Top-level technical requirements:

3 mm band multibeam heterodyne receiver for the Sardinia Radio Telescope

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1 Executive summary

This document summarizes the top-level technical requirements of the 3 mm multibeam heterodyne receiver to be installed at the Gregorian focus of the Sardinia Radio Telescope (SRT). The array receiver will be based on a minimum of nine dual-linear polarization feeds for the 75-116 GHz band (goal band 70-116 GHz) capable of high-efficiency illumination of the antenna. The receiver shall be designed to provide high mapping efficiency by optimizing the geometry and the separation between the projected beams on the sky.

The feed-system of each array element shall consist of a cascade of feed-horn, OrthoMode Transducer (OMT), waveguide calibration noise injectors and HFET Low Noise Amplifiers (LNAs) cryogenically cooled at ≈15 K inside a cryostat. The cryogenic array will provide a minimum of 9 × 2 waveguide outputs to a first frequency down-converter (based on a tunable local oscillator LO1) located at room temperature. This stage shall provide two sidebands, the USB1 (Upper Side Band) and the LSB1 (Lower Side Band), with a total instantaneous bandwidth of 8 GHz per sideband per polarization for each feed. The frequency band of each sideband shall be IF1=4-12 GHz (8 GHz-wide). Therefore, a total of 36×8 GHz-wide sidebands (9 feeds × 2 pols × 2 sidebands) shall be available at the output of the first down-converter. The sidebands can be located anywhere in the 70-116 GHz band. The first downconverter could consist of one or more modules.

An “IF2 stage” will then be used to split the 8 GHz-wide bands into 4 GHz-wide sub-bands spanning the IF2 range 0.1-3.9 GHz. The IF2 stage shall also perform further functions that are described in section “IF2 stage”.

The receiver shall include a calibration system with fast switchable noise calibration injection for the individual receiver chains, a cabinet with racks for biasing all the cryogenic and room temperature active sub-systems, a mechanical derotator, a mechanical support structure for its permanent installation in the receiver cabin and a vacuum pump with remotely controlled vacuum valve. The multibeam receiver shall be monitored and controlled through the SRT software.

The instrument shall be fully characterised in the laboratory and comply with the specification before its shipping to the SRT site. The multibeam receiver shall be provided along with a series of spares of its most critical parts, including the LNAs, the noise calibration injection and downconverter modules.

The receiver shall be installed on the rotating platform of the SRT Gregorian focus and then it will be aligned with its optical axis and tested before its full technical and scientific commissioning by an INAF team.

The timeframe for developing the instrument, delivering it to SRT and pre-commissioning on the telescope is of maximum 28 months following the signature of the contract.

It would be desirable to have a modular design of the nine-element array to allow its possible expansion to a larger number of feed elements in the future.

2 Introduction to SRT

The Sardinia Radio Telescope is a new Italian facility for radio astronomy. Its formal inauguration took place in September 2013. Following a successful Early Science Program carried out in 2016, the antenna was shut down for refurbishment of its active surface. SRT is currently in the re-commissioning phase with the goal of opening it to the international community for scientific observation by early 2019. The antenna is a fully steerable wheel-and-track dish, 64-m in diameter, located 35 km north of Cagliari, on the island of Sardinia. The radio telescope aims at operating with high aperture efficiency from 300 MHz to ≈100 GHz (3 mm band). The antenna gain is expected to be around 0.34 K/Jy across the 3 mm band, when accounting for a surface rms of the optics of ≈180 μm, which should be achievable through microwave holography and a metrological system in operation while in precision environment conditions.

The SRT optical design is based on a quasi-Gregorian configuration (Fig. 1) with *shaped* 64 m diameter primary (M1) and 7.9 m diameter secondary (M2) reflectors to minimize spillover and standing waves. The telescope is designed to host up to twenty receivers installed in six focal positions: Primary focus (F1), Gregorian focus (F2) and Beam-Wave Guide foci (F3&F4 and F5&F6), respectively with focal length to diameter ratio (F/D) and frequency ranges equal to 0.33 (0.3-20 GHz), 2.34 (7.5-116 GHz), and 1.38 & 2.81 (1.4- 35 GHz).

The 3 mm multibeam receiver shall be installed at the Gregorian focus (f/D=2.34).

A key feature of the SRT is its active surface, in total composed by 1008 aluminium panels (with a panel manufacturing RMS<70μm) and by 1116 electromechanical actuators, able to correct the deformations induced by gravity on the primary surface. Effort is underway

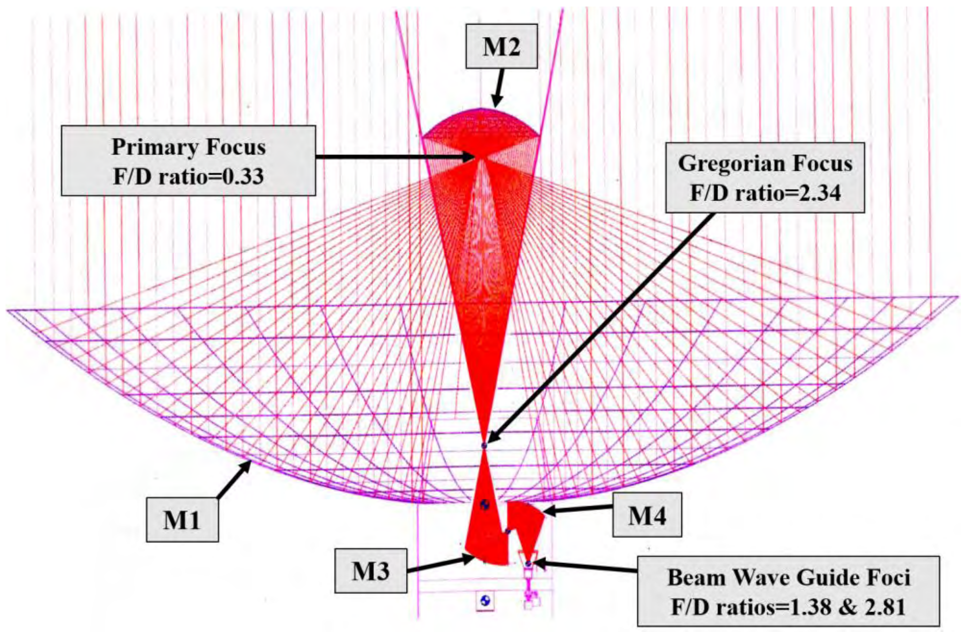


Fig. 1. Optical configuration and ray tracing of the Sardinia Radio Telescope showing the 64-m diameter primary (M1), the 7.9-m secondary (M2), and two additional Beam Waveguide (BWG) mirrors (M3 and M4). Three out of six possible focal positions (primary, Gregorian and BWG) are shown together with corresponding focal ratios.

to employ this facility to also correct for non-systematic errors, such as temperature/wind-related effects.

The 7.9 m diameter shaped sub-reflector surface consists of 49 individual aluminum panels with an average area of about 1 m^2. The sub-reflector back-structure includes six actuators to define the its position, and provide for sub-reflector motion with five degrees of freedom.

The SRT will operate in single-dish (continuum, full Stokes and spectroscopy), Very Long Baseline Interferometry (VLBI) and Space Science modes.

Further SRT details can be found at the following web page: http://www.srt.inaf.it/

3 SRT antenna parameters

Table 1 provides the optical specifications of SRT. The f-ratio at the Gregorian focus, where the 3 mm multibeam receiver shall be installed, is f2/D≈2.34. The edge of the sub-reflector subtended from the Gregorian focus is 12 deg half-angle. Fig. 2 shows a drawing with the main optical parameters of the SRT.

