MHROC - Millimetron Heterodyne Receiver for OI and CII

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Concept

Millimetron will provide the unique possibility to observe the main cooling lines of the interstellar medium, the fine structure lines of ionized carbon [CII] and atomic oxygen [OI], invisible from the ground, at an unprecedented spatial resolution. The 10m unfoldable dish promises a more than three times better spatial resolution compared to the Herschel Space Observatory or the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA).

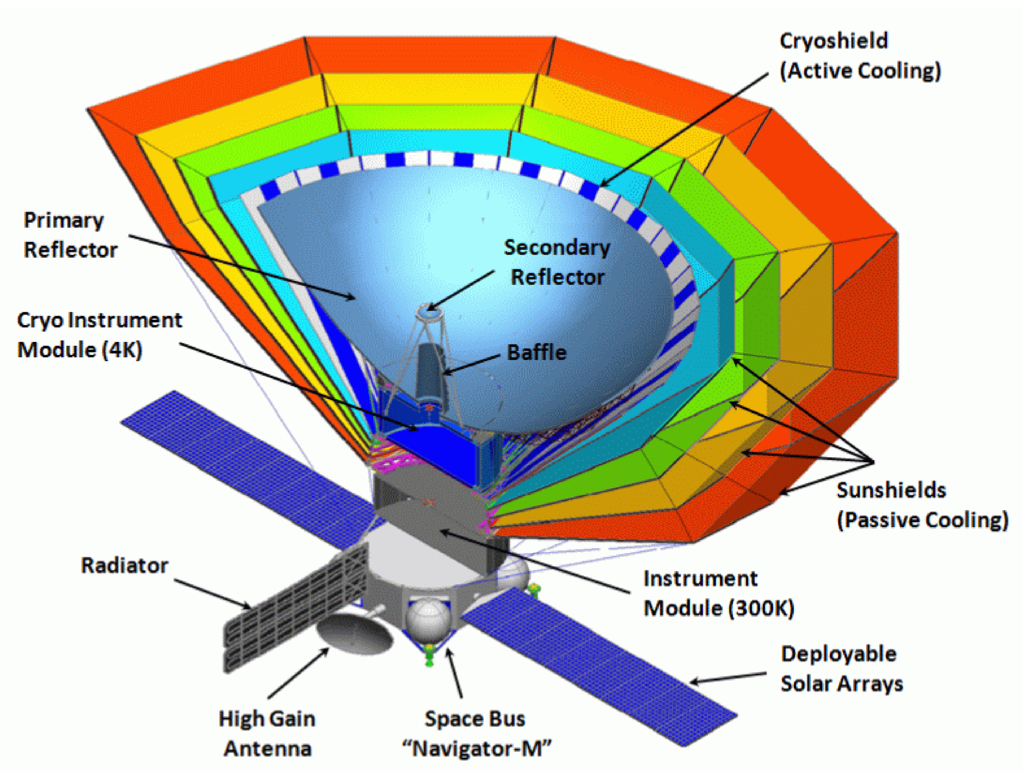

FIGURE 1: Concetual drawing o the Millimetron design, based on the proven mirror concept of RadioAstron (from Smirnov et al. 2015)

Based on the experience with upGREAT onboard SOFIA in terms of instrument design, qualification, and scientific needs we propose to build a heterodyne receiver array for Millimetron dedicated to high spectral and spatial resolution mapping of star formation in galaxies.

