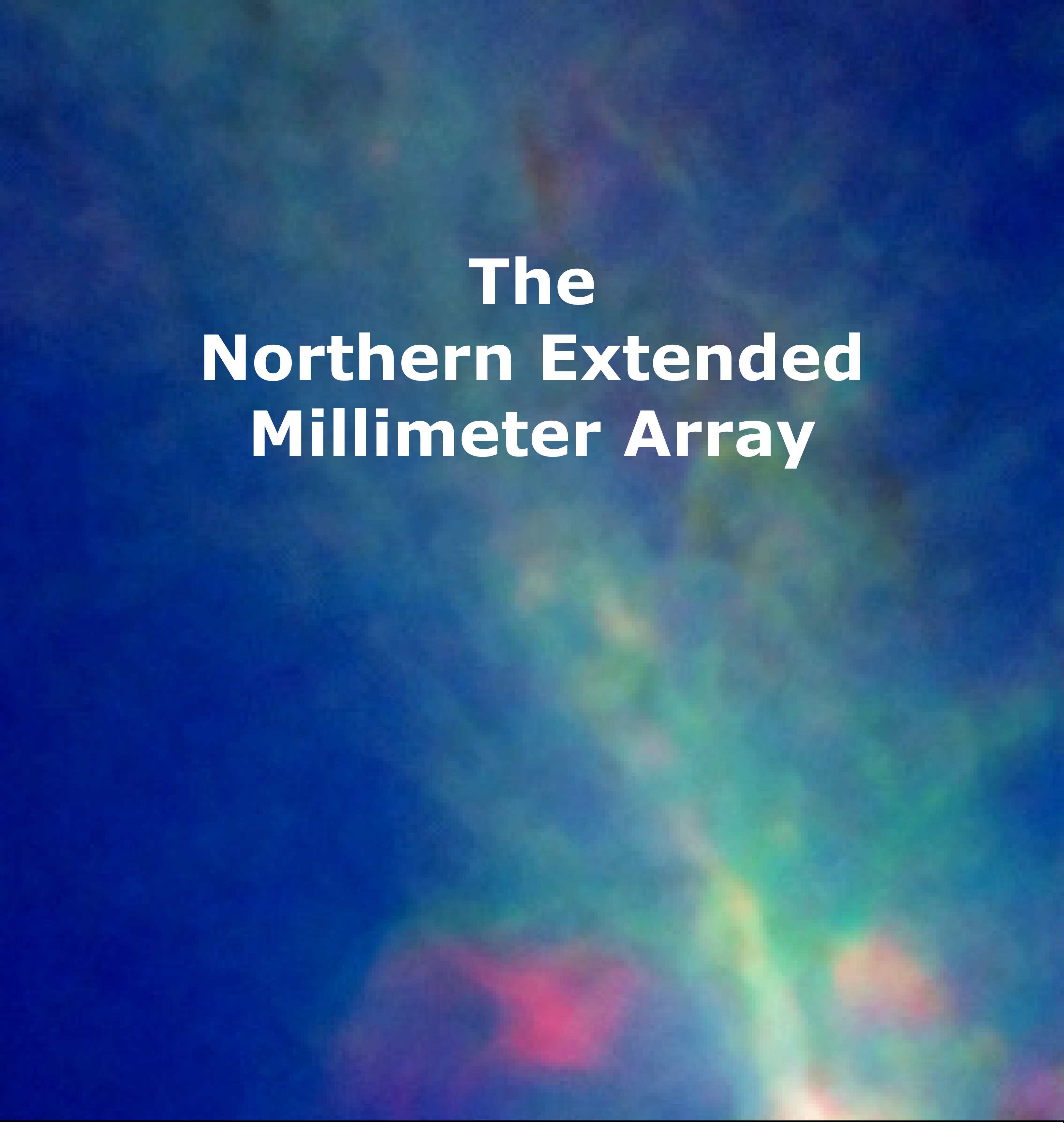
The Northern Extended Millimeter Array



Front Page:
* upper background: Part of the northern sky as seen by SPITZER, courtesy NASA/JPL-Caltech/Univ. of Wisconsin
** lower image: artist impression of NOEMA at the Plateau de Bure site.

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The IRAM NOEMA* Project

A Feasibility Study

Introduction

This study outlines the scientific and technical aspects of a major upgrade of the IRAM Interferometer on Plateau de Bure. The basic elements of the upgrade are:

- **Doubling of the number of 15 m antennas from 6 to 12**
- **Extension of the East-West base line from 0.8 to 1.6 km**
- **Increase of the total IF bandwidth from 8 GHz to 32 GHz**

This extension of the current IRAM PdB interferometer will transform the observatory into a completely new and extremely powerful facility which will give the IRAM community a unique access to the millimeter and near submillimeter window. The study presents key elements of the science case for such an upgrade, a description of the technical building blocks involved, the organization and finally a first schedule and budget outline for construction and operation.

NOEMA Performance

NOEMA will provide significant improvements in two key areas: sensitivity and spatial resolution. Figure 1 draws a continuum sensitivity comparison between NOEMA,

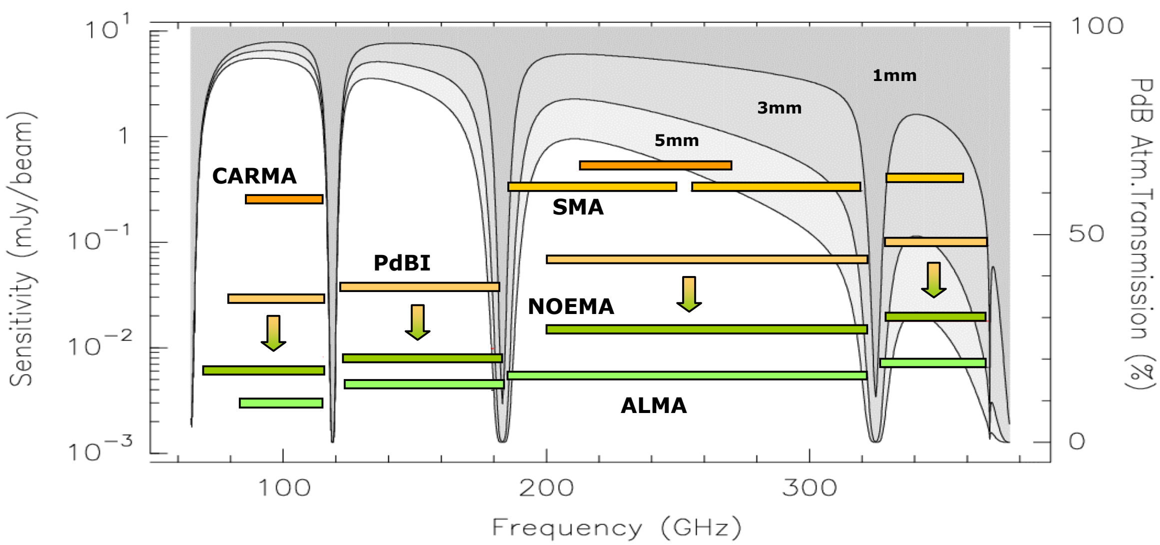

Fig. 1: Point source sensitivity to continuum emission after 8 hrs of current (SMA, CARMA 2008, PdBI 2009) and future millimeter-wave arrays. The calculations assume a mean target elevation of 45^o, 8 hrs of integration (70% on-source), and conditions corresponding to a 1mm column of water vapor at 345 GHz, 3mm at 230 GHz and 5mm at 90 and 150 GHz (see also Annexe 1).

