ALHAMBRA (ADVANCED LARGE HETERODYNE ARRAY FOR MILLIMETER BAND RADIO ASTRONOMY)

A. Hughes[1], S. Maret[2], P. Salomé[3], E. di Folco[4], M. Gerin[3], F. Gueth[5], K. Schuster[6] and S17 participants

Abstract. In this contribution, we provide an overview of the science drivers and instrumental concept for ALHAMBRA (Advanced Large Heterodyne Array for Millimeter Band Radio Astronomy), a dual-band, multi-beam receiver instrument that is currently under study for the IRAM 30m telescope. We conclude with a brief summary of ideas emerging from a round-table discussion about ALHAMBRA during workshop S17 *Recent and future developments of NOEMA and the IRAM 30m telescope.*

1 Introduction

Observations of the cold Universe at millimeter wavelengths are fundamental to understanding the processes of star and galaxy formation. From molecular clouds in our Galaxy to the diffuse circumgalactic medium around distant galaxies, millimeter observations allow us to measure the spatial distribution of the cold interstellar gas, its physical and chemical conditions, and the gas motions that govern mass assembly across a wide range of physical scales. Dust continuum emission traces the mass of the cold ISM, while spectral line measurements trace gas kinematics. Wide-field mapping of millimeter spectral lines, however, is hampered by the extended, low surface brightness nature of the emission. A comprehensive observational picture of mass assembly from galaxy to core scales requires instrumentation capable of reaching much deeper sensitivities and mapping much larger areas of the sky than current facilities allow. The most effective path forward is the development of a large heterodyne multi-pixel camera. ALHAMBRA (Advanced Large Heterodyne Array for Millimeter Band Radio Astronomy) is an advanced dual-band, multi-beam receiver concept for the IRAM 30m telescope. By combining a large number of pixels with excellent receiver noise performance and wide instantaneous bandwidths, ALHAMBRA would provide an order-of-magnitude gain in mapping speed and sensitivity. This capability would open a broad range of scientific frontiers, from studies of cometary and planetary atmospheres to the kinematics of gas flows in star-forming filaments, galactic outflows and accretion onto nearby disks, and the dynamics of large-scale structure in the early Universe.

2 ALHAMBRA Instrument Concept

ALHAMBRA is conceived as a modular, high-resolution, dual-band, dual-polarization, multipixel receiver system, with a 7×7 array operating at 1mm (A230) and a 5×5 array at 3mm (A090). Key design features are summarized in Table 1. ALHAMBRA's architecture is designed to maximize mapping efficiency and sensitivity across both the 1 and 3 mm atmospheric windows. Each band will be hosted in its own cryostat with dedicated biasing, IF processing, and readout electronics. The instrument can operate in single-band mode or in simultaneous dual-band mode, with dichroic filters ensuring co-alignment of the beams on the sky. A K-mirror de-rotator will stabilize the orientation of the pixel array during observations.

[1] IRAP, U. Toulouse, OMP, 31400 Toulouse, France
[2] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[3] LUX, 61, av. de l'Observatoire, Paris, 75014, France
[4] LAB, Allée Geoffroy Saint-Hilaire, 33615 Pessac, France
[5] IRAM, 300 Rue de la Piscine, 38400 Saint-Martin-d'Hères, France

Feature	A230		A090	
	Goal	Baseline	Goal	Baseline
Frequency Range	196 – 280 GHz	200 – 276 GHz	67 – 117 GHz	72 – 116.5 GHz
LO Range	208 – 268 GHz	212 – 264 GHz	79 – 105 GHz	84 – 104.5 GHz
IF Range	4 – 12 GHz	4 – 12 GHz	4 – 12 GHz	4 – 12 GHz
TRX for 80% of the RF band		$\leq$ 83 K (SSB)	50 K (SSB)	$\leq$ 50 K (SSB)
TRX at any frequency		$\leq$ 138 K (SSB)	$\leq$ 60 K (SSB)	$\leq$ 70 K (SSB)
Spread in TRX between pixels	$\leq$ 10%	$\leq$ 30%	$\leq$ 15%	$\leq$ 30%
Backend resolution	$\geq$ 32kHz	$\geq$ 64kHz	$\geq$ 32kHz	$\geq$ 54kHz
Array layout	7x7	7x7	5x5	5x5
Pixel on sky separation at lowest frequency		> 2 HPBW		> 2 HPBW
Alignment accuracy between pixels (on sky)	$\leq 0.5''$	$\leq 1''$	$\leq 0.5''$	$\leq 1''$
Co-alignment between sub-arrays for 7 pixels (on sky)	$\leq 1''$	$\leq 2''$	$\leq 1''$	$\leq 2''$
Co-alignment between sub-arrays for central pixel (on sky)	$\leq 0.5''$	$\leq 1''$	$\leq 0.5''$	$\leq 1''$

Table 1. Specifications for the ALHAMBRA instrument determined during ALHAMBRA Workshop II (November 2024)

The system will use sideband-separating (2SB) mixers, providing high spectral purity and broad instantaneous coverage. A new generation of Fast Fourier Transform Spectrometers (FTS) will serve as backends, with the full configuration offering up to 296×4 GHz bandwidths. In dual-band operation, this translates to a data rate approaching 25 TB per day. ALHAMBRA's data volume will thus necessitate major upgrades to the 30m telescope's data management infrastructure including high-throughput pipelines for calibration and imaging, expanded archiving capabilities, and new control software for the modular front-end.

By combining large pixel counts, low receiver noise, and wide bandwidths, ALHAMBRA will achieve an order-of-magnitude gain in mapping speed and sensitivity. This step change will make it possible to carry out wide-area, multi-line surveys that are unfeasible with existing facilities (see Table 2).