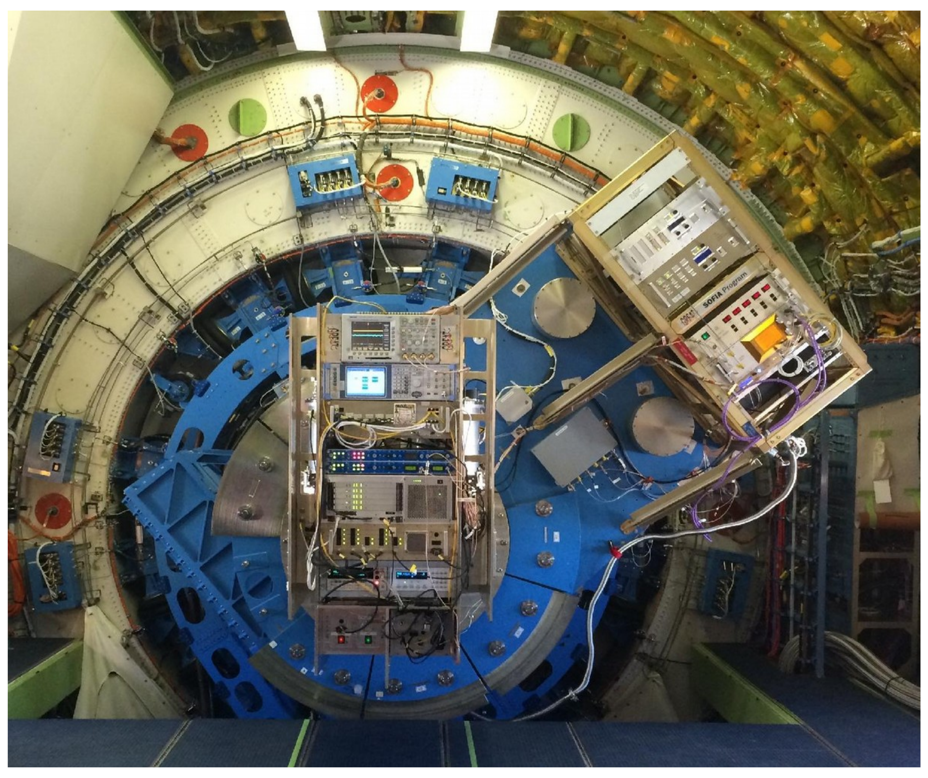

FIGURE 2:upGREAT on SOFIA is a dual frequency, dual polarization array receiver. The 1.9THz channel consists of 14 pixels.

MHROC can inherit a large fraction of the design, components, and NASA qualification from upGREAT. The receiver array in upGREAT is arranged in a hexagonal structure promising the densest possible packing in the focal plane. One array consists of 7 pixels arranged in a hexoganal ring around a central pixels. An expansion with a second ring around that structure is easily possible.

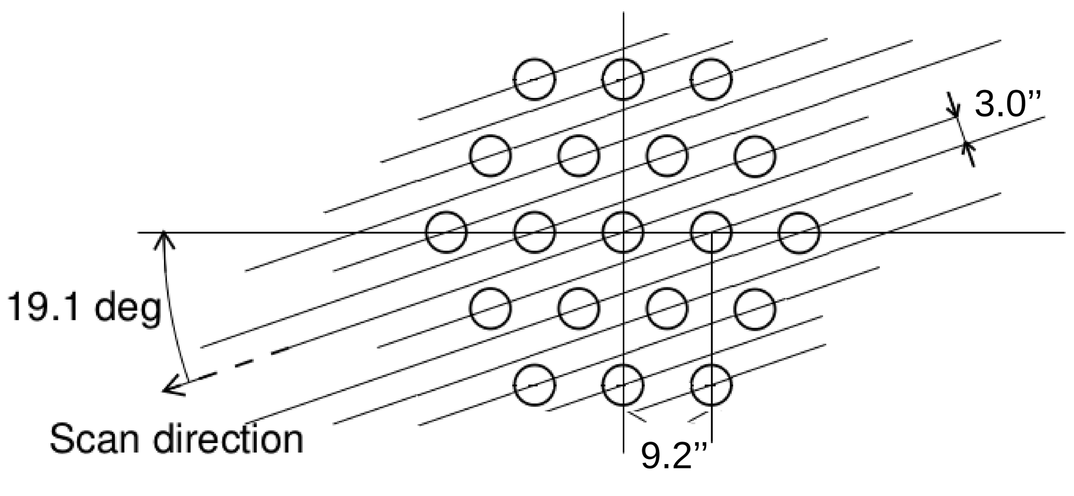

FIGURE 3: Proposed arrangement of the receivers in the focal plane for one polarization. With the 10m telescope dish each pixel corresponds to a beam of 3.8'' FWHM. The pixel spacing then is 9.2''. An optimum mapping strategy is given by a scan titling the array by 19.1degrees. With a line distance of 3.0'' achieved in this way, a fully sampled map can be obtained with two coverages.