ALMA and three major operational interferometers (SMA, CARMA and PdBI). Compared to the present PdBI array, NOEMA with 12 antennas, assuming similar

*__No__rthern __E__xtended __M__illimeter __A__rray (noema: anc. greek for understanding and knowledge) receiver temperatures and improved aperture efficiencies, will increase the spectral line sensitivity in the four bands by a factor of 3 (factor 9 in observing speed). The gain figures become even more compelling when looking at line surveys and the continuum sensitivity: the NOEMA array equipped with sideband separating mixers spanning a total bandwidth of 32 GHz (2SB in dual polarization) will provide a gain in the continuum sensitivity by factors of 5 (or factor 25 in observing speed). This is clearly a major sensitivity breakthrough to probe, for example the weak galaxy populations at high redshift to levels well below the source confusion limits of recent extragalactic surveys at millimeter and sub-millimeter wavelengths. Similar gains will be obtained for line surveys and searches for redshifted CO emission.

Since the sensitivity to extended sources is tightly coupled to the size of the array's synthesized beam, doubling the angular resolution of the PdBI requires a 3-4 times higher sensitivity to optimally match the science requirements. With 6 elements, only an expensive investment in observing time could provide the required sensitivity. A 12-antenna array with baselines up to 1600 m provides excellent mapping capabilities with 3 to 4 times smaller synthesized beam areas and a vastly improved dynamic range (by factors > 20-100). NOEMA, with only two array configurations, will also provide a higher calibration precision, an increased observing efficiency and continuous astronomical operation in the extended configuration for more than 4 months per year. NOEMA's ability for correcting atmospheric phase variations will be a considerable asset to an efficient and flexible operation in the four millimeter bands down to a spatial resolution of 0.1".

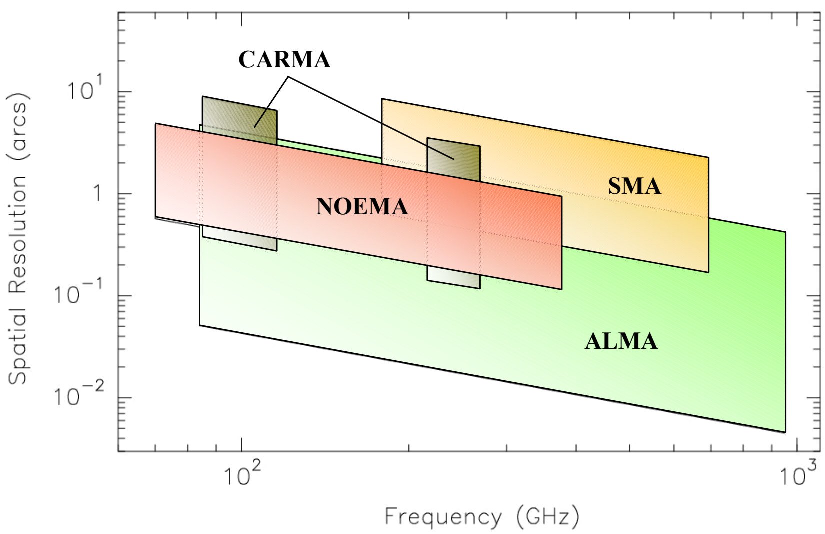

Fig. 2: Spatial resolution of NOEMA compared to current and future (sub)millimeter wave arrays. NOEMA is designed to cover the 70 – 370 GHz range.

Elements of the NOEMA Science Case

Impact of millimeter wave astronomy in a multi-wavelength world

During the last 30 years millimeter wave astronomy has conquered a central place in modern astronomy and astrophysics due to its capability to detect fundamental constituents of interstellar matter such as molecular gas and dust. Both, gas molecules and dust play key roles in the cooling of gravitationally contracting interstellar matter. They are therefore the physical regulators for star formation and their detection delivers fundamental understanding of the underlying processes. Molecular line spectroscopy in the millimeter range delivers dynamical information with very high velocity resolution and important constraints on temperature, densities and local radiation fields.

The investigation of star formation is of paramount interest for astrophysics as star formation is involved in the evolution of the universe from the cosmological processes of galaxy formation in the early universe to the formation of planetary systems in the present epoch. Stars dominate visible baryonic matter in today's universe but have been important from the end of the dark ages to now. The energetic stellar feedback through radiation and supernovae and the generation of the heavy elements by stars are key ingredients needed to form terrestrial planets and the emergence of life.

Millimeter astronomy furthermore has established gas-phase and grain surface chemistry in space, a field with important impact on astrophysics as well as on fundamental chemistry itself. Chemical processes and networks in space are of surprising complexity, with some of the detected molecules being closely related to molecules that form the basis of organic life.

It is a remarkable and lucky fact that millimeter astronomy has been able to generate its own technology with outstanding success. Current techniques and observatories are able to use near quantum-noise-limited detectors and modern observatories can detect gas and dust with very high spatial and spectral resolution out to cosmological distances. After 30 years of great technological progress, millimeter wave technology continues to be a highly dynamic field where further large steps in instrument performance are predictable over the next decade. This will lead to new and even deeper discoveries that will have lasting impact on astrophysics as a whole.

During the last decade astronomy and astrophysics have seen the overwhelming success of research through combination of information from very different wavelengths from gamma rays to radio waves. Millimeter wave observations, as the method to trace emission from cold dense interstellar material, have turned out to be a crucial pillar in this multi wavelength approach.
Multi-wavelength science and the complex nature of modern astronomy however need significant statistical sampling and comparable spatial resolution in the various wavelength bands. Pacemakers are currently large 8m class optical telescopes. These telescopes are now entering the era of large samples with the help of new high efficiency instruments such as large integral field spectrometers or ultra-widefield cameras. Upcoming millimeter wave projects should match these data not only in angular resolution but also in sensitivity and sample size. An essential aspect of sample size resides in the multi transition studies of astrophysical objects. The millimeter domain is very rich in spectral lines, therefore an observatory equipped with very powerful spectrometer has a strong multiplex advantage over one covering only a few spectral lines at once.

IRAMs' Track Record

IRAM is a leading expertise center for millimeter astronomy and as such the institute undoubtedly counts as one of the most successful scientific collaborations between European countries. The institute has managed to generate strong synergy from the wide range of available know-how in the participating countries while maintaining its lean and flexible structure. In this role IRAM has wide and outstanding impact on astronomy and astrophysics but it also is very successful in building a powerful scientific community with generations of scientists and engineers who today are active far beyond IRAM's proper tasks. IRAM is determined to maintain this role in the era of ALMA.

