# Tri-band receivers for the INAF radio telescopes: from procurement to acceptance tests

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## Abstract

In less than 30 months, three different tri-band receivers have been developed for the three Italian radio telescopes. The receivers allow simultaneous observation of three different frequency bands: 18-26 GHz, 34-50 GHz and 80-116 GHz. Each receiver delivers at its output ports a total of 112 GHz bandwidth in two polarizations. The receivers have been designed, fabricated and tested in KASI laboratories and will be mounted in the secondary foci of the INAF radio telescopes as soon as several upgrades to the infrastructures are completed.

## 1 Introduction

In 2018, the Italian National Institute for Astrophysics (INAF) was awarded by the Ministry of Research and University with 18.7 M€ for the upgrade of the 64-m Sardinia Radio Telescope (SRT, [1]) to operate at high frequency (up to 116 GHz) [2]. This upgrade included a new receiver simultaneously operating in three different frequency bands (central frequencies: 22, 42, and 100 GHz). Furthermore, two additional receivers were planned for the other INAF 32-m radio telescopes: Medicina and Noto.

This tri-band receiver is conceived to measure at low frequency (~22 GHz) the phase fluctuations due to tropospheric water vapor and then apply the corrective term at high frequencies (~100 GHz) [3]. Nowadays, this technique is well-established in millimeter-wavelength Very Long Baseline Interferometer (VLBI) observations.

The supply of the three receivers was commissioned by INAF to the Korean Astronomy and Space Institute (KASI). The technical offer from KASI was based on a compact tri-band receiver proposed for the Korean VLBI Network (KVN, [4]) and optimized for the INAF requirements.

This contribution will go through the main steps of the development process, starting from tender requirements and procurement (Section II), the receiver design (Section III), and finally the laboratory characterization (Section IV).

## 2 Procurement

On November 2019, the call for tender "Supply of three compact and simultaneous three-band microwave-receiving systems for the three Italian radio telescopes" was issued by INAF. The tender was awarded to KASI with a bid price of 2 785 000 € and in March 2020 an early start activity kicked off the project.

The scope of the work was the supply of three receivers, each of them composed by a quasi-optical system to split the incoming electromagnetic wave in three different frequency bands. The following receiver for each frequency channel is composed of a passive feed system plus two Low Noise Amplifiers (LNA), a down-conversion section to the Intermediate Frequency (IF), a local oscillator (LO) generator and a noise calibrator. Further components included in the contract are the cryo-refrigerator (compressor excluded) and the vacuum pump, the mounting assembly to install the receivers in each focal cabin and the final characterization. The supply does not include the instrumental phase calibration, the Monitoring and Control (M&C) unit, the acquisition system for data reduction and the installation and integration onto the INAF antennas. The main technical requirements of the receiver as incorporated in the Statement of Work (SoW) of the tender are listed in Table I.

It is important to mention that the penalty paid for the frequency simultaneity is a receiver noise temperature higher by around a factor of 3 in K- and Q-band and a factor up to 1.5 in W-band with respect to state-of-the-art single-band receivers. This is mainly due to losses introduced by the quasi-optical components, such as the dichroic filters, operating at ambient temperature and whose contribution is not masked by the receiver gain.

While the receivers for Noto and Medicina turn out to be identical, as the two radio telescopes are almost twins, the receiver for SRT has slightly different characteristics in terms of the mechanical interface to the anchoring system and on the required illumination of the mirrors.

After three intermediary milestones (Preliminary Design Review: May 2020; Critical Design Review: October 2020; Completion of purchase orders: April 2021), the final acceptance test has been held in July 2022. Then, one month after, all receivers reached the Medicina site. This brings to an overall duration of the contract, which was one of the more challenging constraint of the funding scheme, of less than 30 months.

**Table I.** Main technical requirements of the tender.

| Parameter | K-band | Q-band | W-band |
|---|---|---|---|
| Frequency range | 18-26 GHz | 34-50 GHz | 80-116 GHz |
| Output frequency range | 4-12 GHz | 2-18 GHz | 2-18 GHz (x 2 separate channels) |
| Frequency coverage | Simultaneous observation capability | | |
| Output Polarization | Right- & Left-hand circular | | |
| Receiver noise temperature | ≤ 60 K | ≤ 70 K | ≤ 100 K |
| Receiver net gain | 35±4 dB | 42±2 dB | 43.5±4 dB |
| Sun observation | Feasible without compressing the active stages of the receiver | | |
| Amplitude calibration | By means of a commercial noise source coupled to the receiving chain | | |
| Physical temperature | Double stage: ~70 K and ~20 K | | |
| Dimensions | Compact solution to fit the limited space available at INAF radio telescopes | | |

