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MISTRAL observations during the commissioning phase at the Sardinia Radio Telescope

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Abstract. MISTRAL is a new facility instrument open to the scientific community that will help investigate the 'missing baryon' problem, as well as many other scientific cases from extragalactic astrophysics to solar system science. The MIllimeter Sardinia radio Telescope Receiver based on Array of Lumped elements KIDs (MISTRAL) is a cryogenic W-band camera, operating at 90 GHz (frequency band 78-103 GHz), equipped with 415 LEKIDs which has been mounted at the Gregorian focus of the 64 m fully steerable radio telescope Sardinia Radio Telescope (SRT), in Italy, in May 2023. MISTRAL will take advantage of its 12$''$ of angular resolution, a 4$'$ wide instantaneous field of view and its high sensitivity, which will make this camera one of the most competitive instrument to observe the mm-wave sky. MISTRAL is currently under technical commissioning and in this contribution we will report the current status and performances of the instrument as well as the operations done during the first year of technical commissioning.

1 General picture and science cases

Cosmic Microwave Background (CMB) surveys observe the sky with excellent sensitivity, but with limited angular resolution. In fact, the resolution is limited to $\sim 10'$ for satellite

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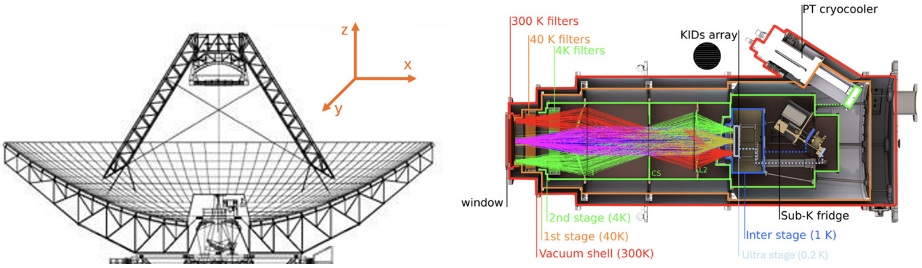

Figure 1. *Left*: Scheme of the Sardinia Radio Telescope structure, where is reported the directions along which the secondary mirror can be moved. *Right*: Scheme of the MISTRAL cryostat and its ray tracing, where PT stands for Pulse Tube and

experiments and to ~1′ for ground experiments, but there is also interesting science to investigate at higher resolution (~ 10″). To achieve this high resolution at 90 GHz, we need a millimeter camera on a large single dish radiotelescope, with a diameter of 50-100 m. MISTRAL is one of the few instruments in the world that has such a resolution. Thanks to its coupling with the Sardinia Radio Telescope, a 64 m Gregorian radiotelescope, MISTRAL can observe with an angular resolution of about 12″ and a field of view of 4′ . This opens the doors to study a plethora of science cases. Through the Sunyaev-Zel'dovich (SZ) effect, an anisotropic spectral distortion of the CMB, we can observe hot gas embedded in large-scale structures, such as the Cosmic Web and galaxy clusters [1], and study their morphology, evolution, and substructures. MISTRAL will not only be used for SZ observations, but it also lends itself well to the study of galactic and extragalactic science, exploiting the dust, free-free and synchrotron emission, as well as solar system science, proto-planetary discs, and star-forming regions.

2 MISTRAL, the instrument

The *MIllimeter Sardinia radio Telescope Receiver based on Array of Lumped elements KIDs* (MISTRAL) is a new millimeter camera, that will observe in the W-band between 77 and 103 GHz, installed at the Sardinia Radio Telescope (SRT) [2] thanks to a Programma Operativo Nazionale (PON) funding[1]. SRT is a versatile instrument, equipped with active optics, that can host up to 13 different receivers observing between 0.3 and 117 GHz (in single-dish or VLBI modes). Thanks to the PON funding, four new receivers were installed at the SRT, including MISTRAL, and upgrades have been done to the antenna, such as the metrology (pointing, tracking, and active surface) to allow more efficient observations in the W-band.

The MISTRAL heart is an array of 415 Lumped Element Kinetic Inductance Detectors (LEKIDs) [3] working at 200 mK [4] and currently not polarization sensitive. MISTRAL cryostat scheme is shown on the right in Figure 1, where the ray tracing of the quasi-optical system of MISTRAL is also shown [5]. This optical system is innovative and the result of studying the specific coupling of MISTRAL with the SRT, to reduce aberrations and stray light, but also widen the nominal diffraction-limited field of view (FoV) of the SRT at 90 GHz from 1.4′ to our 4′.