A large number of discoveries and breakthroughs in millimeter astronomy have been achieved with IRAM instruments. The unique combination of an interferometer and a large single dish telescope at good millimeter sites has been and will continue to be an important asset for the IRAM community. Here, and in order to focus on interferometry, we will give a non-exhaustive list of recent examples of scientifically outstanding results of the Plateau de Bure observatory.

The Plateau de Bure Interferometer, currently the most sensitive of its kind has opened up millimeter astronomy to cosmological distances with line and continuum detections of galaxies up to a redshift of 6.5. With the current sensitivities the PdBI interferometer can detect galaxies with M_{H2} of 10^{10} M_{sun} and L_{FIR} of 10^{12} L_{sun} at the highest redshifts.

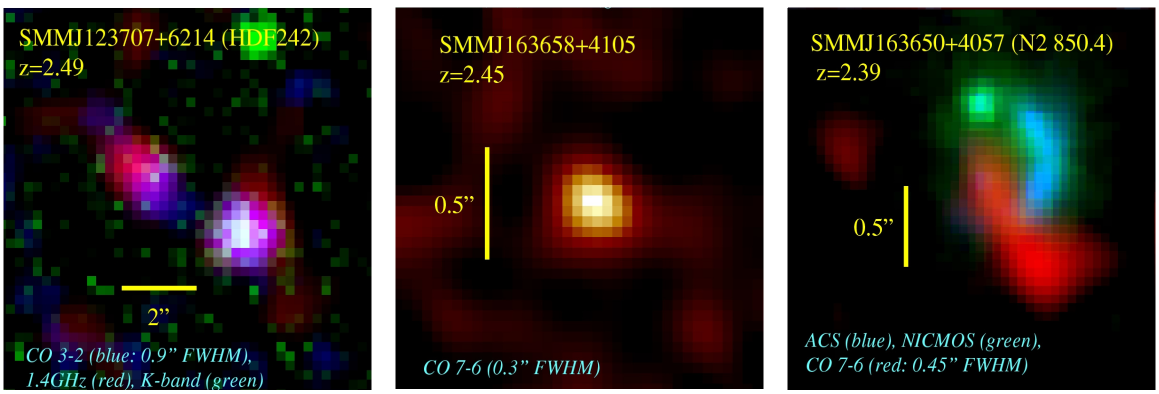

Fig. 3: High resolution maps of the ^{12}CO emission in three SMGs at z~2. Two of the galaxies show double or multiple morphologies, with complex, disturbed gas motions (Tacconi et al. 2008).

The IRAM interferometer (PdBI) has allowed by far the largest number of detections at high redshift – over the last decade more than 80% of the ^{12}CO-line detections have been made with the PdBI, including a number of notable detections of atomic (C^+) and molecular (HCN, HCO^+, HNC and CN) density and star formation tracers in e.g. the Cloverleaf and APM08279+5255. While systematic searches for ^{12}CO emission towards high redshift galaxies have significantly contributed to improving our understanding of galaxy formation and evolution, measurements of the C^+ emission have shown to harbor considerable potential as complementary and independent probes of the gas density and temperature conditions at even higher redshifts. The C^+ line is expected to stay detectable at very high redshift when the rotational lines of ^{12}CO lines shifted to the millimeter range become less favorable due to their increasingly high energy levels and the related decrease in level population. The C^+/FIR ratio might be usable as a general measure of metallicity through the epoch of galaxy formation.

Major recent highlights include the discovery of a (sub)millimeter bright galaxy population (SMG) by means of CO. SMGs are thought to represent extreme, short-lived, star-forming events in the highly dissipative merging of gas-rich galaxies (Tacconi, 2008).

The detection of absorption line systems towards quasars at various redshifts is an excellent tool to probe cold interstellar matter of the present and early Universe. The detection of such systems permits to investigate interstellar chemistry in nearby and far galaxies along the line of sight of quasars and temperature variations of the cosmic background. A broadband and sensitive interferometer like NOEMA is able to detect absorption lines of molecules in various states of excitation, abundance and density, towards a large number of quasars. The recent detection of a remarkably strong line absorption variability (z=0.9) towards the gravitationally lensed quasar PKS1830-211 (z=2.5) opens the path to investigate molecular cloud structure and composition in weak intervening lensing galaxies.

In the local universe PdBI has made important contributions to the understanding of gas dynamics and studies of physical conditions in gaseous galactic disks. With the resolution and sensitivity of PdBI it was possible to zoom into the regions where gas is interacting with jets from super-massive black holes or nuclear star bursts. Dynamical studies have provided crucial information on the mechanisms which are active when gas is transported to the central region where strong star formation can take place (NUGA, Fig. 4). These processes involve gas densities where all gas is molecular and therefore atomic hydrogen cannot be used as a gas tracer.

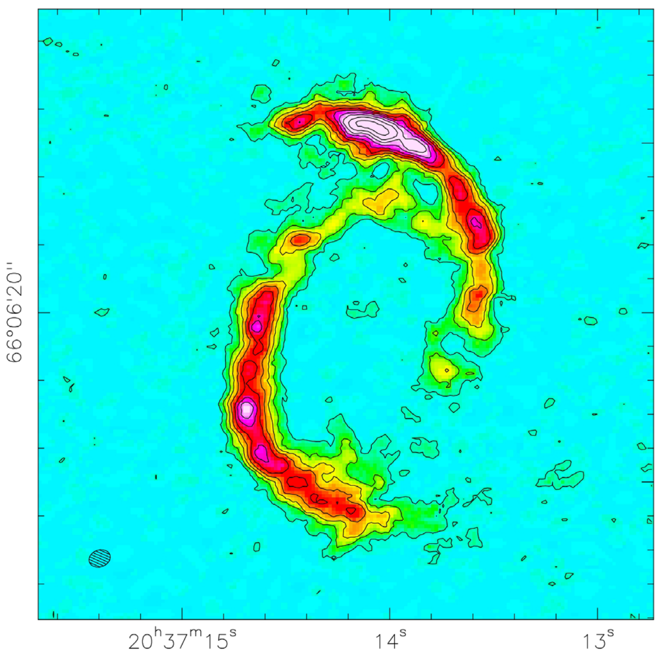

Fig. 4: The Seyfert 2 NGC 6951 is part of the NUclei of GAlaxies (NUGA) project, a combined effort to produce a high resolution and high-sensitivity ^{12}CO survey of a consistent sample of nearby AGN/starburst spirals with the PdBI. The $^{12}CO(2-1)$ (left) map shows the velocity integrated emission of warm molecular gas down to a linear scale of 50 pc, in the starbursting, circumnuclear regions of NGC 6951 (Garcia-Burillo, 2003).

With the spatial and spectral resolution of PdBI it is possible to trace also enshrouded unexpected mass distributions such as close pairs of galactic nuclei, a configuration which is not detectable in the optical/NIR due to extinction nor within the FIR due to the lack of resolution with current and upcoming space based FIR observatories. Recently IRAM Plateau de Bure studies revealed the dynamical signature of a supermassive black hole as one of the two nuclei in the prototypical ultraluminous infrared galaxy ARP 220 (Fig. 5).