Optical configuration	Shaped Gregorian
Subreflector geometry	Numerical
Prime mirror diameter, D (m)	64.008
Subreflector diameter, d (m)	7.9060
Focal length, f (m)	21.0236
Prime focus focal ratio, f_1/D	0.3285
Secondary focus focal ratio, f_2/D	2.342
Distance from Prime to Gregorian foci (m)	17.4676
Subreflector eccentricity, e	
Magnification, M (m)	7.13
Prime focus to subreflector vertex (m)	2.8524
Secondary focus to subreflector vertex (m)	20.3200
Secondary focus to Prime mirror vertex (m)	3.5560
Distance from Prime mirror vertex to aperture plane (m)	12.1415
Distance from Prime focus to aperture plane (m)	8.8821
Prime mirror half-angle (degree)	74
Subreflector half-angle (degree)	12

Table 1 Optical parameters of the Sardinia Radio Telescope

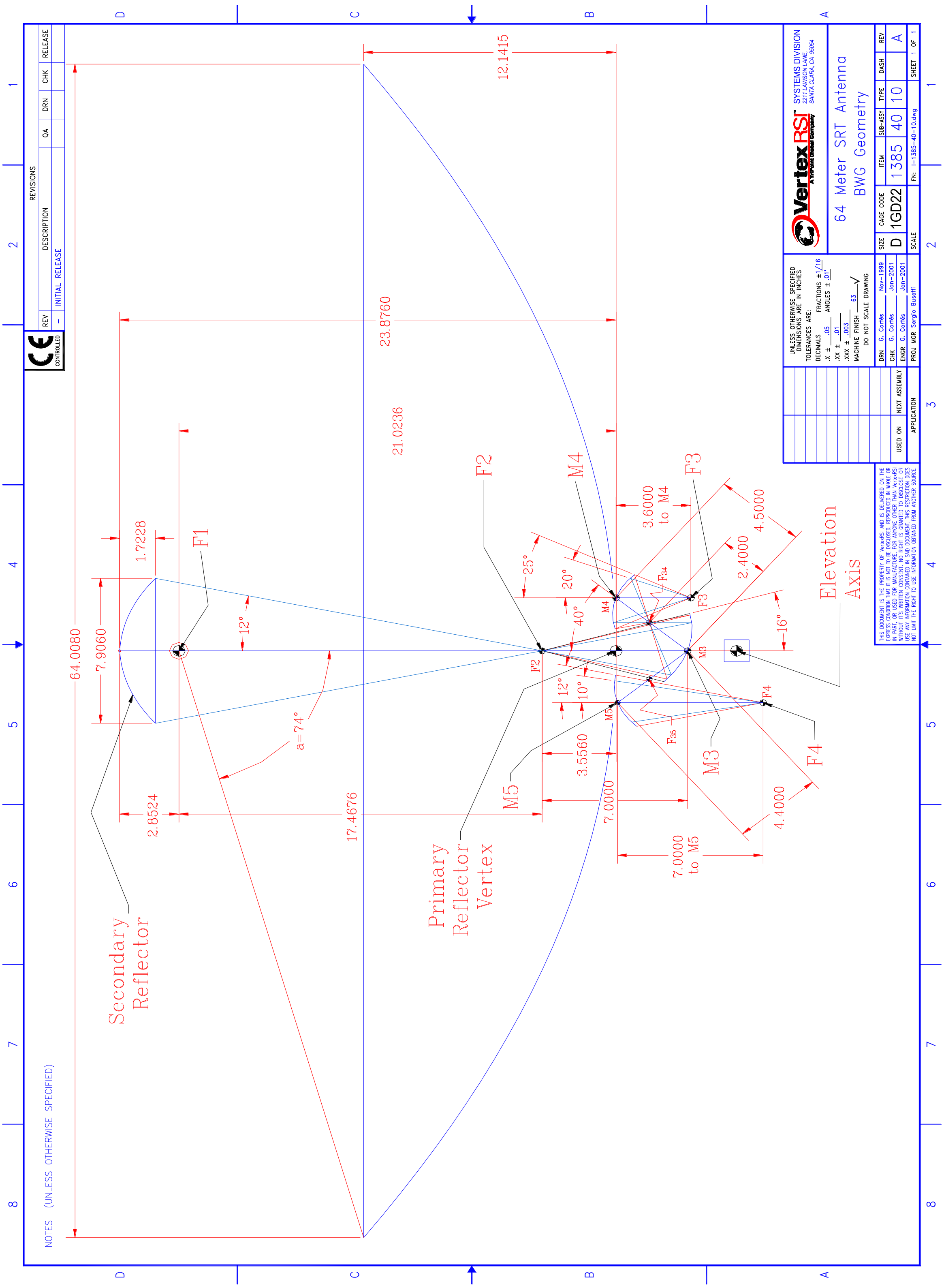


Fig.2. Optical parameters of the SRT antenna

4 Mounting of the array receiver at the SRT Gregorian focus

Figures 3 and 4 show 3D views of the Gregorian and Beam Waveguide focal points and the location where the 3 mm multibeam receiver shall be mounted along with its mechanical support frame. The instrument shall be located on the Gregorian secondary focus positioner, a rotating platform eccentrically mounted in the Gregorian focal plane. The rotating platform has a decagonal shape and can host up to eight cryogenic receiving system for operation over a range of frequencies from 7.5 GHz to 116 GHz, one receiver on each side of the decagon. The platform has two free slots to allow observations from the Beam Waveguide focal points. Currently, one of the decagon side hosts a K-band (18-26.5 GHz) seven-beam receiver. A drive system can rotate the turret so that any of the receivers can be positioned on the optical axis of the telescope. The mechanical dimensions and weight limits of the 3 mm multibeam receiver (including mechanical support) are listed in Table 3.

Figure 5 shows two pictures of the rotating platform. Additional three-dimensional drawings and pictures of the SRT receiver cabin can be found at the following link: https://drive.google.com/drive/folders/1WkPPg4mKO2eieX1Az4zo6qSFeC_egQ5r?usp=sharing

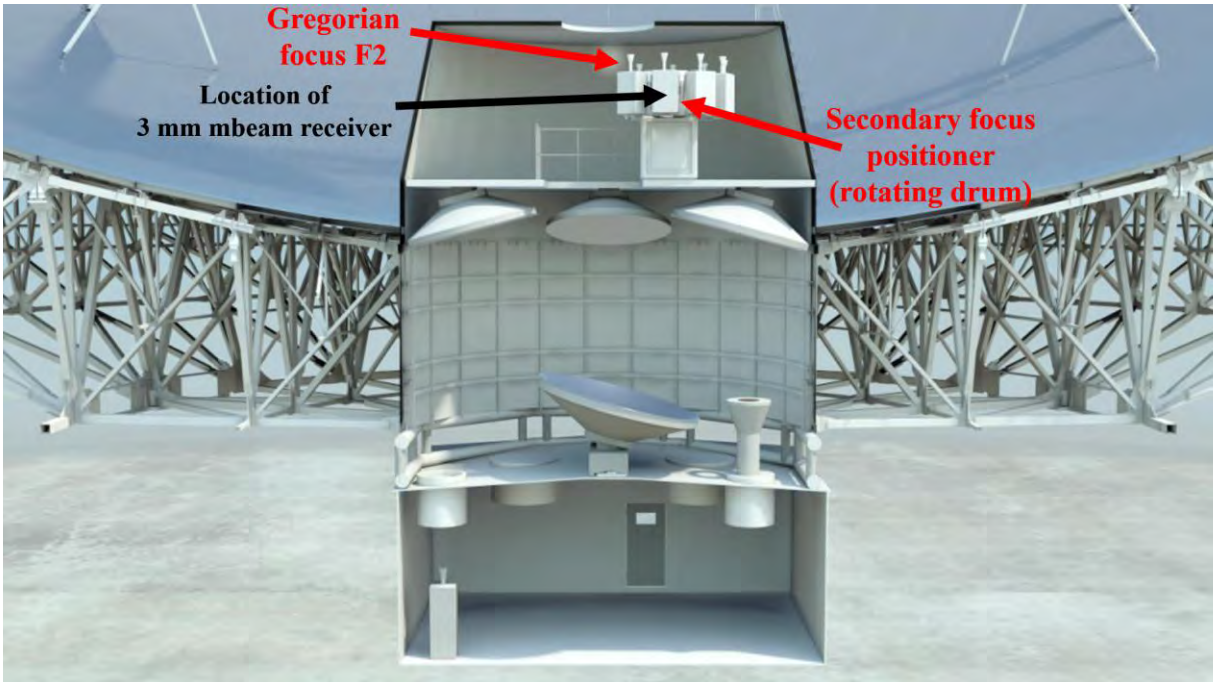


Fig.3. Gregorian and Beam Waveguide receiver cabins. The 3 mm multibeam receiver shall be installed on the Gregorian focus rotating platform.