The hexagonal structure consists of 19 HEB mixers. Both polarizations would add up to 38 receiver channels. Practically, the array size is, however, limited by the available cooling power at the 4K stage and the power consumption of the backends onboard the satellite.

The scientific need for MHROC

Radiative feedback from massive stars in dense clusters regulates the dynamics, thermal balance, and chemistry of the ISM. The [CII] emission from bright PDRs is one of the best tracers of massive, star formation (Goicoechea et al. 2015). If spectrally resolved, it can measure the dynamics of radiative feedback. Galaxy evolution models critically depend on an observational calibration of this kinetic feedback. It will enable us to interpret the fraction of starburst galaxies in terms of a global star formation history in the universe. Moreover, [CII] observations provide a tool to quantify the thermal feedback of star formation on the surrounding interstellar gas by measuring the gas heating efficiency (Okada et al. 2013) that governs the distribution of the phases of the interstellar medium.

However upGREAT observations have proven that the two main cooling lines, [CII] at 158µm and [OI] at 63 µm, are usually optically thick so they do not trace the underlying structure.

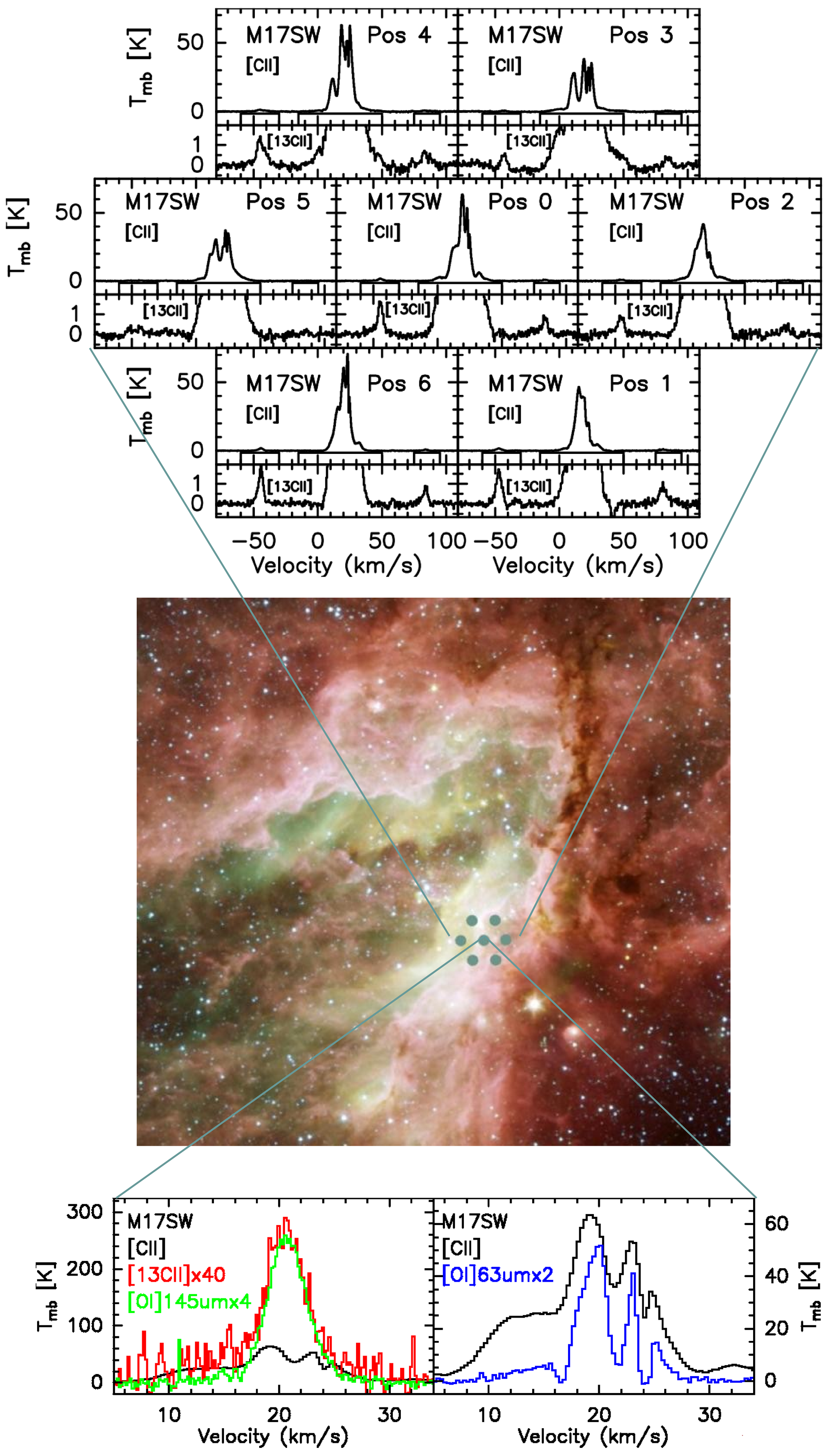

FIGURE 4: upGREAT spectra measured in M17SW (Guevara et al. 2019, 2020). The *upper plot* shows the [^{12}CII] and [^{13}CII] spectra taken in one footprint. They demonstrate a variability of the shape of the spectra well below the array spacing, that actually continues down to the resolution limit. Both the emission and the absorption components vary significantly between neighbouring pixels indicating unresolved substructure. Furthermore, [^{12}CII] and [^{13}CII] lines show completely different profiles, those of [^{12}CII] are dominated