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[1] `https://sites.google.com/a/inaf.it/pon-srt/home?pli=1`

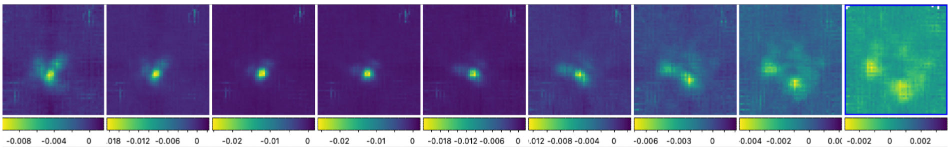

Figure 2. Example of focus scan in which the secondary mirror is moved from TZ=-3 mm to TZ=-11 mm (relatively to the nominal position). The colorbar is adapted to each image.

3 Technical commissioning

MISTRAL was installed at the SRT in May 2023 and technical commissioning was done from April 2024 to June 2025. We obtained on average five observational nights per month, about 400 hours of observation in total. During the technical commissioning, we tested the correct functioning of the instrument and its coupling with the radiotelescope. First, we tested the cryogenics and LEKIDs performances. During cryogenic tests, we observed that the fridge can hold a temperature of about 200 mK for the entire observational night up to 24 hours, with very good stability. In fact, for the duration of the cycle, the temperature stability is 1 mK, while in one hour, we have a stability of 0.1 mK [4, 6]. The stability of the temperature during observations is very important because it affects the performance of the detectors. Regarding the LEKIDs performances, we saw that on average, on an observational night, we have about 350 alive pixels.

An important process that we had to study during the technical commissioning was the mirror alignment. These with MISTRAL are the first W-band (so high angular resolution) observations from the SRT and because of this, the setup of the antenna and the mirror alignment that worked well for other receivers at lower frequencies (so with lower angular resolution) did not work for a more resolute instrument like MISTRAL. As described below, the study of the mirror alignment resulted in the creation of new look-up-tables (LUTs) for DISCOS[2], the control software of the antenna. Implementing these LUTs will allow the software to automatically manage the alignment during standard observations. The secondary mirror (M2) of the SRT can be moved and rotated along the x, y, and z axes (left panel of Figure 1), that respectively are the azimuth (TX), elevation (TY) and vertical (TZ) directions. We studied the alignment only along the TY and TZ directions because we did not find evidence of instability along the TX axis. This process consists of finding the TY-TZ position of the secondary mirror (M2) that minimizes the beam area and maximizes the amplitude of the signal (without aberrations) for as many elevations as possible. The process has to be repeated for different elevations because when observing at different elevations, we are tilting the antenna causing mechanical deformation due to gravitational stress to which we have to add thermal deformation depending on the ambient temperature and solar illumination, so the position of the secondary mirror can slightly change, and we have to adjust for that small shift.

Moving M2 along the TZ axis consists of focusing the instrument. With this operation, we are adjusting the distance between M2 and MISTRAL in order to find an optimal beam. To find this position, we make maps of a point source for different positions of M2 and after fitting the beam in each of them, we find the best TZ position (the one that has the maximum signal but minimum beam size). In Figure 2 an example of a focus scan is reported, where you can see how the focus changes when the mirror is moved a few millimeters.

After focusing, we have to correct the aberrations that affect the beam. Specifically, we found to be affected by coma aberration (as shown at the top of Figure 3), a type of aberration

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[2] `https://discos.readthedocs.io/en/latest/user/srt/source/index.html`

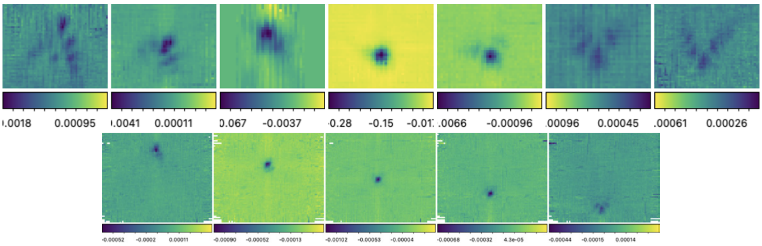

Figure 3. Two different scan of a point source while moving the secondary mirror in the TY axis where the two main effect of this process are shown. *Top*: The evolution of the coma aberrations when moving M2 of few centimeters (±2 cm from nominal position). *Bottom*: Pointing offset introduced by moving M2 of few centimeters (±5 mm from nominal position). The colorbar is adapted to each image.

