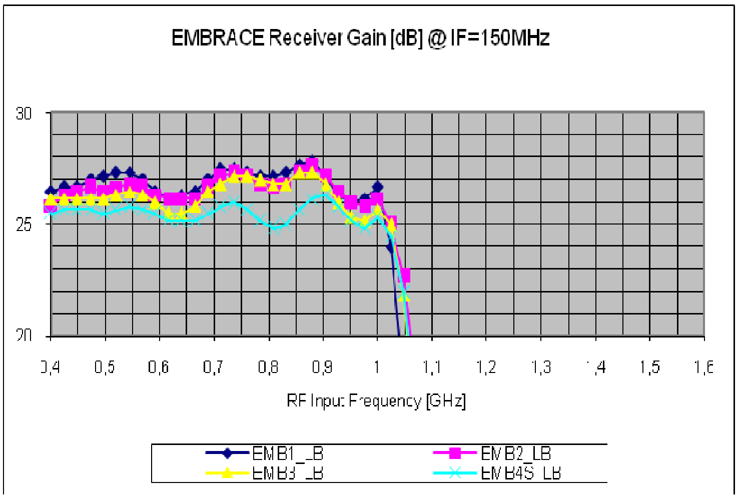


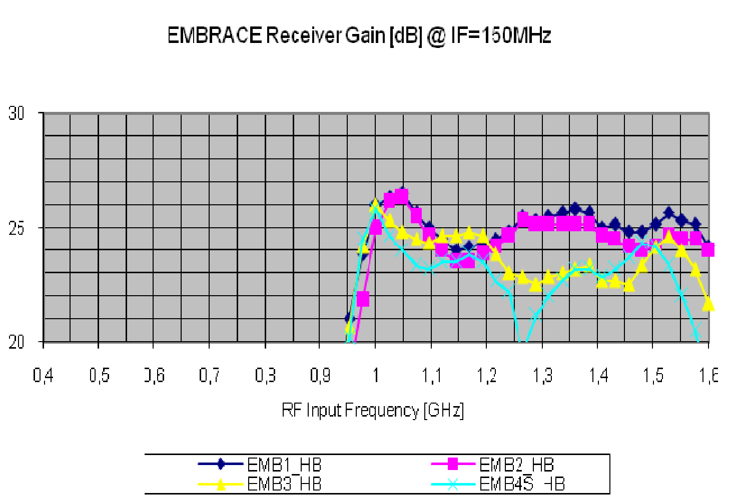


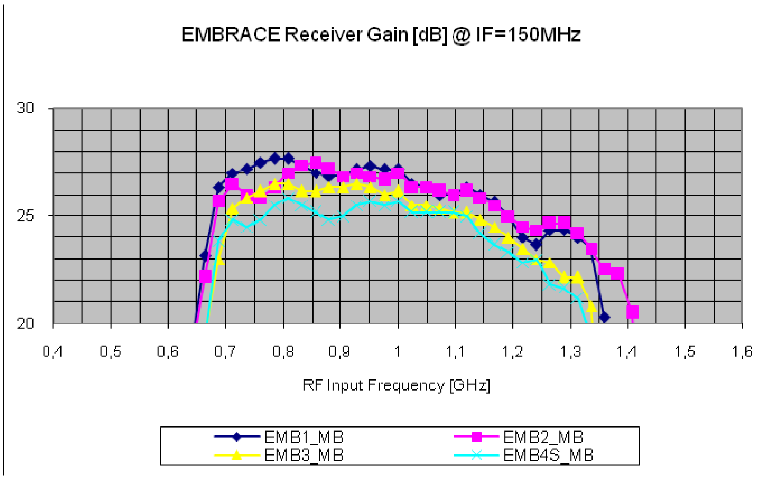
Comparision Gain Vs. Frequency between 4 prototypes full band