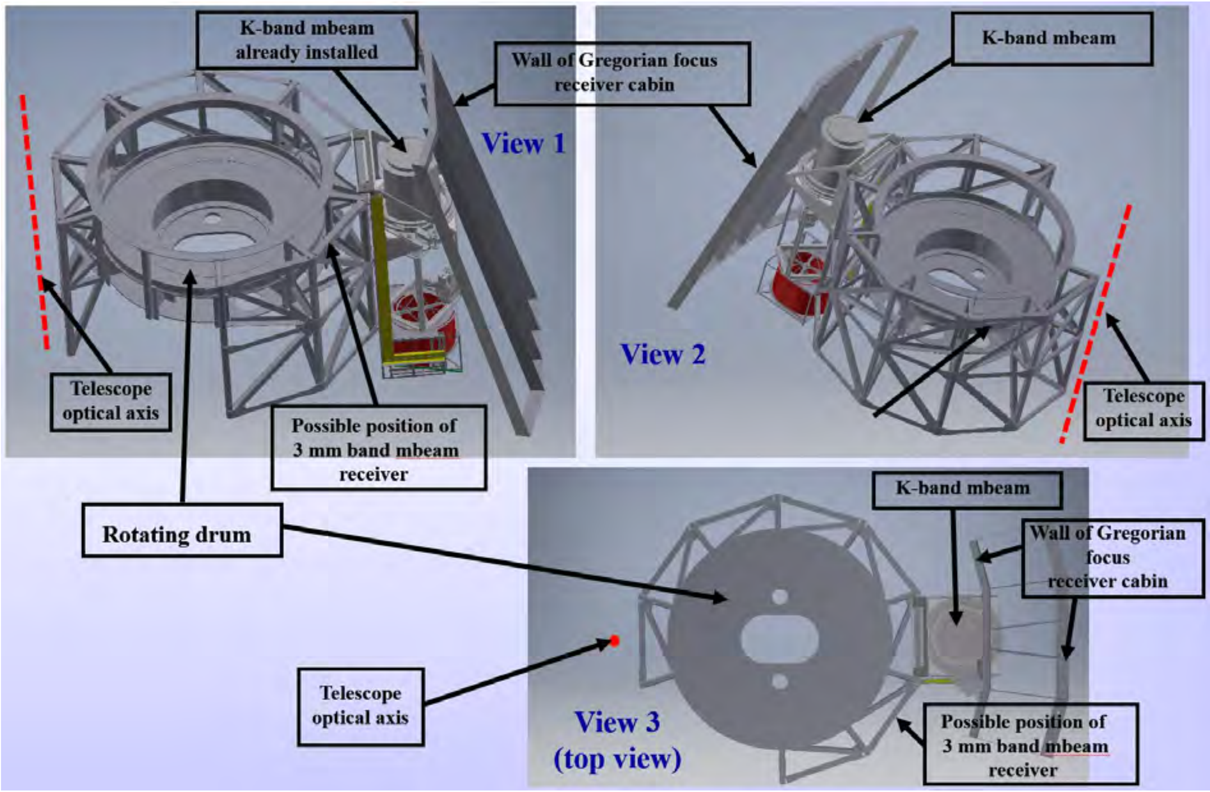


Fig.4. Three different views of the Gregorian focus rotating platform showing one of the possible locations of the 3 mm multibeam receiver on one of the platform sides.

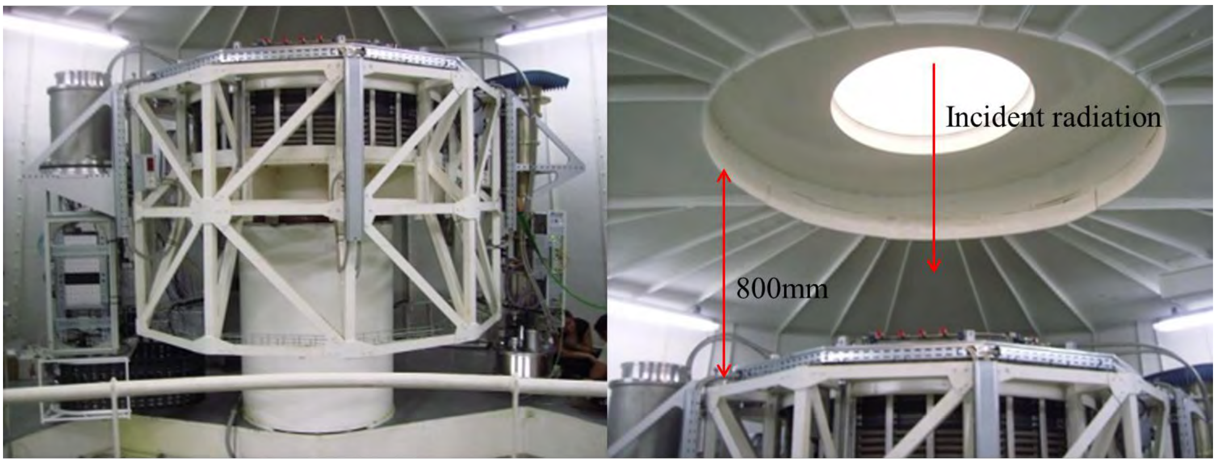


Fig. 5. Pictures of the rotating platform supporting the receiver(s).

5 Optical configuration of the 3 mm band multibeam receiver

The array receiver shall be designed for high-efficiency illumination of the SRT dish with low sidelobes, low cross-polarization level and high beam circularity for both the on-axis and off-axis feeds. The receiver shall also be designed to provide high mapping efficiency by optimizing the geometry and the separation between the projected beams on the sky. For large-area mapping purposes it would be desirable to achieve the smallest possible separation between the projected beams, compatibly with high-efficiency dish illumination corresponding to a minimum 2 × HPBW (Half Power Beam Width), where HPBW is wavelength and illumination dependent and of order 1.22 λ/D, with D=64 m (diameter of SRT primary mirror). For λ=3mm, HPBW≈11 arcsec.

The simplest configuration of the array would consist of nine dual-linear polarization feed horns arranged in a square 3×3 configuration similar to the one shown in Fig. 6, left panel. The feed-array could be placed either on the Gregorian focus or illuminate the dish through a suitable re-imaging optics. If placed at the Gregorian focus, this simple configuration cannot achieve the minimum beam spacing in the sky of 2 × HPBW, unless the separation of the feeds in the focal plane is of order 31 mm. However, the integration of a dual-polarization feed-system in such a small 31×31 mm^2 footprint would be technically challenging. The optimum configuration will be finalized using electromagnetic simulation and scanning algorithms.

The shaping of the SRT primary and secondary surfaces affects the telescope field of view (FoV) achievable from the Gregorian focus. The dashed circle on Fig. 6, left panel, indicates the points on the Gregorian focal plane where the antenna gain is -0.6 dB below the on-axis gain at 100 GHz. The radius of circular FoV on the focal plane corresponding to this loss is approximately 21 λ (≈63 mm at λ≈3 mm). We have assumed that the radiating feeds are diffraction limited and have an aperture of diameter ≈21 mm, suitable for high-efficiency illumination of the antenna with ≈12 dB edge taper at 12 deg half-angle (f_2/D=2.34) at 93 GHz (central frequency). An array consisting of 3×3 feeds with spacing between contiguous horn of ≈45 mm can fit inside the ≈63 mm FoV radius. We note that such feed spacing allows accommodating two standard UG387 waveguide flanges side-by-side, which would minimize the integration problems of the two independent cold polarization receiver chains of each feed-system.

The projection of the beams on the sky for the simple 3×3 optical configuration is shown on Fig. 6, right panel. The beam separation is frequency-independent and equal to ≈62 arcsec, corresponding to 5.3 × HPBW at 116 GHz, where HPBW≈11.6 arcsec, and to 4 × HPBW at 70 GHz, where HPBW=15.2 (see Appendix A). The maximum acceptable value for the ratio beam-spacing/HPBW is 5.5 at all frequencies.

Appendix A provides additional details on the optical design of an array placed at the SRT Gregorian focus without reimaging optics. It shows the results of some preliminary electromagnetic simulations of such optical system carried out with the Grasp software. The degradation of the antenna efficiency obtainable for the four feeds placed at the vertices of the square configuration (n. 3, 5, 7, 9) is ≈18% at 116 GHz and ≈5% at 70 GHz with respect to the on-axis feed (n. 1). Such optical configuration would allow Nyquist mapping of large-scale astronomy fields with three passes using suitable scanning techniques.