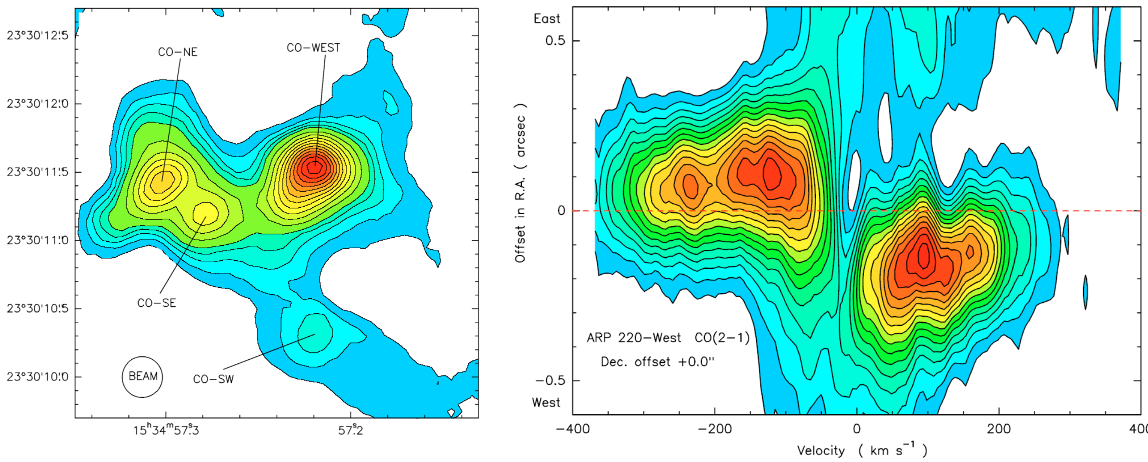

Fig.5: High resolution CO maps of the nuclear disks of Arp 220. The diagrams show the CO(2-1) integrated intensity (left) and a position-velocity cut (right) east-west, through the West nucleus, as mapped with the IRAM Interferometer. The beam (lower left corner) is 0.30". In this beam, the CO-West peak is 57 Jy km/s. Note the strong CO self-absorption in the position-velocity diagram, over the central part of the line (Downes & Eckart, 2007).

Chemical fingerprinting of galaxies by the observations of a large number of different molecular lines allows now distinguishing heating processes across the galactic disk and might ultimately allow to improve constraints on metallicity gradients.
PdBI has also allowed investigation of interaction/feedback between galaxies and the intergalactic matter. The investigation of such processes in the local universe is important in order to understand similar events in the z~2-3 epoch where interaction is more frequent and where feedback is strongly enhanced through the high star formation rate.

PdBI has played a key role in the detection and mapping of proto planetary disks. The IRAM PdB interferometer has provided for the first time data of sufficient quality to allow precision measurements of fundamental parameters like gas mass and temperature distribution, as well as the dust emission coefficients. First chemical investigations of proto planetary disks have been possible with the mapping of isotopomeres of CO and other molecules like HCO^+, HCN, CN. With these data, modeling of the chemical evolution of protoplanetary disks has made important progress. With its recently extended baselines, PdBI was able to show the presence of evacuated large holes in gaseous disks such as expected by clearing through tidal forces of giant planets. The precise measurement of Keplerian orbits within protostellar disks has also been used to make first independent determinations of the mass of young stars, a fundamental parameter very difficult to assess otherwise.

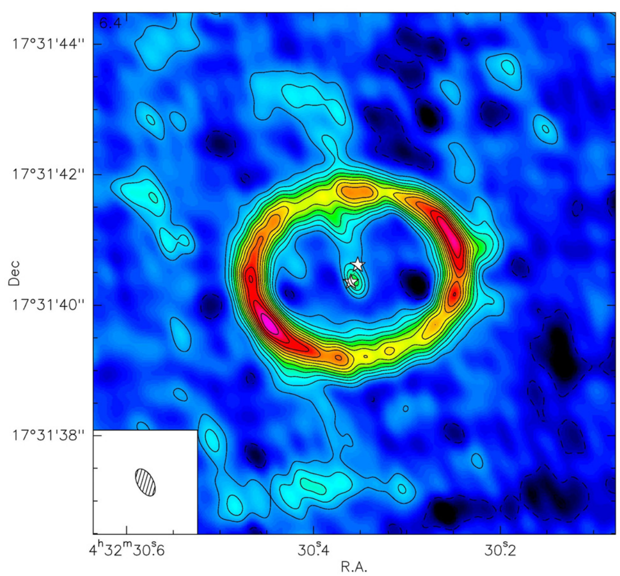

Fig. 6: Dust emission of circum binary ring around the T-Tauri binary system GG-Tau at 267 GHz. The image has been obtained in a single track and in track shared mode together with three other sources. The angular resolution is 0.25"x0.45" and allows to resolve the ring width as well as to constrain the size of the central continuum emission (Pietu et al. 2008).

The Plateau de Bure Interferometer has been able to demonstrate its cutting edge performance in many other areas. These include the high resolution mapping of mass loss processes in molecular jets from young pre-main sequence objects (Fig. 7), the investigation of the complex mass-loss pattern in late type stars and proto-planetary nebulae and investigations of chemistry and physical processes in shocks.

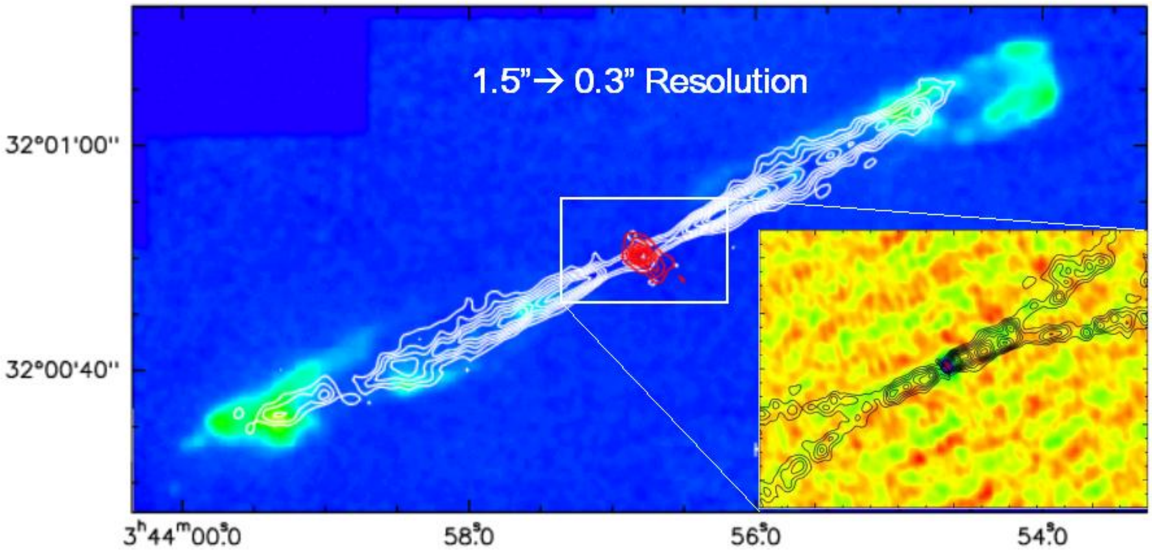

Fig. 7: Zoom into the launch region of the molecular flow of HH211 in the CO(2-1) line as enabled by the PdBI baseline extension to 750m in 2006. The measurements allow for the first time to detect a collimation in close to the source. The red contours in the large map indicate continuum emission from dust (Gueth et al 2008).