3 Key Science Drivers of ALHAMBRA

Science opportunities for ALHAMBRA range from Solar System studies to the earliest epochs of cosmic structure formation. Within the Solar System, the instrument will allow sensitive mapping of minor species in cometary atmospheres, shedding light on the chemical inventory of primordial material and the processes that release molecules into the coma. It will also enable flexible, multi-epoch monitoring of planetary atmospheres, such as Venus, where mesospheric winds and thermal variability remain poorly understood.

In our Galaxy, ALHAMBRA will transform studies of star formation. For the first time, it will be possible to conduct complete surveys of dense cores across entire molecular clouds, linking core mass distributions to the stellar initial mass function. Wide-area surveys of the Galactic plane will complement continuum projects by providing kinematic information, thereby delivering a true three-dimensional view of cloud structure and evolution. At the same time, ALHAMBRA's broad frequency coverage will permit chemical inventories of molecular clouds and wide-field mapping of molecular emission lines beyond the bright low J CO transitions, tracing density, temperature, and ionization conditions with unprecedented spatial completeness. Sensitive multi-line

Receiver	**Telescope**	**Freqy [GHz]**	$N_{\rm pix}$	$N_{\rm pol}$	$\mathbf{T}_{\rm RX}$ **[K]**	**BW [GHz]**	**Status Notes**
SEQUOIA	FCRAO/LMT	115	4x4	1	$55-90$	0.8	At LMT since 2017
FOREST	NRO45m	115	2x2	2	$15-30$ DSB	2x2	2015 -
ARGUS	GBT	115	4x4	1	$40-80$	1.5	2017 -
SSAR	Delingha 13.7m	115	3x3	1	55	1	2010 -
7BEE	NRO45m	115	7	2	50		In prep
HERA	30m	230	3x3	2	120	1	2001 - 2003
HARP	JCMT	345	4x4†	1	105 - 185	2	2005 -
LASMA	APEX	345	7	1	80 - 100	2x6	2017 -
SUPERCAM	HHT/APEX	345	8x8‡	1	250 DSB	0.25	2012 -
CHAMP+	APEX	690/810	2x7	1	300/600		2007 - 2020
CHAI	CCATp	460/810	8x8	2			In prep

Table 2. A list of relevant past, existing and planned multibeam receivers at mm and submm wavelengths.
† 13 operational pixels. ‡ 49 operational pixels

mapping will illuminate the dynamics of hub-filament systems, allowing us to follow how gas flows along filaments onto the dense hubs where high mass star formation is triggered.

In nearby galaxies, ALHAMBRA will enable systematic studies of feedback and disk-halo connections. By mapping thick molecular disks and outflows in edge-on systems, it will constrain the roles of star formation and active galactic nuclei in regulating gas cycling. In the Local Group, the telescope will be able to map dense gas tracers across the disks of M31 and M33 at cloud-scale resolution, delivering the first spatially complete inventories of dense molecular gas in external galaxies. Beyond the Local Group, ALHAMBRA will make it possible to trace molecular gas in cluster environments, following its distribution in bridges, tails, and filaments that link interacting galaxies.

At higher redshifts, ALHAMBRA will allow statistical studies of molecular gas in proto-cluster environments at cosmic noon, probing the role of environment in galaxy growth. Even more ambitiously, it will enable the detection of [C II] emission in dusty proto-clusters at redshifts beyond six, offering a unique opportunity to observe the earliest stages of galaxy cluster assembly.

In summary, observations with ALHAMBRA will enable a coherent view of mass assembly across environments and cosmic epochs, linking the physics of small-scale star formation to the build-up of large-scale structure.

4 Summary of Roundtable Discussion

Following the presentation of the instrument concept and its principal science drivers, the workshop participants discussed how best to organize the French community to take full advantage of ALHAMBRA's capabilities. The discussion centered on scientific synergies, technical requirements, data management, and community coordination.

A key point was the strong complementarity between ALHAMBRA and other facilities operated at the IRAM 30m telescope, notably the NIKA2 camera (and its planned successor, NIKA3), as well as the NOEMA interferometer. Together, NIKA2 and ALHAMBRA will provide a complete view of the interstellar medium: NIKA2 tracing the dust continuum emission, and ALHAMBRA mapping the molecular gas in spectral lines. The wide-field mapping capabilities of ALHAMBRA will also be essential for recovering the extended emission filtered out by interferometric observations with NOEMA, ensuring that total fluxes and large-scale gas dynamics can be properly characterized.

Participants emphasized the importance of high spectral resolution, particularly for Galactic science cases where narrow line profiles carry crucial kinematic information. While the instrument's final configuration remains under study, the use of Fourier Transform Spectrometer backends provides inherent flexibility and can readily accommodate high-resolution modes as needed.

The expected data volume from ALHAMBRA will present new challenges for data management. Although the computational complexity of single-dish heterodyne data is considerably lower than that of interferometric datasets, the storage and handling of tens of terabytes per day will require a dedicated strategy. Developing efficient pipelines, archiving systems, and user tools will be essential, and synergies with emerging national and European data infrastructures—such as the future French node of the SKA Regional Centres—should be explored.

Finally, the discussion turned to community organization and scientific coordination. Many of the key science goals identified for ALHAMBRA will naturally require large collaborative efforts, potentially in the form of IRAM Large Programs. The appropriate balance between Large Programs and open General Projects remains to be defined, but early coordination will be important to maximize scientific return. The community agreed that dedicated meetings focused on specific scientific themes should be organized in the coming years to prepare for future observing campaigns and to foster collaboration between Galactic, extragalactic and instrumentation teams.

We thank all the S. participants for their contributions and lively discussion, and the SF2A 2025 LOC for their assistance with the workshop organisation.