typical of telescopes with parabolic mirrors that have components off-axis. This aberration can be removed by moving M2 in the TY direction. However, when moving in this direction, we also introduce a pointing offset. In fact, as shown at the bottom of Figure 3, in each TY position, the source is shifted with respect to the center of the map (up or down, because we are moving in the elevation axis) and the TY position for which we do not have coma aberration not necessarily coincide with the one in which the source is centered on the map. Consequently, after aligning the mirrors, we also had to correct the pointing model of the antenna.

In order to perform mirror alignment in the fastest way possible, we came up with the strategy of observing TZ-TY matrices, an example is shown on the left in Figure 4, for as many elevations as possible, and from these matrices we extract the aberration merit function, shown on the right in Figure 4, with which we can study the evolution of the focus and the coma aberration. We estimated the aberration merit function (or surface) computing, for every TZ-TY position and after fitting every beam with a 2D circular Gaussian function, the ratio between the signal of the primary beam and the signal outside the beam itself, in order to have an estimate of how much aberration we have. After analyzing the merit function and finding its minimum, we find the best TZ-TY position for that specific elevation. Repeating this process for many elevations, we built the TZ and TY LUTs for MISTRAL, shown in Figure 5. These LUTs are now implemented in DISCOS and these corrections are done

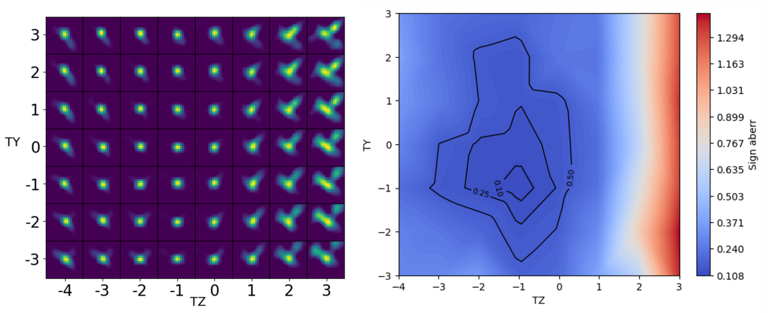

Figure 4. *Left*: TZ-TY matrix. The shifts along the y and z axis are in units of mm. *Right*: Aberration merit surface extracted from the matrix, where 0.10 contour line highlights the position of the minimum of the merit function, so the best TY-TZ position for this elevation.

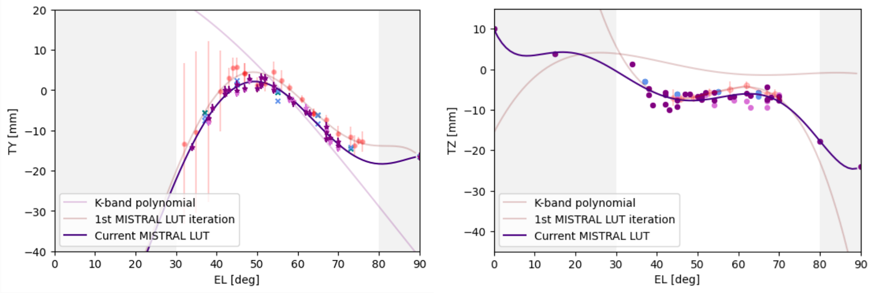

Figure 5. *Left*: TY look-up-table. *Right*: TZ look-up-table. The gray bands in the plots indicate the elevations below and above which MISTRAL can not operate. The K-band polynomials (purple line) in the two plots indicate the LUTs that were used before MISTRAL.

automatically. To test the right functioning of these LUTs, we observed point sources with other receivers using MISTRAL LUTs and we found an improvement of their performances as well. However, it is worth specifying that the TZ LUT can be considered only as an indication of where the focus is, given that the focus depends heavily on the thermal condition of the antenna. This means that every time the environmental temperature changes during the observations, we have to focus the instrument. We adjust the focus for this small shift using a software that, after observing a point source at different TZ positions of the secondary mirror, finds the best focus (TZ) position with the optimal beam (minimum beam size, no aberration and maximum source signal).