The Big Next Questions and NOEMA

Within the next years millimeter astronomy will see a shift from single object studies to observing programs where data from many objects are collected in order to allow statements on evolution and correlations with other data or environmental variables.

Some of the most important questions to address will be:

- What is and what determines the star forming efficiency throughout the epoch of galaxy formation?
- How can one find "real" pre-stellar cores? What is the path from molecular cloud structure to IMF and which are the conditions necessary to form the stars with the lowest and highest masses?
- What determines the mass and lifetime of disks around stars of different mass and multiplicity and which role plays the interstellar environment in this question?

Understanding global star formation from the first stars to the present epoch requires investigation of the gas fuel and its physical state. Molecular line emission of carbon monoxide is the preferred tracer of molecular hydrogen. To use this tracer throughout cosmological distances it will be necessary to find a reliable calibration of the CO/H_2 ratio under widely varying conditions. While for some parts of the parameter space in the local environment recent optical and UV measurements have allowed good calibration of this ratio, investigations with large samples of "calibration sources" will be required for the understanding of this factor for redshifts out to 7-8. NOEMA will be the ideal instrument for such an undertaking.

High sensitivity CO observations will allow the next step from a phenomenological Schmidt-Kennicutt description of star formation towards a physical model that takes into account different input parameters such as metallicities, temperatures and densities and other variables. Sensitive observations of the continuum dust emission will provide an independent measure of column densities and allows improving the measurement of the total luminosity.

To distinguish different star formation trigger mechanisms it will be required to spatially resolve the correlation between gas column densities and SFR. Only interferometers with sub-arcsecond resolution and the required sensitivities can achieve this goal.

Together with the wealth of information from other wavelengths with similar angular resolution and in particular with optical and NIR data, large samples of high angular resolution millimeter wave observations will allow to study the formation process of galactic bulges and therefore the origin of the stellar bulge black hole mass correlation.

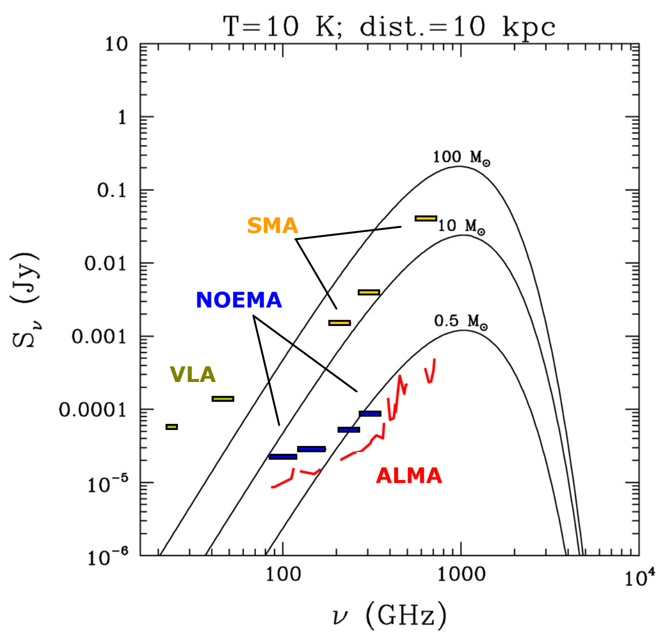

Fig. 8: Spectra of the dust emission from molecular cores at a distance of 10 kpc with temperatures of 10 K and masses as indicated beside each curve. The 3σ sensitivity of NOEMA, ALMA, SMA and the VLA assume an on-source integration time of 5 hrs (adapted from Cesaroni 2008).

Although many aspects of star formation have been revealed during the last years the basic question about which conditions have to be fulfilled in a specific case in order to start the individual star forming event remains open. As a result another key question, that of how the cloud conditions transform into a stellar IMF remains also without answer even if some investigations suggest similar mass spectrum of clouds and stars.

The very cold cores which precede star formation are very particular objects were many molecular species are frozen out onto dust grains. This effect drastically changes the observable line spectra but also the dust emission coefficient. High angular resolution, high sensitivity millimeter wave observations are required to observe the faint emission of these pre-stellar cores (Fig. 8). Interferometry with NOEMA will allow distinguishing different chemical and dynamical zones of the cores on distances out to several kiloparsecs and therefore will be able to include high mass star forming regions. Interferometry will also be essential to investigate possible seeding of stellar multiplicity through the pre-stellar core configuration. As star formation is a process of fundamentally statistical character the full picture however will only be obtained through large samples of sources in various environmental conditions.

Circum-stellar gaseous disks are the birthplaces of planets. In addition, for the higher mass objects, disks are likely to play an important role in the early phase of stellar mass accretion. With the rapidly increasing number of detected extrasolar planets it is a prime task of millimeter and submillimeter astronomy to determine the conditions under which these planets, some of them with much unexpected properties and orbits, can form and how they evolve. While ALMA has made the high-resolution observations of planet forming disks one of its main science goals, these observations with angular resolutions in below 0.05" will be very time consuming.

Up to now most detections have been made in the nearby Taurus region, a place with very particular conditions. The existing studies have shown that about 8 molecular species are accessible with the current PdB interferometer (Pietu et al 2006, 2007). It is important to extend the samples in general and in particular to include regions like the Orion molecular cloud. With its improved angular resolution, sensitivity and IF bandwidth, NOEMA will be able to generate very efficiently large samples of precise continuum detections and observations of a largely increased number of molecular lines. It will thus be possible to adapt to the need of large samples including chemical fingerprinting.

In particular the concept of the NOEMA backend where the continuum signal is always generated by the full IF-bandwidth while having simultaneous high-resolution windows for line detection will further increase NOEMA's throughput compared to ALMA which will have reduced continuum bandwidth in case of simultaneous high resolution spectroscopy.

With the sensitivity of NOEMA it will further be possible to investigate disks around brown dwarfs. Measurement on size and mass of such disks will yield precious information on possible fragmentation or ejection scenarios during the formation of such very low mass objects.

Beyond the described specific astronomical questions NOEMA will be a powerful observatory for countless other investigations. Its resolution will allow proper motion studies for a large number of objects such as molecular shocks and rapid bullets in molecular flows as well as for the movement of deeply embedded multiple systems. With its sensitivity and angular resolution, NOEMA can investigate the energy and momentum redistribution within clouds on the smallest scales. Further on it will enable to investigate the mechanisms of mass loss in late type stars with great detail and therefore help to understand how these objects nourishing interstellar space.