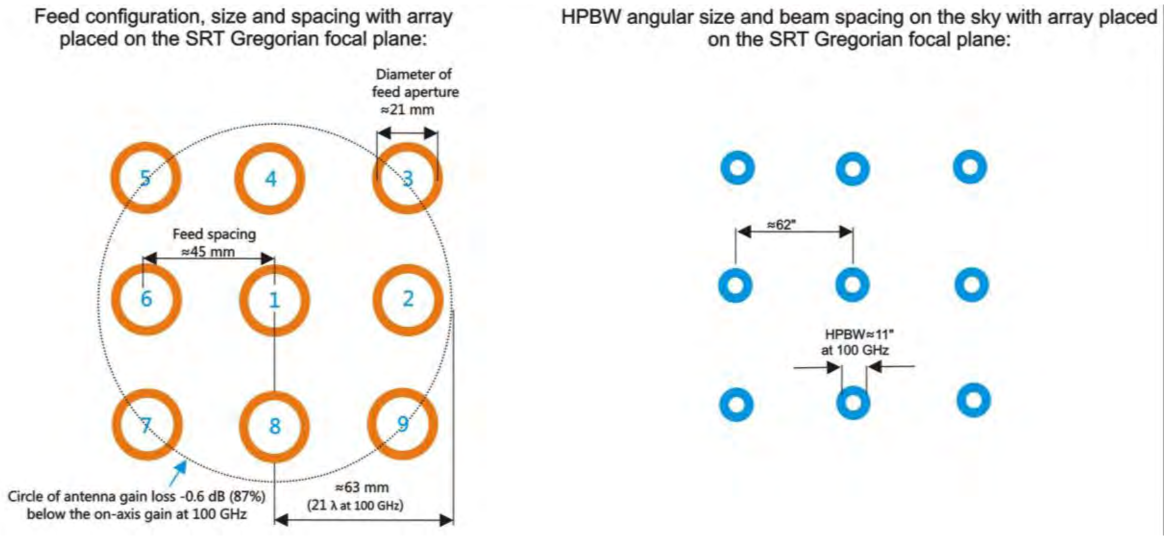


Fig. 6. Configuration of the array of 3×3 feeds on the Gregorian focal plane (left) and corresponding beams projected on the sky (right). The example refers to an array of feeds placed on the Gregorian focus without reimaging optics.

It would be desirable to reduce the feed spacing below ≈45 mm to further improve the radiation patterns of the off-axis beams. It is estimated that a cryogenic dual polarization feed-system chain could be developed to fit in a spacing of 35 mm. The spacing on the sky between contiguous beams corresponding to a 35 mm spacing in the focal plane would be ≈48 arcsec, i.e. about 4×HPBW at 116 GHz and about 3.2×HPBW at 70 GHz.

A re-imaging optics (for example based on a Gaussian Beam Telescope) could be used to reduce the spacing between the projected beams on the sky to a value of 2-2.5 HPBW at all frequencies without requiring further reduction of the feed spacing in the focal plane. However, the re-imaging optics should induce negligible optical aberrations of the off-axis beams. The design of a re-imaging optics system for coupling the beams to the *shaped* SRT optics would need to be carefully designed.

6 Possible architecture of the 3 mm band multibeam receiver

Fig. 7 shows a block diagram with a possible architecture of the 3 mm band 9-element receiver array for the SRT Gregorian focus. Such architecture employs nine dual-linear polarization chains inside a cryostat and two modules of first downconversion outside the cryostat (at room temperature). The cryogenic part utilizes a cascade of feed, OMT dual-polarization noise injection module, and waveguide band pass filter (BPF) located between two stages of cryogenic LNAs, each providing approximately 23 dB of gain. All the cryogenic components should cover the 70-116 GHz band with state-of-the-art performance.

We note that this receiver architecture does not require a polarizer (Differential Phase Shifter) between the feed-horn and the OMT because the circular polarization with full-Stokes capabilities will be generated by the backend.

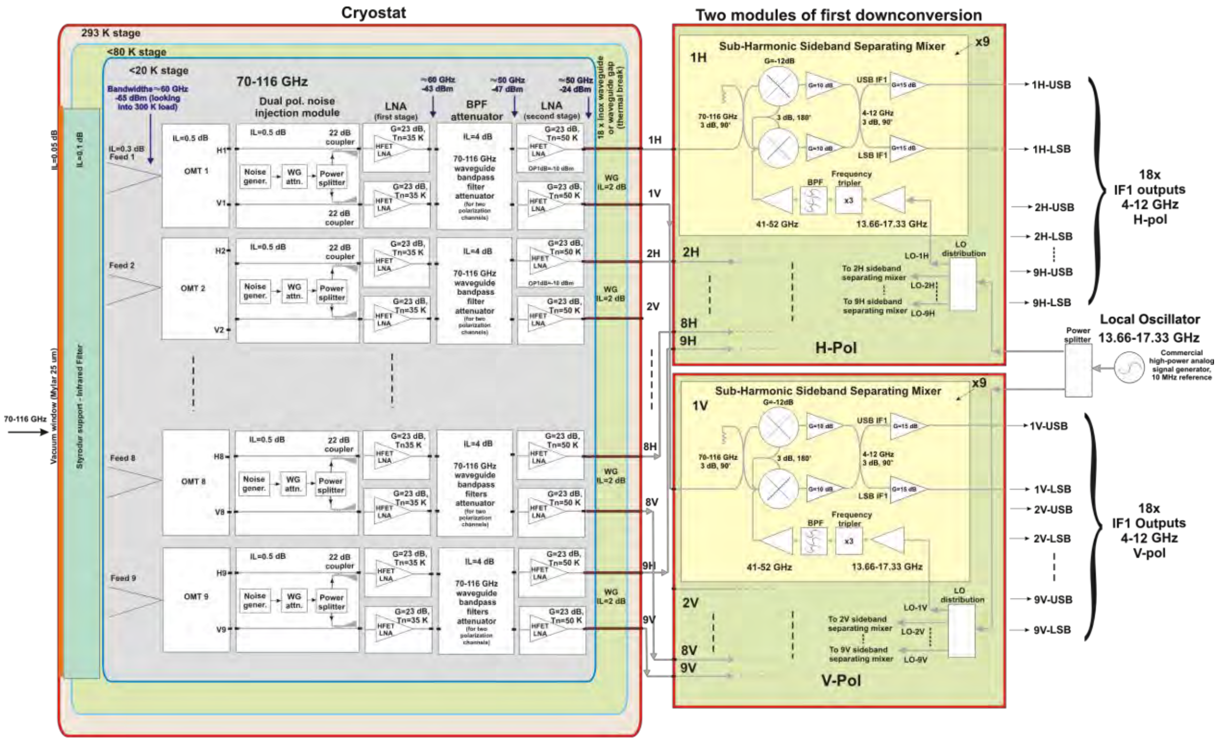


Fig. 7. Possible 3 mm multibeam receiver architecture showing the cryogenic components and the two warm first downconversion modules (one per polarization channel), each delivering 18×IF1 outputs across 4-12 GHz.

The design of the cryogenic components and assembly (choice of LNAs, number of LNA bias wires, infrared filter, etc.) shall minimize the thermal power dissipation to allow proper cooling of the parts by a single close-cycle commercial cryocooler, either a Cryodine CTI 350 or a CTI 1020, which is compatible with the compressor (CTI 9600) and helium lines that will be available at the SRT. The compressor is not part of the deliverables (already available at SRT).

The amplified signals available from the nine cryogenic dual-polarization feed-system are transported by 9×2 waveguides to the receiver cryostat outputs. We define with "H" and "V" the channels corresponding to the horizontal and vertical polarization, respectively. Each of the two modules of first downconversion, located at room temperature, receives the signals from nine waveguides (1H to 9H for H-polarization and 1V to 9V for V-polarization) and downconverts them using a sideband separating (2SB) scheme based on subharmonic mixers to 18 × 4-12 GHz IF1 outputs. The mixers are pumped with a local oscillator signal provided by a commercial high-power signal generator (phased-locked with the 10 MHz antenna reference) delivering a tone tuneable across the 13.666-17.333 GHz frequency range. Such local oscillator signal is distributed to 9 × 2SB mixers inside the downconversion module, multiplied by a frequency tripler, band pass filtered and amplified before its injection into the subharmonic mixer that doubles it to produce a final LO1 tone tuneable in the 82-104 GHz band. With this sideband separating mixer scheme, the LO1 signal is mixed with the mm-wave astronomy signal received from the antenna at the USB1 and the LSB1; two IF1 outputs are available at the same time, one for each sideband (see Fig. 7). For example, let's consider two of the available sidebands, the 1H-USB and the 3V-LSB. The former indicates the USB of H polarization output of feed 1, while the latter indicates the LSB of V polarization output of feed 3. A similar definition is used to identify all feeds (1-9) and both polarizations (H and V). For further simplification, we shorten the names of USB and LSB and define them as U1 and L1, where "1" stands for "first downconversion". Thus, 5H-U1 indicates the USB available after the first downconversion for the horizontal polarization of feed 5.

The image sideband rejection of the first downconversion depends on various parameters and shall be greater than 15 dB at all frequencies across the 4-12 GHz IF1 band. Thus, two 8 GHz-wide sidebands centered at ν_{IF1C}=8 GHz and separated by 2 × ν_{IF1C}=16 GHz can be observed at the same time for each of the polarization channels. Fig. 8 shows an example of the horizontal polarization channel with LO1 tuning at 100 GHz resulting in the two sidebands H-L1=88-96 GHz and H-U1=104-112 GHz.