by saturation and self-absorption in an optically thick configuration. The *lower plot* compares the different line profiles for the central pixel, including the two [OI] transitions. The ground state line is completely dominated by foreground absorption. The line hardly traces emission from the source itself. In this example, the upper 145µm [OI] line shows a velocity profile that is very similar to that of [^{13}CII], measuring the true emission from the source, but in other sources this similarity between the two lines is not observed..

This can be overcome by using optically thin lines such as the [^{13}CII] lines or the [OI] 145µm line. By observing the lines of [^{12}CII], [^{13}CII] and [OI] at 145µm MHROC is the ideal tool to trace star-forming regions affected by the UV radiation of young stars, i.e. to measure both star-formation activity and the dynamic feedback effect from star-formation, including triggered star-formation.

In this approach the spatial resolution of Millimetron is essential because the existing velocity resolved observations show substructure well below the spatial scale that is resolved today (Fig.4).

Implementation

The MHROC design is aiming for simplicity. Only a narrow the frequency range between 1.90THz and 2.07THz containing the most important lines is to be covered. This allows for an optimization of mixer and Los for a narrow frequency range. In terms of the mixer units junctions and mixer blocks as produced for upGREAT can be reused..

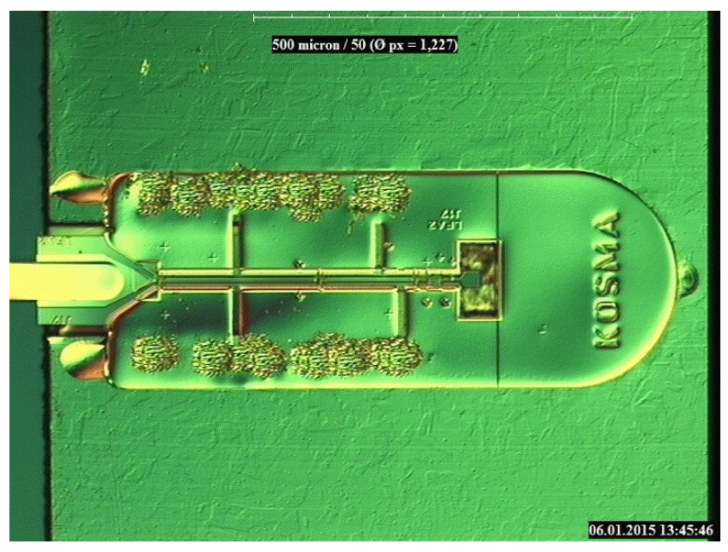

FIGURE 5: Two-Microscope photograph of a 2.0THz HEB device mounted on its waveguide block developed for upGREAT. The actual device is seen right of the center of the image. The conical shaped waveguide probe antenna can be recognized by eye. The HEB microbridge left of it cannot be seen at this resolution (from Pütz et al. 2015).