In addition, with point source observations, we were able to map the position of each detector, as shown to the left of Figure 6, but also characterise the beam of MISTRAL, as shown to the right of Figure 6. We found a primary beam Full Width at Half Maximum of 12$''$, perfectly consistent with our expectations of 12.2$''$. In the latter plot, the reported beam is an average beam of all KIDs, fitted with a model consisting of a primary Gaussian profile plus a halo. The halo is essentially a broader Gaussian that accounts for residual aberrations and the power scattered out of the primary beam due to the surface roughness of the telescope mirrors.

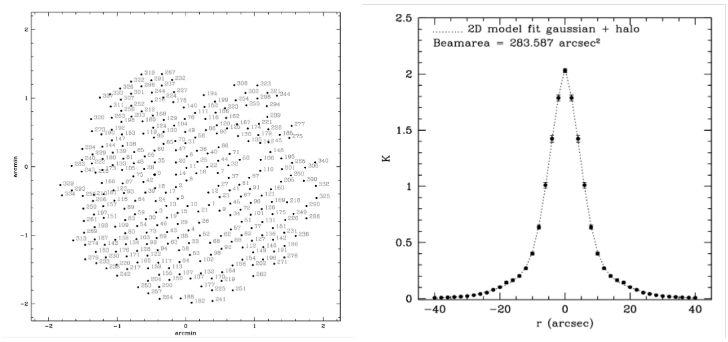

Figure 6. *Left*: Pixel recognition. *Right*: 2D profile of MISTRAL beam.

Lastly, we report two preliminary maps made during the commissioning as a test of mapping extended sources. Figure 7 shows three 8$'$x8$'$ maps made in one hour of the Orion

Nebula (left), of the supernova remnant Cassiopeia A (center) and of the Crab Nebula (right). A detailed analysis of these images properties will be presented in a forthcoming commissioning paper.

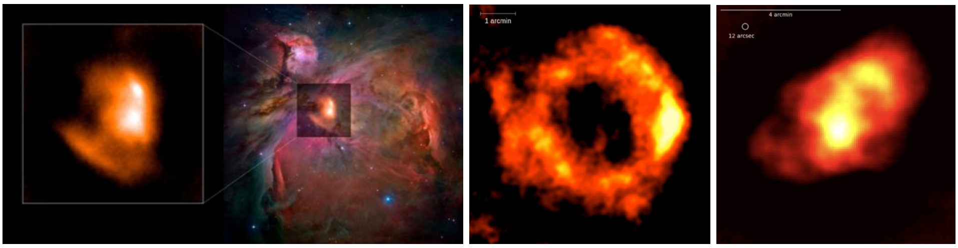

Figure 7. *Left*: Zoom-in of a map made with MISTRAL of the Orion Nebula, with an overlay with a wider-field image obtained by the Hubble Space Telescope. *Center*: Image of the supernova remnant Cassiopeia A, where is shown the scale of 1′. *Right*: Image of the Crab Nebula. All three images show a 8′x8′ region and the scales of the FoV and angular resolution of MISTRAL are reported in the Crab Nebula image.

4 Conclusion

In this contribution, we present MISTRAL, a new millimeter camera installed at the SRT that observes at 90 GHz with an expected angular resolution of $\sim 12''$. MISTRAL is equipped with a 415 LEKIDs array and, thanks to its innovative optical system, it has a diffraction-limited field of view of $4'$. During the technical commissioning, we installed the instrument on the antenna and checked its proper functioning. We report a cryogenic cycle that can reach 200 mK with an hold-time between 16 and 24 hours with a very good stability. An important aspect that we had to investigate during the commissioning was the mirror alignment; in fact, the high precision of MISTRAL highlighted a small misalignment of the primary and secondary mirror, negligible for other low-frequency instruments operating from the SRT up until the usage of MISTRAL. To correct this effect, we moved the secondary mirror along the y- and z-axes and observed the TZ-TY matrices, from which we were able to build the look-up-tables for MISTRAL, now implemented in the DISCOS software that automatically manages these corrections. These corrections have greatly improved the quality of the beam, but, despite this, we still see small residual aberrations that can only be corrected by acting on the active surface of the telescope, currently under investigation. We are continuing to work on improving the performances of this instrument which represents a valuable addition to the group of few instruments capable of observing with such high angular resolution.

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