Figure 9 shows a diagram of the frequency bands that can be covered with two different LO1 tunings, one for observing in the upper part of the 70-116 GHz frequency band (in red color) the other for observing in the lower part of the 70-116 GHz band (in blue color). The frequency ranges of the local oscillator at the LO1 frequency as well as the tripler output and at the first signal generator outputs are also shown. We note that the entire 70-116 GHz band can be covered with four separate tunings of LO1.

It would be recommended to utilize a modular design of the cryogenic sub-systems and possibly also of the room temperature sub-systems to allow a future expansion of the instrument to a larger number of feed elements.

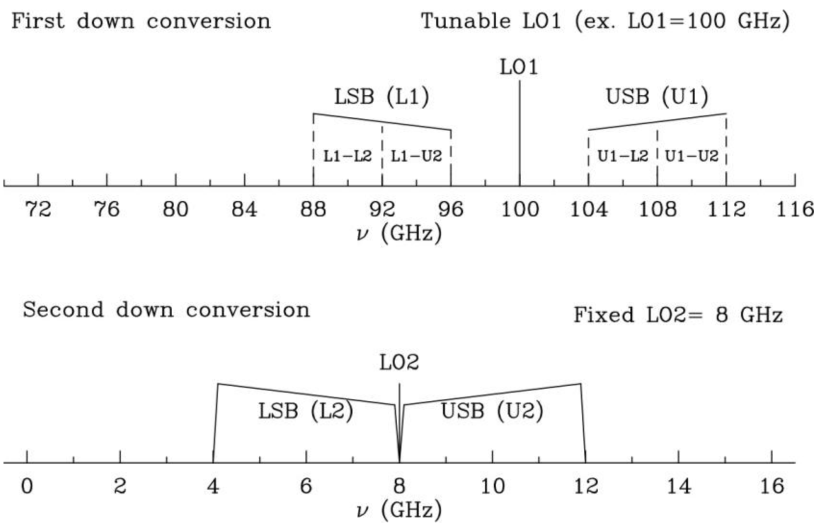


Fig. 8. Top: Example of heterodyne downconversion with LO1 at 100 GHz. The names of the Upper Side Band (USB) and of the Lower Side Band (LSB) of the first downconversion are shortened, respectively to U1 and L1: U1=104-112 GHz, L1=88-96 GHz (IF1=4-12 GHz). Bottom: Second downconversion with fixed LO2 at ν_{LO2}=8 GHz to convert both U1 and L1 sidebands to the IF2= 0.1-3.9 GHz baseband. The U2 and L2 symbols following the U1 or H1 symbols on the top figure refers to, respectively the USB and to the LSB of the second downconversion.

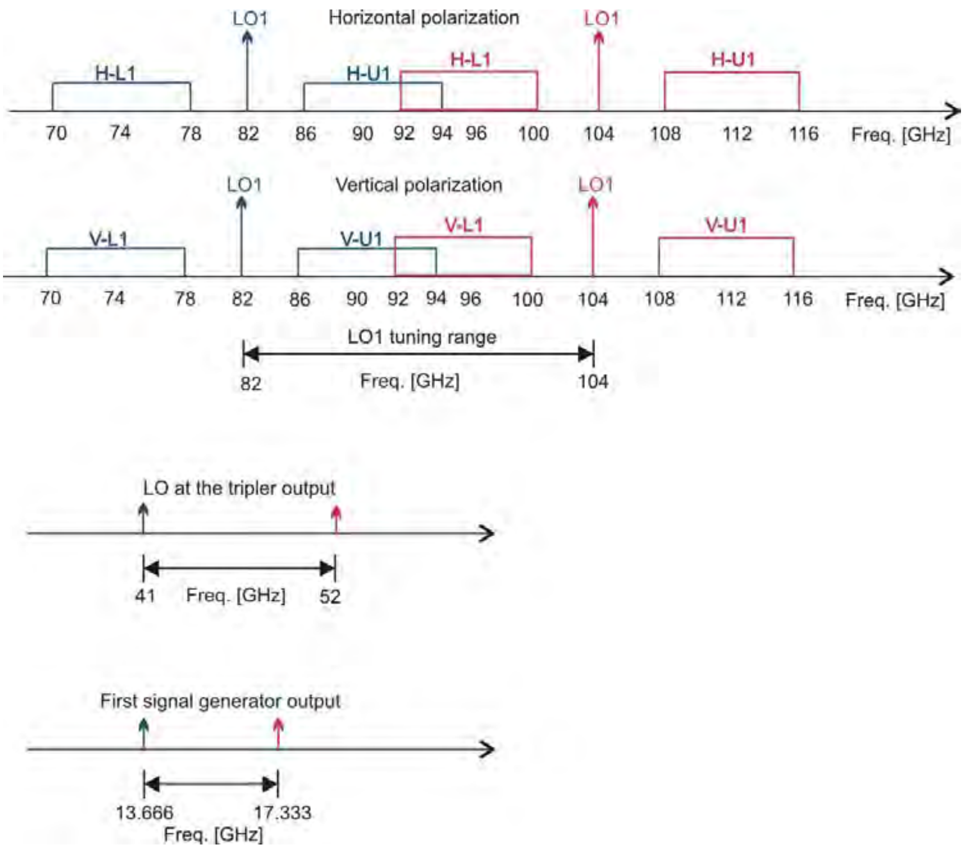


Fig. 9 Possible heterodyne downconversion scheme of 3 mm band multibeam receiver. Top diagram: downconverted bands with two different LO1 settings tuned for operations in the upper part of the 70-116 GHz band (LO1 at 104 GHz, red color) and in the lower part of the lower 70-116 GHz band (LO1 at 82 GHz, blue color). Both the Horizontal and Vertical polarizations are shown along with a diagram of the LO1 tuning range, 82-104 GHz. Bottom diagrams: local oscillator tuning ranges at the tripler output (41-52 GHz) and at the first signal generator output (13.666-17.333 GHz).

6.1 IF2 STAGE: SECOND DOWNCONVERSION, TOTAL POWER BACKEND AND SUB-BAND SELECTION

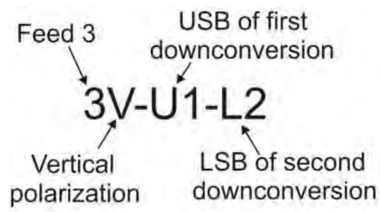
The 36 × 8 GHz-wide IF1 signals at the output of the modules of first downconversion (9 feeds ×2 polarizations ×2 sidebands) are sent to the “IF2 stage”. The IF2 stage shall perform the following functions:

a) downconvert the 36 × 8 GHz-wide IF1 inputs to 36 × 2 × 4 GHz-wide sub-bands across the IF2 band 0.1-3.9 GHz (≈4 GHz) using a fixed LO2 at ν_{LO2}=8 GHz. The LO2 signal shall be provided by a second synthesizer and will be part of the receiver;

b) detect the 72 × 4 GHz-wide IF2 sub-band signals for total power measurement and monitoring purpose;

c) select a suitable combination of up to 36 IF2 feeds and/or sub-bands for delivery to the digital spectroscopic backend through analog fiber optics links operating across 0.1-4 GHz.

The definition of the feeds and sub-bands follows from Fig. 8 and is explained with the following example that refers to the sub-band LSB2 (second downconversion) of USB1 (first downconversion) of feed n. 3, vertical polarization:



In this example, if LO1 is set to a value of 104 GHz, the 3V-U1-L2 sub-band refers to the 108-116 GHz frequency range (of feed n. 3, vertical polarization).

Two main feeds/sub-bands combinations shall be available at the output of the IF2 stage for spectroscopic observation, *Mode A* and *Mode B*:

- *Mode A for nine feeds:* this mode shall allow selection of four out of eight possible IF2 sub-bands available from each dual-polarization feed for *all* the nine elements of the array and send all of the 36 available sub-bands to the digital backend. A list of eight proposed user-selectable combinations of *Mode A* sub-bands (*Mode A1* to *Mode A8)* is given in Fig. 10. For example, *Mode A1* shall allow simultaneous observation of U1-L2 and U1-U2 for both H and V polarization channels for the 9-element array. We note that selection of *Mode A1* with LO1 tuning at 104 GHz (first synthesizer frequency at 17.333 GHz) allows simultaneous observation of the ^{13}CO and ^{12}CO lines respectively at ≈110 GHz and ≈115 GHz.
- *Mode B for four feeds:* this mode shall instead select a sub-set of four feeds and send all the 32 available sub-bands to the digital backend.

Figure 11 shows the block diagram of a module of the IF2 stage performing the second downconversion, the detection and the selection of the feeds/sub-bands. One module processes two dual-polarization feeds. Therefore, five modules in total are required to accomplish Mode A and Mode B functions for the nine-feed system (one module will be used partially).