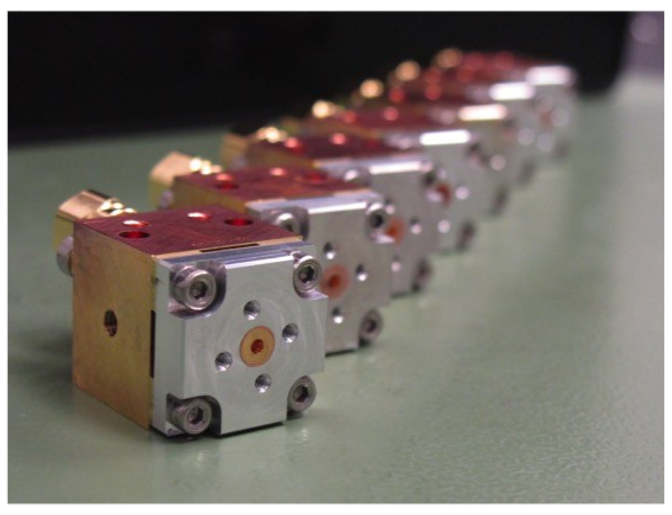

FIGURE 6: Mixer blocks without feed horns. In the focal plane each mixer block occupies a square of 16.5mm edge size (Pütz et al. 2015).

At 2 THz both multiplier-chain based or QCL based local oscillators (LOs) are available. For the multiplier-chain based approach we could use reuse design and qualification from HIFI but will be limited in the array size by the output power. A QCL-based LO is possible because of the limited frequencies but has not reached space test readiness levels yet.

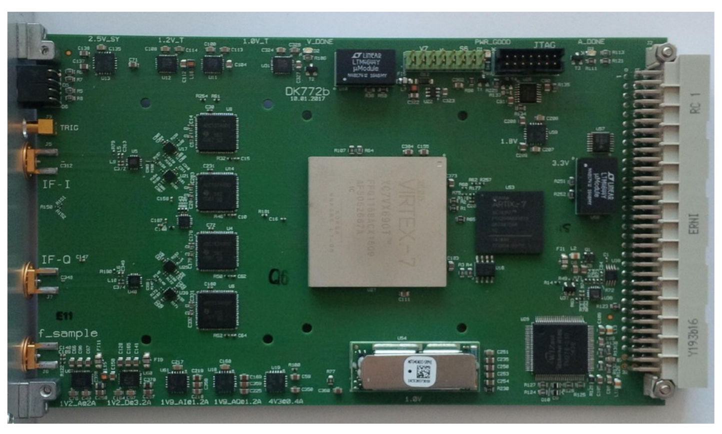

FIGURE 7: dFFTS board used for upGREAT without heat sink The FPGA allows to digitize 64k channels over 4GHz bandwidth but MHROC requirements rather favour fewer channels.

As backends digital Fast-Fourier-Transform-Spectro-meters (dFFTS) are available, actually providing more bandwidth and spectral resolution than needed for MHROC. The current FPGA-based design requires about 50W electrical power per backend channel. An ASIC-based design promises to work with about 10W per spectrometer but requires additional qualification efforts.

Open questions

The actual MHROC array size is limited by the available cooling power at the 4K stage and the electric power supply for the dFFTS backends. The number of pixels could be as low as 7 and as big as 38 without major change of the instrument design. With today's technology we arrive at a need of 3mW cooling power at 4K.

When using a large array and two polarizations, it needs to be decided whether the two polarizations get a fixed assignment to the two frequencies and which LO design can pump all pixels.

A thorough design study is, however, only possible when DLR funding for the project becomes available.