# 3 Design

The receiver element enabling the frequency-simultaneous observation is the quasi-optics (element (a) in Fig. 1). An optical bench, operating at room-temperature, composed of dichroic low-pass filters, elliptical mirrors and lens is responsible for splitting the incident electromagnetic wave into three frequency bands. An additional feature of this section is to provide a frequency independent illumination efficiency, which means flat aperture efficiency over each band, keeping good cross-polar (≤ -25 dB) and loss (≤ 0.4 dB) levels. This system is designed by applying Gaussian beam theory and then validated by the commercial software GRASP [5].

Each frequency band is then coupled to a feed-system, shown in Fig. 2, composed of a circular corrugated horn, a polarizer and an ortho-mode transducer (OMT). Additionally, after the OMT, a noise signal is injected in the two polarization channels for receiver amplitude calibration. The two output ports of the OMT are connected to cryogenic LNAs developed by Low Noise Factory. It is remarkable to note that only one cryogenic chamber is used to host the three frequency channels (element (b) in Fig. 1). The cooling time of the chamber to reach a steady cryo-temperature is about 50 hours. Finally, coaxial (in K-band) and waveguide (in Q- and W-band) vacuum feed-trough allow the RF signal to exit from the cryo-chamber. The vacuum and cooling are performed through commercial components: dry and turbo pumps and CTI-350 refrigerator, respectively (element (d) in Fig. 1). Four temperature sensors are installed inside the chamber to monitor the temperatures of the LNAs (one for each band) and of the first stage shield.

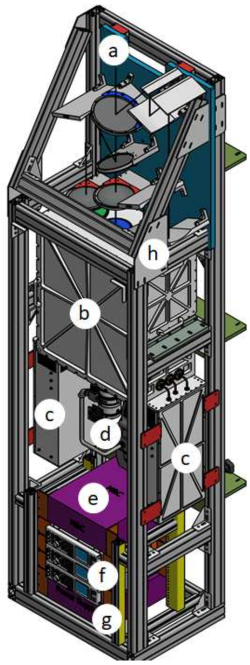


**Figure 1.** 3D drawing of the receiver for SRT. The main elements are the following ones: (a) Quasi-optics system; (b) Cryogenic feed system; (c) Warm RF/IF sections; (d) Pump & CTI-350; (e) M&C unit (provided by INAF); (f) Synthesizers; (g) Power supplier; (h) Anchoring system.

The next element of the chain is the warm RF/IF section (elements (c) in Fig. 1, one box for K- and Q-band and one for W-band only) which filters, amplifies and down-converts the RF signals. Another functionality implemented in this section is to by-pass the W-band warm amplifiers through waveguide switches in the event of observing the sun. While in both K- and Q-band, there are two parallel RF/IF chains (one for each polarization), in W-band there are four to cover both the low-band (80-98 GHz) and high-band (98-116 GHz) signals. Furthermore, additional microwave components are included in this section for local oscillator generation (based on a continuous wave produced by an external commercial synthesizer, (f) in Fig. 1) and for noise source generation, which is then carried to the cold section. The external synthesizers are set to generate fixed frequencies in K-band

(14 GHz) and in Q-band (16 GHz then multiplied by 2) to feed the LO port of the mixers, while in W-band the synthesizers can be tuned (around 16 GHz then multiplied by 6) to cover also the 4-GHz inter-band between low and high band (96-100 GHz). The local oscillator frequency of the low part of W-band is higher than the RF and therefore this results in an inverted IF band. Most of the components of this section are purchased off-the-shelf from electronic suppliers and have been carefully selected and measured to satisfy the receiver performance in terms of gain, linearity (in particular for solar observations), out-of-band rejection and noise contribution.

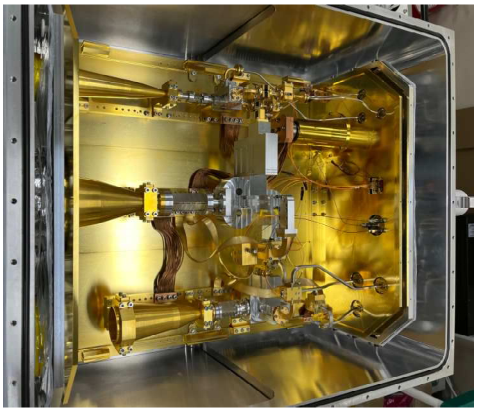

**Figure 2.** Picture of the passive components inside the cryogenic chamber. The three feedhorns are visible in the left side of the photo.