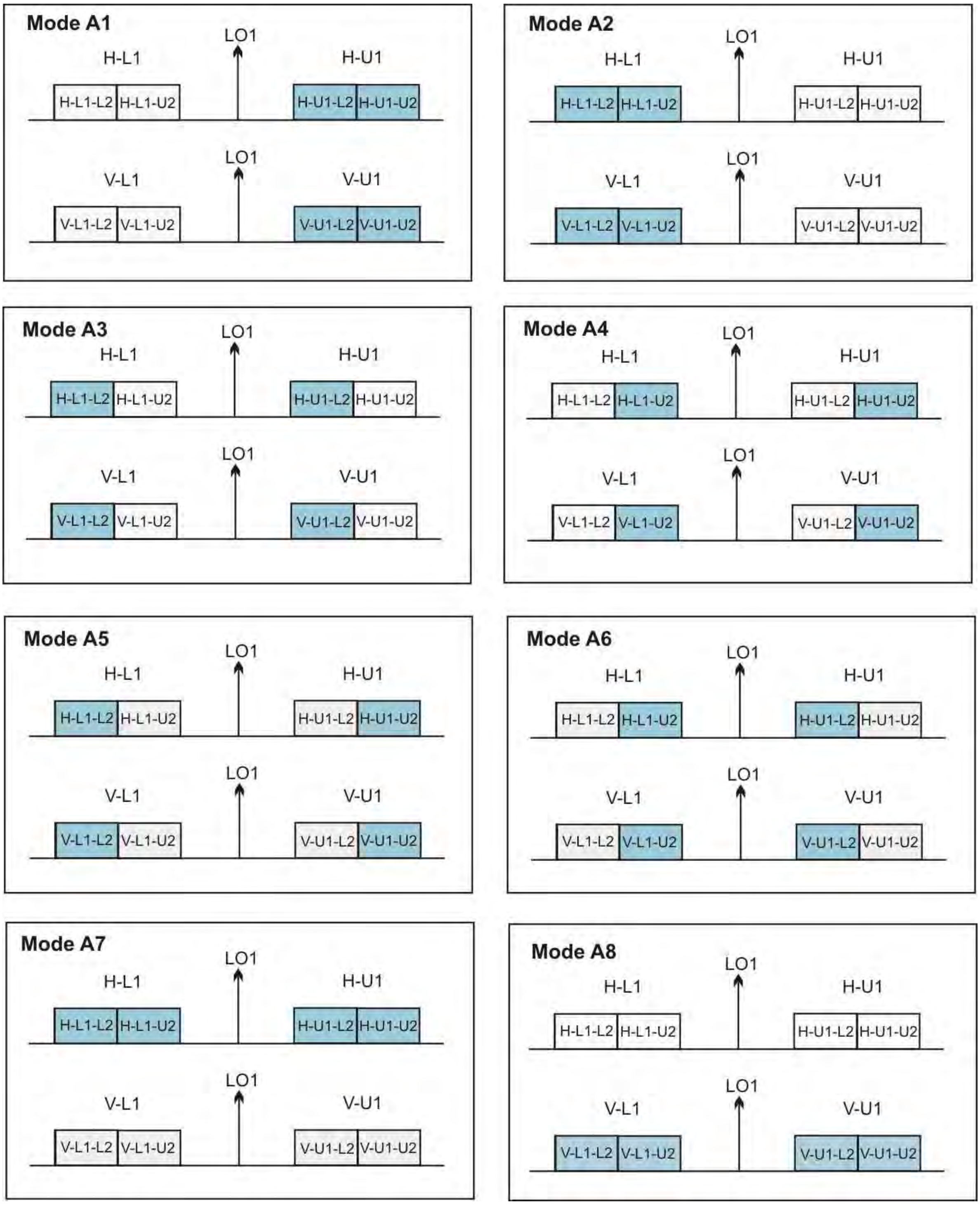


Fig. 10 Mode A for the IF2 stage. Eight possible configurations of observable sub-bands (filled in blue) for all the nine dual polarization feeds: Mode A1 to Mode A8.

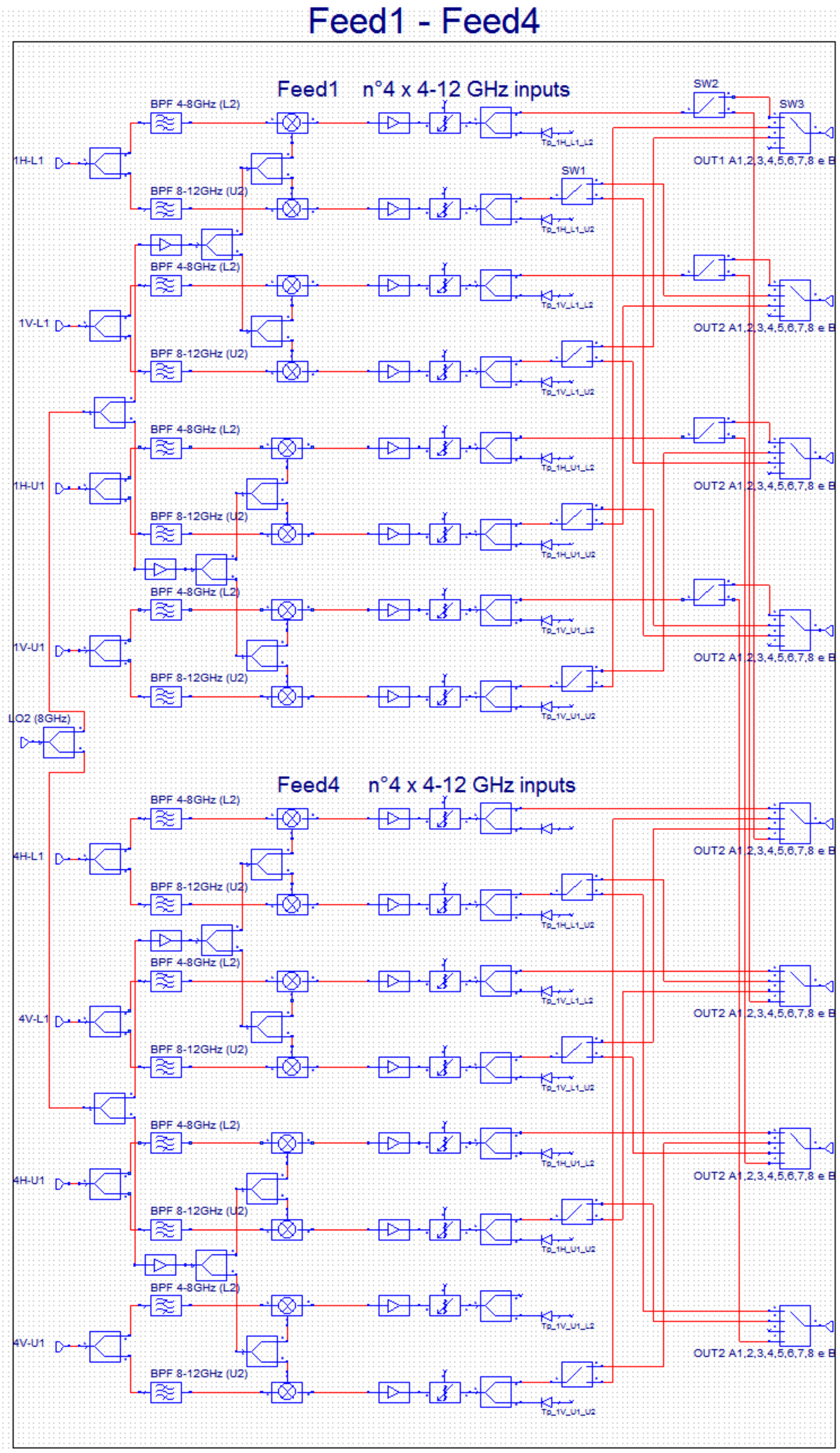


Fig. 11 Block diagram of one of the five IF2 modules for the IF2 stage. This microwave board processes the 2 × 4 × [4-12 GHz] IF1 inputs from two dual polarization feeds (the example refers to Feed 1 and Feed 4). It performs the second downconversion, the detection of 16 × IF2 sub-bands (2×2× 4× [0.1-3.9 GHz] IF2) and the sub-band selection through a switch matrix.

Table 2 shows the user-selectable switch and output numbers of the block diagram of Fig. 11 to achieve the above-mentioned feed/sub-bands selection.