We conclude that **NOEMA** is the next logical step in IRAM's highly successful path. With the new sensitivities, spatial resolution and imaging dynamics NOEMA will be essential for millimeter astronomy and the astronomy of the coming decade in general. NOEMA will give to the scientists of the IRAM community/countries a powerful tool to:

- **Perform dedicated large-scale programs in the millimeter range with long-term impact in astronomy.**

- **Enable unique and exclusive access to high sensitivity observations in the northern hemisphere.**

- **Create very important science enhancement within the IRAM community by providing a powerful observatory to prepare ALMA observations at higher spatial resolution and/or higher frequencies.**

- **Test new and unconventional ideas with a powerful and flexible instrument on short timescales.**

- **Assure fundamental competence within the partner organizations in the field of millimeter interferometry for the next decades.**

With the upcoming ALMA project in the southern hemisphere, NOEMA will be placed in a competitive context. However it is important to emphasize the complementary nature of the two observatories and at the same time recall some basic differences between them. NOEMA will allow pursuing dedicated large and ambitious programs that will not be possible with ALMA in the first years of operation.
The size of the ALMA project implies that technological progress in the field will not transform into instrumental upgrades on short terms. The main obstacles for upgrades are the large number of antennas (requiring many receivers) and the very large number of baselines (requiring vast amounts of correlating power). For an array with less antennas of larger individual collecting area as proposed for NOEMA, technical advances can be turned into working instruments on much shorter timescales and with strongly reduced costs. It is thus certain that in the technologically still very dynamic millimeter domain advanced instrumentation will allow NOEMA to stay extremely competitive. On the other side we state that modern astronomy needs full sky coverage with comparable sensitivities in the crucial millimeter range and therefore both instruments will ultimately be parts of a global service to the scientific community.

The Plateau de Bure Site

The Plateau de Bure site (Longitude: 05:54:28.5 East, Latitude: 44:38:02.0) is a unique limestone plateau in the southern French Alpes at 2550 meters above sea level (see Annex 2). Its topology allows for an extended east-west baseline of more than 1600m and a north south track of 450m. The site is fully radio-protected and is largely immune to interference in the IF bands (2-12 GHz). IRAM has created a powerful facility at Plateau de Bure which allows continuous astronomical activities, antenna construction, observatory maintenance and comfortable staff lodging for up to 15 persons.

The access to the site will be stabilized in the coming year with a modern cable car. The proximity of the IRAM headquarters and the Plateau de Bure observatory allows for extremely efficient interaction between the site and the headquarters astronomy and technical staff.

Over its 20 years of operation, Plateau de Bure has turned out to be a reliable millimeter site with excellent winter conditions allowing astronomy up to 360 GHz. Although yearly variations exist, long-term site performance in transmission and phase stability is very good. Extensive water vapor radiometry shows that phase fluctuations are dominated by water vapor with structure functions that can be corrected for by 22GHz 3-band radiometry. Data monitoring over the Jan 2001 to Apr 2008 period suggests that the atmospheric phase stability (seeing) and transparency conditions are usually very good at Plateau de Bure (Fig. 9 and 10).

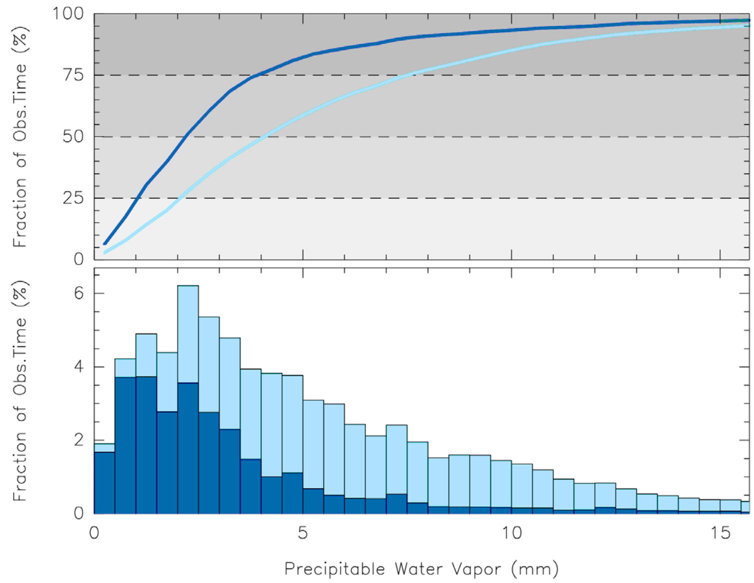

Fig. 9: Top: PdB quartiles of precipitable water vapor (dotted lines) during observation for the scheduling year 2007/2008. Curves show the cumulative distributions for winter conditions (dark blue) and the whole year (light blue). Bottom: corresponding distributive distributions. The precipitable water vapor distributions were derived from astronomical observations in the 3 frequency bands (100 GHz, 150 GHz and 230 GHz). They testify to mean columns of 2mm and 4mm water vapor, respectively for the 25% and 50% quartiles. The columns are lower by a factor 2-3 in winter conditions (November to March, dark blue histogram). Overall observing time accounts for 76% of total time in the scheduling year 2007-2008 (the 24% time-out is due to precipitation, wind, maintenance and configuration changes).

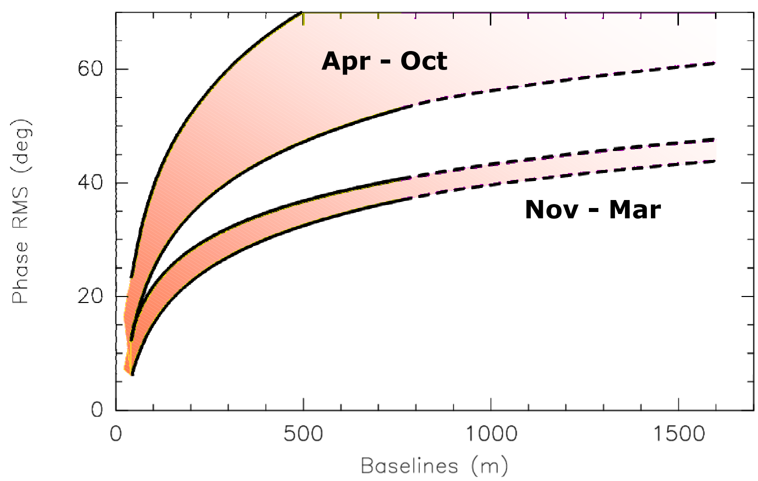

Fig. 10: Median phase noise at 100 GHz on baselines of 20 to 760 m over the Jan 2001 to Apr 2008 period. The PdB site provides excellent atmospheric phase stability in the winter period (Nov. to Mar.) for observations on baselines up to 1500m. The plotted noise medians are not corrected for calibrator elevation – this suggests that the real distribution is actually better than indicated in this diagram.