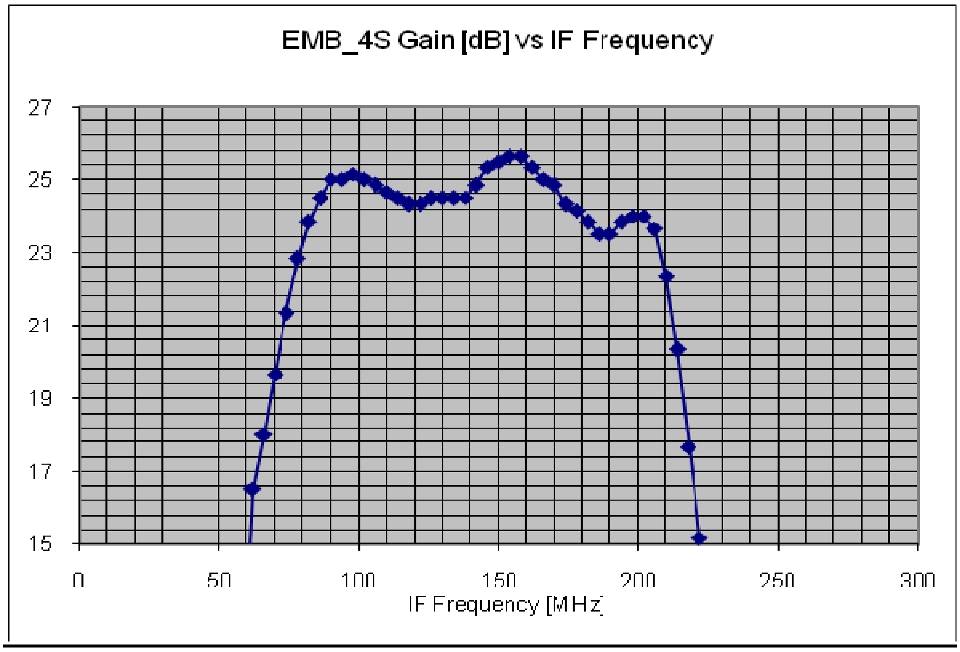
Comparision Gain Vs. Frequency between 4 prototypes High, Low, Mid band





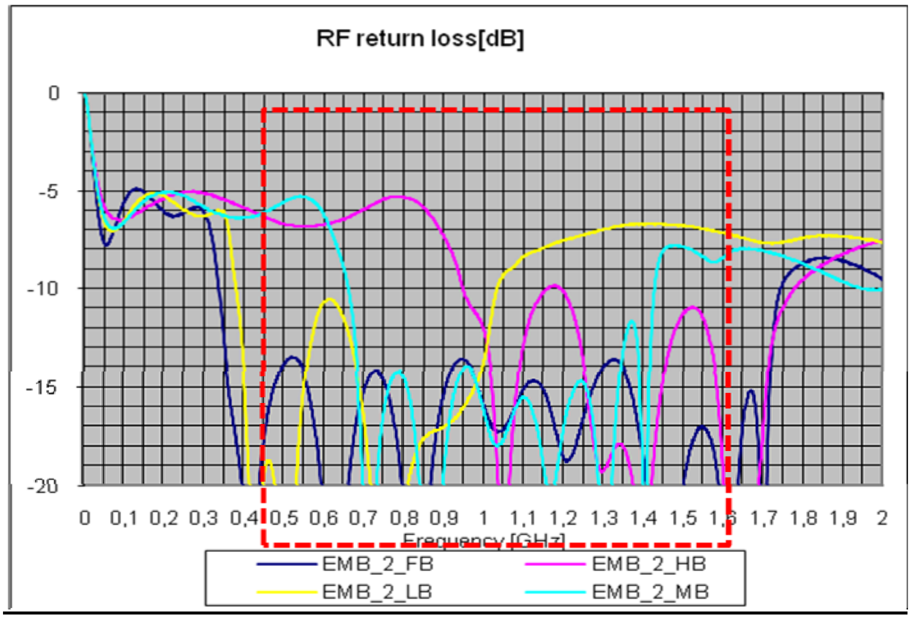


Gain Vs. frequency (Fixed LO1, Swept RF)[5]

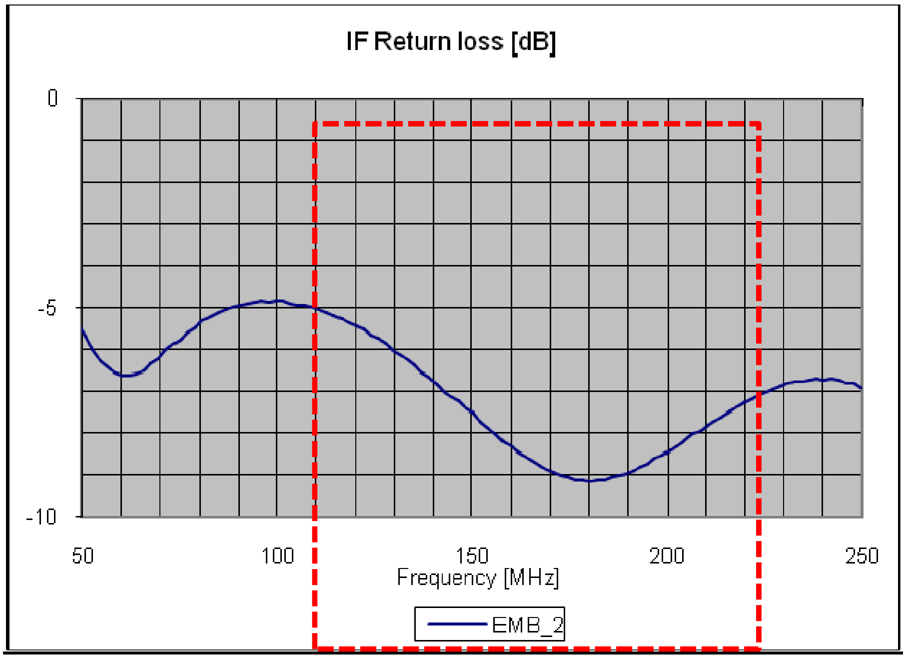


[5] RF=550-750MHz; LO1=2350MHz

RF return loss[6]