		SW1	SW2	SW3	Out
A1 all FEEDS	H-U1-L2	1		2	2
	H-U1-U2		1	1	3
	V-U1-L2	1		2	1
	V-U1-U2		1	1	4
A2 all FEEDS	H-L1-L2	2		3	4
	H-L1-U2		1	1	1
	V-L1-L2	2		3	3
	V-L1-U2		1	1	2

		SW1	SW2	SW3	Out
A7 all FEEDS	H-L1-L2	2		3	4
	H-L1-U2		1	1	1
	H-U1-L2	1		2	2
	H-U1-U2		1	1	3
A8 all FEEDS	V-L1-L2	2		3	3
	V-L1-U2		1	1	2
	V-U1-L2	1		2	1
	V-U1-U2		1	1	4

		SW1	SW2	SW3	Out
B FEEDS 1265	H-L1-L2		2	4	5
	H-L1-U2		1	1	1
	H-U1-L2		2	4	7
	H-U1-U2		1	1	3
	V-L1-L2		2	4	6
	V-L1-U2		1	1	2
	V-U1-L2		2	4	8
	V-U1-U2		1	1	4

Table 2. Switch matrix configuration associated to Modes A and B selectable by the IF2 stage.

7 Specifications and requirements for the multibeam receiver

Table 3 shows the top-level specifications and requirements for the 3 mm band multibeam receiver. It provides a list of all hardware and software components to be delivered. The receiver shall be monitored and controlled using the SRT control software (see http://discos.readthedocs.io/en/latest/ and http://discos.readthedocs.io/en/latest/).

Array receiver specification	
Baseline RF band (GHz)	75-116
Goal RF band (GHz)	70-116
Polarization properties	Two orthogonal linear polarizations, named H & V, shall be available
Number of beams and array configuration	9 beams in square 3 x 3 configuration (see Fig. 2) or alternative hexagonal configuration (TBD)
Angular spacing in the sky between contiguous beams	23” to 62” (HPBW≈12” at 100 GHz)
Ratio beam-spacing/HPBW	2 to 5.5 at all frequencies
Mechanical de-rotator	Required to maintain the parallactic angle during source tracking. Shall include the servo-system and encoder controllable by the SRT “Nuraghe” control software. Angular rotation +/- 120 deg. Rotation speed shall allow derotation while tracking sources up to an antenna elevation of 85 degrees
Mechanical frame	Yes, to mount the receiver on the Gregorian focus rotating platform
Illumination Taper for each of the feeds (dB)	-12 @ 12° sub-reflector edge half-angle at 93 GHz (central frequency)
Maximum gain loss for off-axis feeds compared to central feed at all frequencies (dB)	-1
Return loss (dB)	>20 (at input of all feed-horns and OMTs)
Crosspol (dB)	< -25 (at any frequency within the receiver tuning range, the cross-polarised component for each of the two polarization channels shall be at least 25 dB below the desired co-polar signal component)
Receiver calibration	Yes, for all receiver chains. Noise calibration injection through waveguide coupler before the cryogenic LNAs. The noise cal injection shall be fast switchable (min. 100 Hz)
Noise calibration coupling	Such that the noise calibration value be around 10% Tsys and negligible when the cal is switched off (average Tsys≈150 K)
Noise cal signal	via commercial noise source
LO1 frequency	Tunable at sub-harmonic frequency across 13.666-17.333 GHz, via high phase stability synthesizers (e.g. Keysight analog signal generator or YIG oscillator)
Phase and amplitude stability	Determined by the synthesizers and multiplication chain
First downconverter	Based on Sideband Separating Mixer (2SB) scheme with subharmonic mixer
IF1 frequency range (GHz)	4-12 GHz sidebands
Number of IF1 outputs from first downconverter modules	36 (9 × 2 × 2 × IF1 sidebands)
IF1 output power and power variations (flatness)	TBD
LO2 frequency	8 GHz, fixed, via high phase stability synthesizer
IF2 frequency range (GHz)	IF2: 0.1-3.9 GHz
Number of IF2 outputs from IF2 stage	72 (9 × 2 × 2 × 2 × IF2 sub-bands)
IF2 output power and power variations (flatness)	TBD
Total power backend	Yes, full-band continuum backend for 72 × IF2 sub-bands incorporated into the IF2 or equivalent system
Feed/sub-band selection	Yes, up to 36 × IF2 sub-bands selectable with both Mode A1-A8 and Mode B
Reference signals for LO1 and LO2	10 MHz
Image sideband rejection for first downconverter (dB)	> 15
Image sideband rejection for second downconverter (dB)	> 20
Intermodulation products	as low as possible, best effort
Reference signals for LO1 and LO2	10 MHz
Cryogenic LNAs	From commercial companies or research institutions
Cryogenic LNA gain (dB)	TBD
Cryogenic LNA gain flatness	As flat as possible, best effort. It affects the receiver sideband rejection.

RX noise temperature (K)	< 60 K (measured in front of vacuum window for all sub-bands)
Gain of the first downconverter (dB)	TBD
Gain saturation	The large signal gain compression shall be less than 5% between the situation that a 77 K load is placed at the RF input port and the situation that a 300 K load is placed at the same RF input port.
Waveguides, connectors and interfaces	TBD
Electromagnetic compatibility	The receiver and its sub-system shall not generate Radio Frequency Interference
VACUUM and CRYOGENICS	
Vacuum level (mbar)	$10^{-6} \div 10^{-7}$
Cold head	One CTI Cryogenics, either model 350 or 1020 (compatible with available compressors)
Compressor	CTI 9600 (not to be supplied)
Temperature at stages	1st stage : < 70 K typical, 2nd stage : < 20 K typical
Temperature Monitor	Yes, on both cryogenic stages
Vacuum Sensor and Monitor	Yes, and remote control of vacuum valve
PHYSICAL	
Dewar diameter (mm)	≤ 590
Overall diameter (mm)	< 800 (a bigger diameter is allowed below the Gregorian focus)
Height (mm)	≤ 2400
Weight (kg)	< 250
ENVIRONMENTAL	
Ambient Temp. and RH	RXs are located in air-conditioned room
ORIENTATION	
	The receiver shall meet all performance requirements over a range of gravity vectors from 0 to 90 degrees (antenna elevation angles)
PRIMARY POWER	
1. Voltage (V)	230
2. Frequency (Hz)	50
Consumption (W)	TBD
MONITOR and CONTROL	
	To switch on/off cryocooler, vacuum, LNAs bias, mechanical derotator, compatible with the SRT "Nuraghe" control software (http://discos.readthedocs.io/en/latest/)
MTBF and LIFETIME	
MTBF	The Mean Time Between Failure of the receiver shall exceed 20 years
Lifetime	The receiver minimum lifetime shall be 15 years from date of delivery
Delivery time, installation and pre-commissioning validation	
Delivery period	26 months after signature of contract
Installation on SRT telescope and instrument pre-commissioning validation	Max 28 months after signature of contract. With support from local INAF SRT team.
Spare parts	Yes, to guarantee full operation of the instrument for at least 10 years after installation
Spare of active components	LNAs, noise calibration injection modules, first downconverter sub-parts
Spare of passive components	One additional feed, OMT and waveguide filter

Tab. 3 Top-level specification of 3 mm band multibeam receiver

8 Additional recommendations

Cryogenic LNAs and observations of the Sun

The gain of the 70-116 GHz cryogenic LNAs should be carefully chosen to avoid risk of saturation of the last LNA stage due to the large input bandwidths. The input power expected at the first cryogenic LNA input when observing a 300 K load is of order -65 dBm assuming an input bandwidth of ≈60 GHz. A total gain of the LNAs of ≈45 dB (for example, a cascade of two LNAs with ≈23 dB gain each) would run the last stage of the LNA in the non-linearity regime if we assume an output P1dB of order -10 dBm (input P1dB≈-33 dBm).

Three solutions are proposed to mitigate this problem: (a) use a band-pass filter and slightly attenuate the signal before the last LNA stage (solution proposed in the diagram of Fig. 7); (b) drive the last LNA stage to higher current to get higher IP1dB (supposing the gain does not increase by driving to higher currents); (c) use a single cryogenic LNA with gain of approximately 33 dB, sufficient to reduce the noise of the following receiver stages to a negligible level, and to cascade it with a room temperature LNA with high IP1dB. It is unclear if a cryogenic LNA with ≈33 dB gain exists or could be produced, and also if a room temperature LNA with high IP1dB is available.

During observation of weak radio astronomy sources, the power at the input of the first LNA stage is proportional to the system noise temperature, expected to be of order 150 K at 45 deg elevation in average weather conditions. Thus, in a standard observation the power level at the input of the LNA would be approximately half of that from a 300 K load.
It would be recommended that the multibeam receiver be designed to allow observation of the Sun without driving the receiver in the non-linearity regime. The Sun emissivity around 100 GHz is expected to be equivalent to a ≈7000 K load. The solution proposed in the schematic diagram of Fig. 7, based on cryogenic LNAs with IP1dB≈-35 dBm does not allow this option.