The monthly statistics on phase fluctuations shows that there is considerable potential for observing on the longest baselines (up to ~1600m) of NOEMA's extended A configuration: the January to March, day and night statistics suggests that it will be possible to observe in excellent seeing conditions that allow the use of NOEMA's spatial resolution of 0.5" at 100 GHz, for a source at a declination of 45° for ~60% of the observing time. Noting that the same period offers excellent conditions of atmospheric transparency for observations at 350 GHz, we also assume that NOEMA will be able to map astronomical sources in the A configuration with phase RMS <40° at the highest observing frequencies (350 GHz) for ~10% of the total yearly observing time. Such phase stability is adequate to map astronomical sources with a complex morphology with up to 50:1 intensity dynamic range.
The largely enhanced possibilities for self-calibration with NOEMA as compared to the current PdBI as well as the upcoming absolute phase calibration by water vapor radiometry will further improve these figures significantly. NOEMA will therefore be a highly efficient sub arcsecond imaging instrument.

Array Configurations

While the PdB array provides excellent mapping capabilities with four configurations, the NOEMA array is designed to produce images of higher dynamic range and spatial resolution, with only two array configurations.

Topological considerations preclude the possibility of a track extension to the north, but possibilities to enlarge the array in the west, south and east directions are being considered (Fig. 11) – potentially excellent areas were the target of geophysical investigations by Géolithe (elements in prelim. report Annex 1). With 6 additional antennas, track extensions of ~160m westwards and ~600m eastwards, and 5 new stations (4 antenna pads on the eastern track, 1 pad on the western track), several extended and compact configurations have been found that provide beams of startling quality.

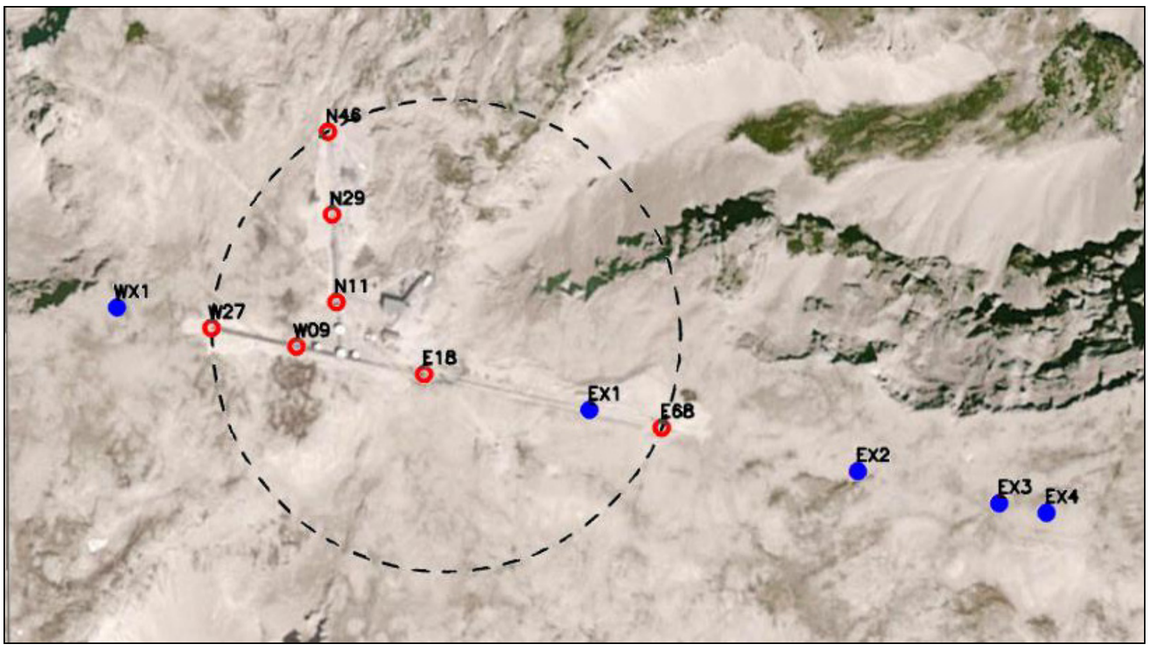

Fig. 11: The 12 locations of the A configuration pads (red: existing stations, blue: planned stations) overlayed on an aerial view of the Plateau de Bure Observatory (E is right, N is top). The tracks of the current PdB array are confined within a circle (dashed) of ~760 m diameter.

The design of these configurations has been a product of careful consideration and in a first step the properties of the synthesized beams were derived. The main aim of these investigations has been the design of two configurations (A and D – Fig. 12), well-matched to each other in the uv-coverage, that result in close to circular beams with very low sidelobe levels (Fig. 13; see Boissier et al 2008 for more details). Simulations to assess their impact on image fidelity are planned for the near future, but first analysis shows that already a single 12 antenna configuration makes it possible to significantly reduce uncertainties in the overall calibration of the array and, thereby, to guarantee a very high dynamic range in the images. Further studies will include investigations of super-compact configurations for low surface brightness objects.

With 12 antennas, there will be no configuration change in winter conditions, and not more than two changes are required per year. Realizing that changes of configuration are all the more demanding and time-consuming in winter conditions and that they are generally carried out in good to excellent meteorological conditions (e.g. in winter 2006/2007, the 4 changes have summed up to 7 days of best observing time), a significant gain in observing time and in the scheduling efficiency are expected with the Plateau de Bure interferometer scaled-up to a 12 antennas array.

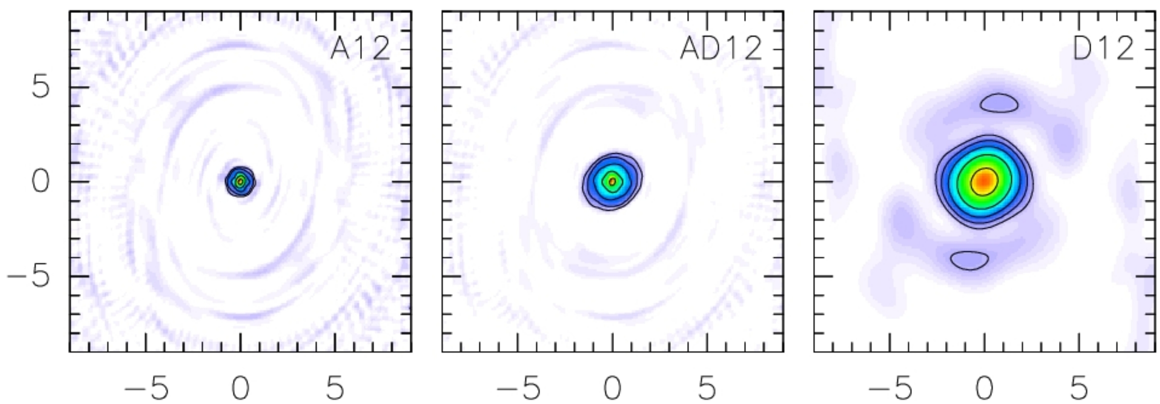

Figure 12: Synthesized beams with natural weighting at a frequency of 100 GHz for a source at declination 45°. The A configuration (left – zoom on inner 16”) provides an angular resolution of 0.58”x0.44”, the D configuration (right) an angular resolution of 2.61”x2.33” and the AD set of configurations (center) of 1.17”x1.09”. The contour levels are at 5%, 10%, 20%, 40% and 80% of the peak; colors start at 1%. The extended configuration (A) was optimized to provide the highest spatial resolution and very low sidelobes levels, while the more compact configuration (D) was designed to provide a large number of short sensitive baselines to map extended emission out to a large fraction of the primary beam (Boissier et al 2008).