The receiver's operations are monitored and controlled by a standard equipment implemented in the INAF radio telescopes and responsible for the following operations (element (e) in Fig. 1): *i)* bias of the cryogenics LNAs; *ii)* vacuum and cryogenics; *iii)* switches in the W-band RF/IF warm section and *iv)* on/off of the noise source with a 80 Hz switching.

The receiver anchoring system has been designed to be compatible with the mechanical support available in each radio telescope. A Finite Element Analysis was carried out to assess the robustness of the whole system for several rotation scenarios (corresponding to different antenna pointing).

The overall dimensions of the receiver for the SRT are: 2.85 x 0.76 x 0.55 m (H x W x D) and the total weight is 330 kg. Similar dimensions apply also to the Noto and Medicina receivers.

## 4 Characterization

The RF performance have been measured by KASI both for the individual components of the receiver and for the final assembled solution. A short selection of the most significant results is presented in this contribution.

The feedhorns designed by KASI have been intensively measured to assess the illumination function both in far-field in an anechoic chamber and, together with the quasi-optical circuit, in near-field conditions. By applying the equations reported in Section II.C of [6] to the measurement conducted in near-field and then transformed to far-field, the efficiency contributions of the receiver developed for SRT have been computed (see Fig. 3). Overall, the aperture efficiency is above 78% with, especially in W-band, remarkable flatness across the band. In this analysis, the actual surface RMS of the antenna and the blockage effects from struts and secondary mirror are not taken into account.

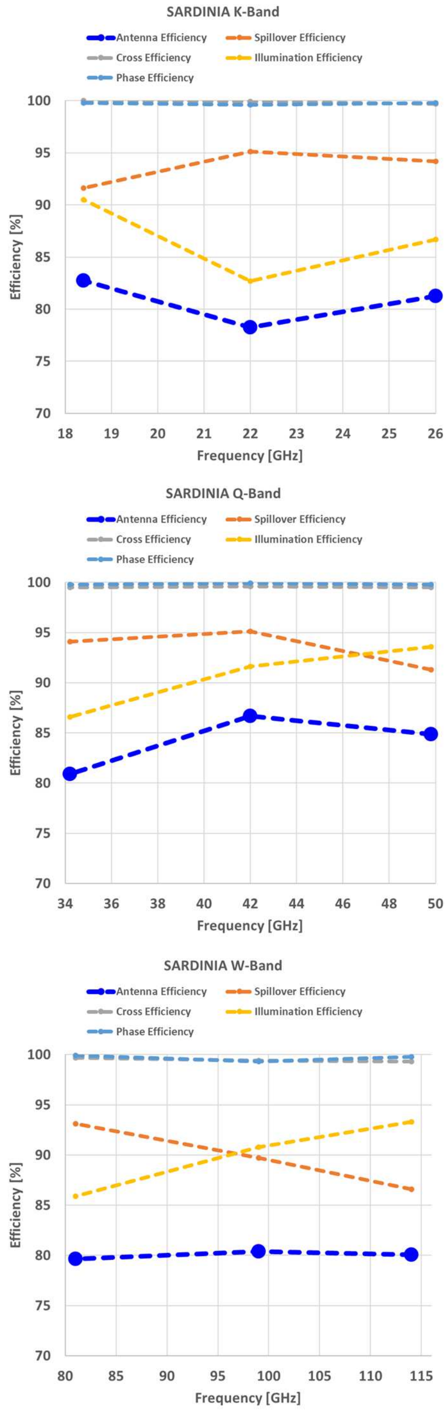


**Figure 3.** Aperture efficiency and individual efficiency terms for the tri-band receiver of the SRT.

By alternating a cold load immerged in nitrogen liquid and an ambient temperature load in front of the optical bench, it has been possible to characterize the receiver noise temperature, gain and noise signal level. This has been done by KASI for the three receivers and the receiver noise temperature results are given in Fig. 4 for both polarizations. In K-band, all receivers work almost uniformly, well below the requirement with a value at the central frequency half of the required 60 K. In Q-band, the trend is different with the high end of the frequency band exceeding by maximum 10 K the threshold. Furthermore, Q-band shows also a peak centered at 46 GHz reaching around 110 K. This is caused by the reflection coefficient of the second low pass filter in the quasi-optics, which exhibits an anomalous resonance and introduces a loss contribution much larger (0.9 dB) than the desired 0.2 dB. In W-band, results are more scattered with the Medicina receiver fully satisfactory, while the other receivers show at the two ends of the frequency band (especially the lower) noise temperatures larger than desired. This variability is mainly due to the gain of the cryogenic LNAs, which is not fully able to mask the noise introduced by the later stages of the chain.