Noise cal injection

The INAF receivers installed on the SRT use a noise source and a device to couple a specific amount of attenuated Excess Noise Ratio (ENR) into the receiver chain. In fact, the SRT does not have a fast nutating secondary or wobbler to remove the instrumental and atmospheric effects during observations. The 3 mm multibem receiver shall include a fast switchable noise calibration system (min 100 Hz) to track the drift of receiver gain up to the knee frequency of the LNA. The noise source shall be calibrated in the laboratory, before shipping the receiver to SRT, for example by measures with calibration loads at the temperature of the liquid Nitrogen (77 K) and at room temperature (296 K). Alternative calibration methods to the cryogenic noise calibration system could be used, which need further analysis.

LO signal generation

A LO1 signal generation tunable across 13.666-17.333 GHz is required for the first downconversion of the radio astronomy signals down to 4-12 GHz. A high phase stability synthesizer embedded in the receiver rack can be used. A second synthesizer shall generate the fixed LO2 signal at 8 GHz; it could be located in the IF2 stage rack.

Vacuum pumps

Vacuum pumps shall be permanently installed and connected to the receiver cryostat. For maintenance purposes the cryostat vacuum pressure shall be remotely monitored and a valve remotely controlled for switching on/off.

Monitor & Control

The temperature of the two cryogenic stages of the cryostat (20 K and 80 K) shall be monitored, including the currents and voltages for biasing the LNAs.

APPENDIX A: SRT optics simulation

Electromagnetic simulation of 3×3 array optics across 70-116 GHz

We used the Grasp software to perform electromagnetic simulations of the array receiver coupled with the SRT optics. These simulations assumed the SRT shaped surfaces and the array placed at the Gregorian focus. We used the GTD (Geometrical Theory of Diffraction) method to model the secondary mirror and the PO (Physical Optics) method to model the primary reflector. The modeling accounts for the radiation patterns of an illuminating diffraction-limited feed-horn optimized for operation across the full 70-116 GHz bandwidth.

Figure A1 shows the array geometry where the feeds are color-coded based on their distance from the optical axis. Table A1 provides the results of the electromagnetic simulation for the on-axis feed and for the off-axis feeds n. 2, 3. At 93 GHz, the central frequency of the 70-116 GHz band, the loss of the antenna gain for feed n. 3, which is located at one of the vertices of the square, is approximately 10% of the on-axis value. This loss is 18 % at 116 GHz (lower than the maximum acceptable level of 20%) and 4.7% at 70 GHz.

Fig. A2, left panel, shows a possible scanning geometry of the array used for mapping large angular areas in the sky. A nearly Nyquist-sampling (0.59 HPBW offset) is achieved at 116 GHz with three sub-scans (right panel). The profiles shown on the left of each panel represent the overlapping level of all the combined beams. Fig. A2, right panel, shows that a uniform sampling can be achieved with three sub-scans.
At the lowest frequency of the band, 70 GHz, the HPBW is ≈15 arcsec, and a Nyquist oversampling (0.45 HPBW) would be achieved if using the same scanning configuration.

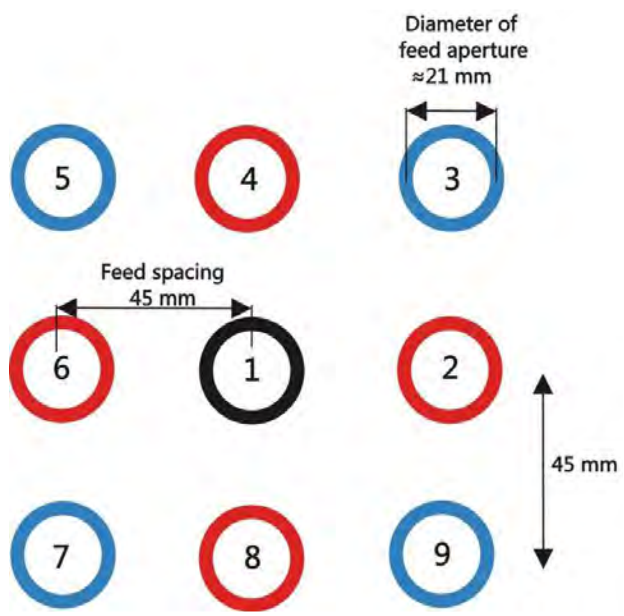


Fig. A1. Configuration of the 3×3 array with 45 mm spacing between contiguous feeds. The diameter of the feed aperture is about 21 mm.

Optical parameters of 3x3 multifeed with 45 mm feed spacing illuminating the SRT from the Gregorian focus (simulated with Grasp software)				
Frequency [GHz]	**70**	**93**	**100**	**116**
Gain CoPolar [dBi]	91.50	94.68	95.02	95.14
	91.38	94.42	94.71	94.62
	91.27	94.19	94.44	94.20
3dB BeamWidth [arcsec]	15.23	12.38	11.95	11.59
	15.19	12.35	11.88	11.30
	1.,08	12.20	11.74	11.27
Angular offset from optical axis θ [arcsec]	0.00	0.00	0.00	0.00
	62.24	62.07	61.98	61.65
	87.96	87.80	87.72	87.42
Pointing direction ϕ [deg]	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00
	45.07	44.98	44.93	44.71
Antenna efficiency[1] [%]	64	76	71	54
	62	71	66	48
	61	68	62	44
Gain loss with respect to illumination with central feed [%]	0.0	0.0	0.0	0.0
	3.1	6.6	7.0	11.1
	4.7	10.5	12.7	18.5
Cross-polarization level [dB]	-48.82	-39.22	-38.33	-35.73
	-43.67	-38.67	-37.91	-34.84
	-47.85	-38.43	-37.55	-34.16

Table A1. Grasp simulation of the SRT Gregorian optics illuminated by the array of feeds shown in Fig. 10. Black refers to the on-axis feed, red to feed 2 and blue to feed 3.

[1] The values of the antenna efficiency in Table A1 assume no deviations from the ideal optical surfaces. When accounting for a Ruze error distribution due to a surface rms of order 180 μm (goal to be achieved with an active primary surface and a metrology system) the antenna efficiency is reduced by a factor of ≈2.

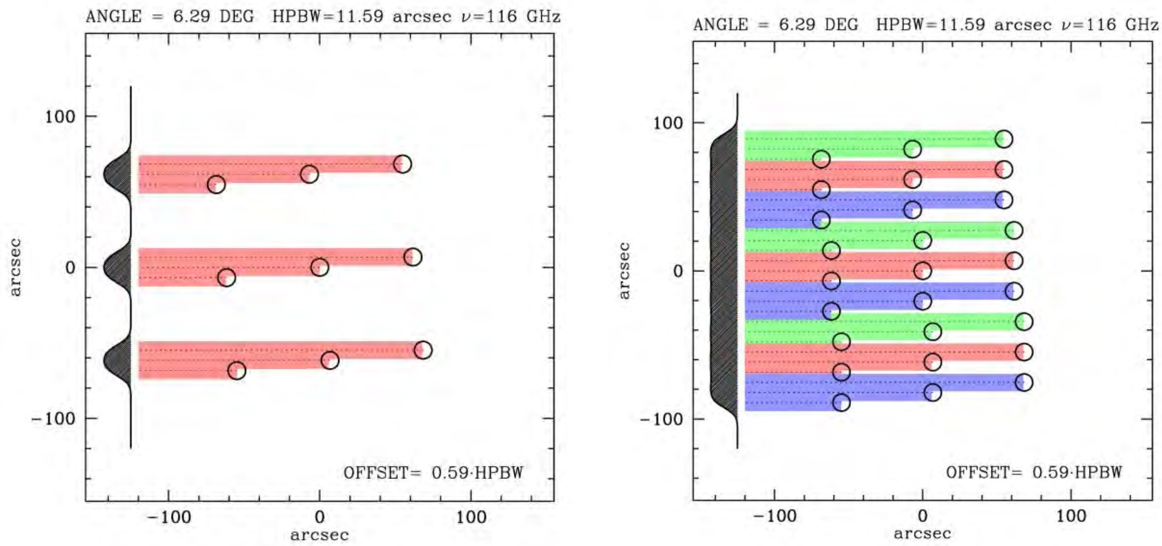


Fig. A2. Scanning geometry with the 3x3 array for mapping at 116 GHz. The array is oriented at an angle of ≈6 deg with respect to the scanning direction. Three sub-scans with 0.59 HPBW offset allow achieving near-Nyquist sampling of the source. The overlapping of the beams is shown on the left of each panel (courtesy of M. Murgia).