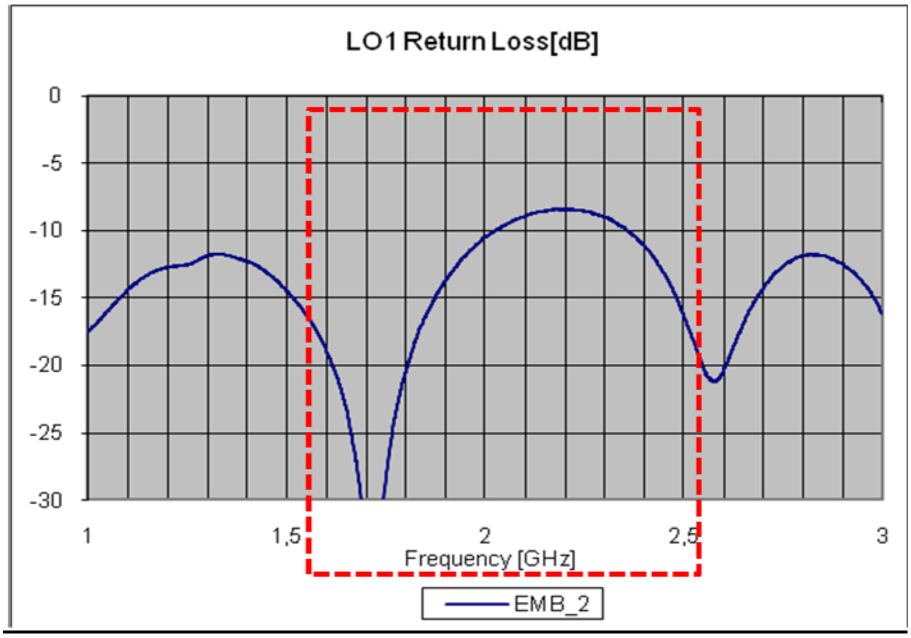


IF Return Loss

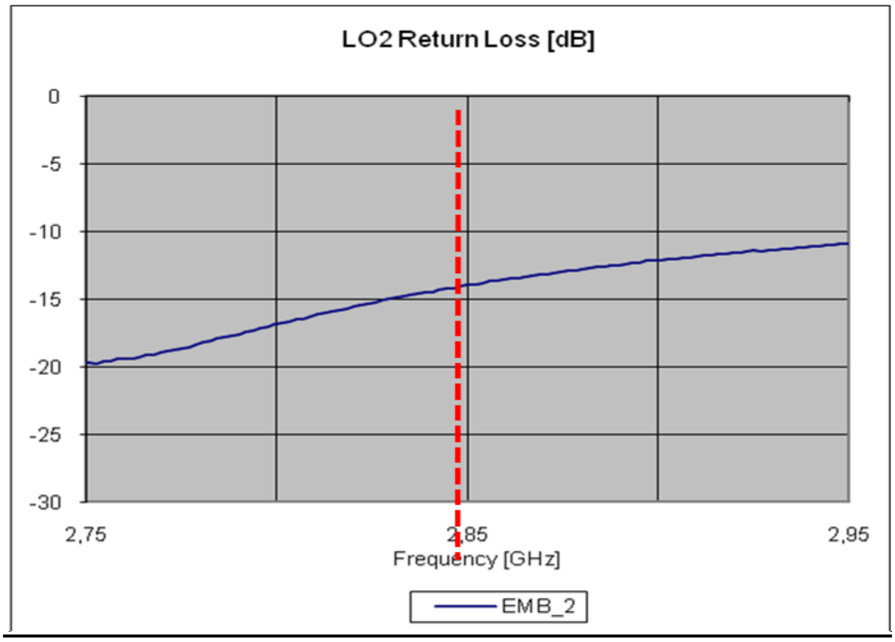


[6] Measured with HP8753C

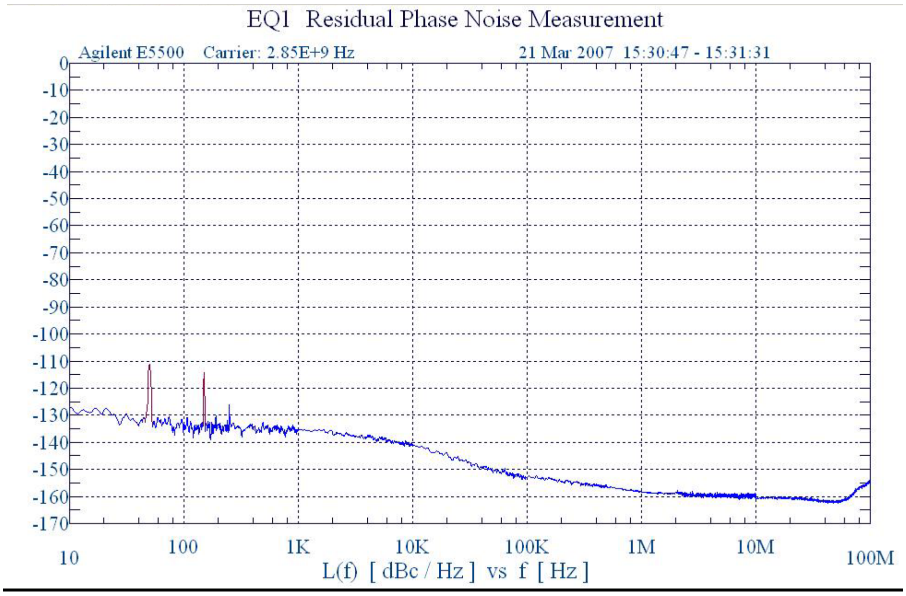
LO1 Return Loss



LO2 Return Loss



Residual phase noise[7]

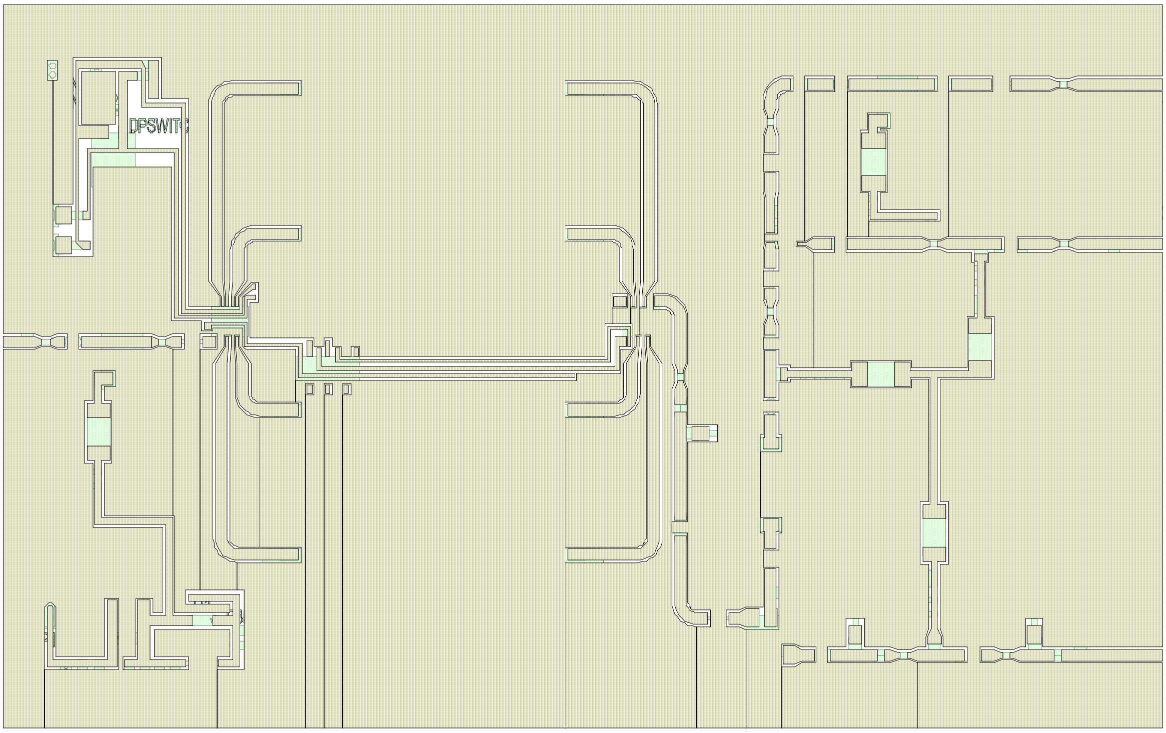


Integrated phase noise(rms) <0.02°

7 Measures referred to LO1, LO2 branches drivers with Agilent E5500 Phase Noise Measurement Subsystem. For further details about this measure, please take as reference the Internal Report 407/07

9 *Mechanical Dimension*

<u>Layout</u>[8]



• [8] Substrate FR4, 1.6mm, 1Oz Cu. Eurocard Standard Dimension (160x100mm)

Shielded Box Outline