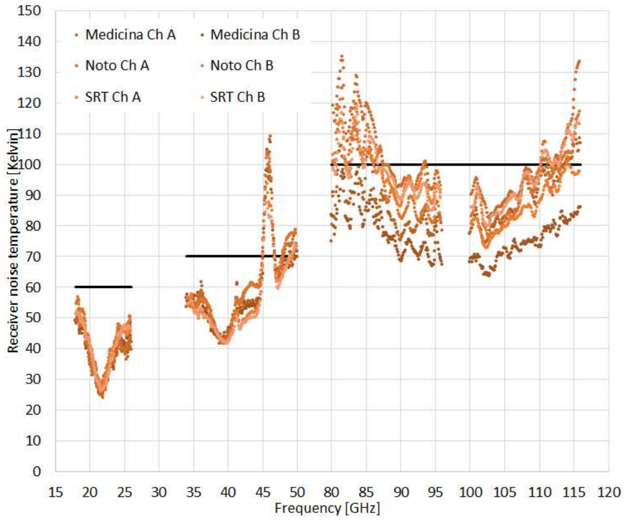

**Figure 4.** Receiver noise temperature of the three receivers for two polarizations (Ch. A and Ch. B) in the three bands. For W-band, LO is set to 98 GHz. However, the noise temperatures between 96 to 100 GHz can be measured by tuning the LO frequency. The horizontal black lines are the requirements (see Table I). For visual purposes, the gap between 50 and 80 GHz has been shortened to zoom in on the actual receiver response.

The final result plotted in Fig. 5 is the measured gain of the receivers. Both in K- and in Q-band there are two amplifiers (one cryogenic and one warm) in each receiving chain, while in W-band in addition to the cryogenic and warm amplifiers there is also a third amplifier operating at the IF. A good uniformity in the gain is reached by all receivers and all polarizations, but overall the gain is lower (up to 10 dB) than the requirements especially at the extremes of the frequency ranges. It is important to highlight that additional gain is expected to be given by external sections of the receiver such as the active optical link and switch matrix to transport and route the IF output to the digital acquisition units.

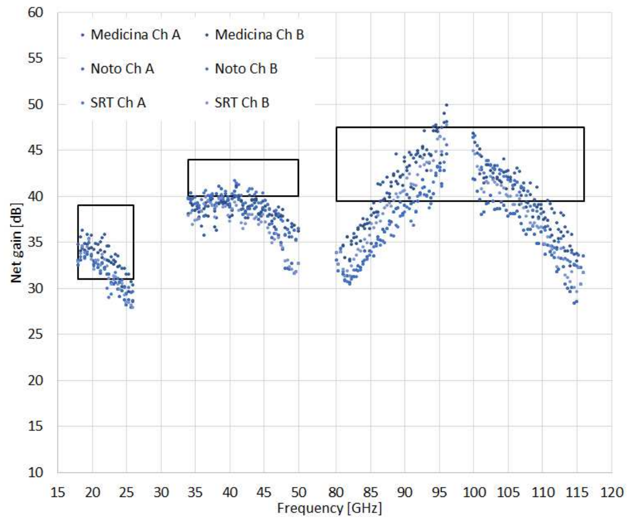

**Figure 5.** Overall gain of the three receivers for two polarizations (Ch. A and Ch. B) in the three bands. For W-band, LO is set to 98 GHz. However, the gain between 96 to 100 GHz can be measured by tuning the LO frequency. The black rectangles are the requirements (see Table I). For visual purposes, the gap between 50 and 80 GHz has been shortened to zoom in on the actual receiver response.

## 5 Conclusions

Through a fruitful and disciplined cooperation between KASI and INAF, it has been possible to develop three frequency-simultaneous receivers for the Italian radio telescopes. The final acceptance test has proven that the technical requirements are met. Only the insertion loss of one dichroic in a narrow frequency region of Q-band and the receiver noise temperature in the low part of W-band for SRT and Noto receivers are not fully compliant with requirements but these issues are not expected to have a significant impact on the scientific performance of the receivers. In 2023, at each site, local staff will proceed with the receiver installation and the first light. After that, the INAF radio telescopes will join the mm-VLBI network.

## Acknowledgements

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