These first simulations include the gradual evolution of the NOEMA project within the time-span of the construction phase and provide a number of conclusions for the array’s best scientific return and observing efficiency.

The conclusions of this investigations are: (1) it is necessary to add new antennas before building new stations, (2) any track extension calls for additional antennas, (3) with two new antennas, but without additional stations, it is already possible to halve the number of configurations of the six-element array, (4) with more than two antennas, new stations are needed to keep spatial resolution requirements to a suitable level, and (5) with six additional antennas and track extensions of ~160m westwards and ~600m eastwards, extended configurations can be designed that provide significant gain in spatial resolution and beams of excellent quality.

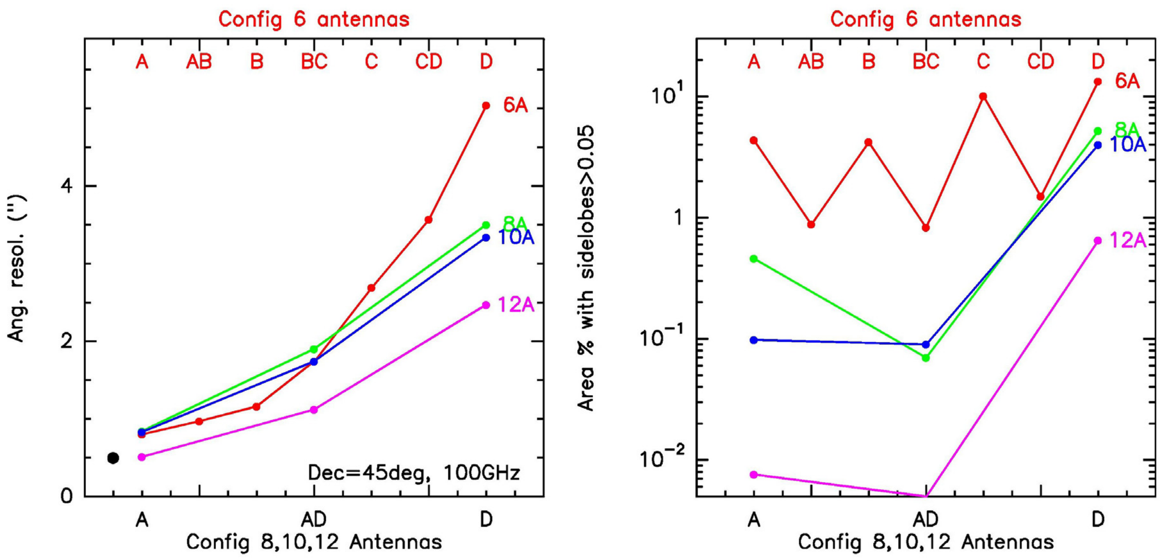

Fig. 13 Left: Comparison of the synthesized beam sizes at **100 GHz** and at 45° declination for optimized configurations of an array with 8, 10 and 12 antennas and the six-element PdB array. **Right:** Corresponding fractions of the primary beam area with sidelobes below the 5% level (Boissier et al 2008).

Table 1: NOEMA spatial resolution

Source	Distance	Frequency		
		115 GHz	230 GHz	345 GHz
GG Tau	140 pc	60 AU	30 AU	20 AU
NGC 1333	300 pc	130 AU	65 AU	43 AU
M31	700 kpc	1.5 pc	0.7 pc	0.5 pc
z = 1	1.66 Gpc[a]	3.5 kpc	1.7 kpc	1.2 kpc
z = 4	1.46 Gpc[a]	3.0 kpc	1.5 kpc	1.0 kpc

[a] the angular size distance assumes a flat $\Omega_M = 0.27$ Universe.

Antenna Specifications

NOEMA foresees to build 6 new 15m antennas following closely the design of the existing antennas (Fig. 14). The resulting 12-antenna array will be homogenous. This will result in a simplified calibration and optimum sensitivity over the field of view. NOEMA will maintain the ideal and IRAM-specific combination of a large single dish telescope (the IRAM 30m telescope equipped with array receivers) for short spacing measurements and a high-resolution interferometer.

The current design of the PdB antennas has only been changed slightly during the period of construction of the 6 antennas (1987-2001). The most important upgrade has been the design and installation of rugged aluminum panels to replace the initially used and much more fragile epoxy-carbon fiber (CF) panels. Apart from the stability problem of the original CF panels, the IRAM antenna design has turned out to be cost-effective, reliable and easily maintainable. Other changes concerned the

cabin and cladding design to improve thermal insulation and stability against environmental stress.
The IRAM 15m antennas are fully steerable parabolas with a classic Azimuth-Elevation mounting. The carriage forming the base of the antenna is fully motorized to run on rail tracks. An internal diesel generator provides electrical power during antenna movement or power cuts.
Two counteracting motors on each axis generate the azimuth and elevation movements via normal gear drives. On the antenna platform the antenna is locked to within 1mm precision with the help of eight clamping lockers.
The whole carriage and forge structure is built in compartment steel technology. The parabola consists of a central hub made of steel and a mixed steel-carbon fiber back-structure. The aluminum panels are mounted on the back structure nodes via flexible aluminum feeds to compensate for differential thermal expansion.
The quadrupod structure is made from carbon fiber beams and carries the subreflector mechanism which follows a modified hexapod principle. The subreflector of the latest generation is made from aluminum alloy similar to the one used for the reflector panels. The back structure is on ambient temperature while the panels are, if required heated to a surface temperature of 5 C° to prevent surface humidity or ice buildup.
The receiver cabin contains the receiver rack, which is directly attached to the central hub. The receiver rack carries the main 4-channel SIS receiver, the pre-optics including the calibration carousels as well as the 22GHz water vapor radiometer. A dedicated port on the receiver rack is foreseen for future multibeam extensions.

Primary	Diameter	15 m
	Focal Ratio	0.325
Secondary	Diameter	1,55 m
	Magnification	15,7
Cassegrain to Prime Focus		7,834 m
FWHM Beam Size at	90 GHz, 150 GHz	54”, 32”
	230 GHz, 350 GHz	21”, 14”
Panels	Surface Quality	20 µm
	Wind (5 m/s) and Gravity (15° – 75° El)	5 µm
	Thermal Deformations	5 µm
Backstructure	Wind (5 m/s) and Gravity (15° – 75° El)	15 µm
	Thermal Deformations	15 µm
Total RMS (Panels and Backstructure)		30 µm
Holography: Amplitude Weighted Surface Quality		35 µm
Pointing rms		1.5 arcsec
Tracking rms		0.2 arcsec
Max antenna speed Azimuth		1°/sec
Max antenna speed Elevation		0.5°/sec
Maximum operation wind speed		14 m/s
Survival wind speed		56 m/s
Operating Temperature Range		-20°C to +20°C

Table 2: Main Antenna Specifications

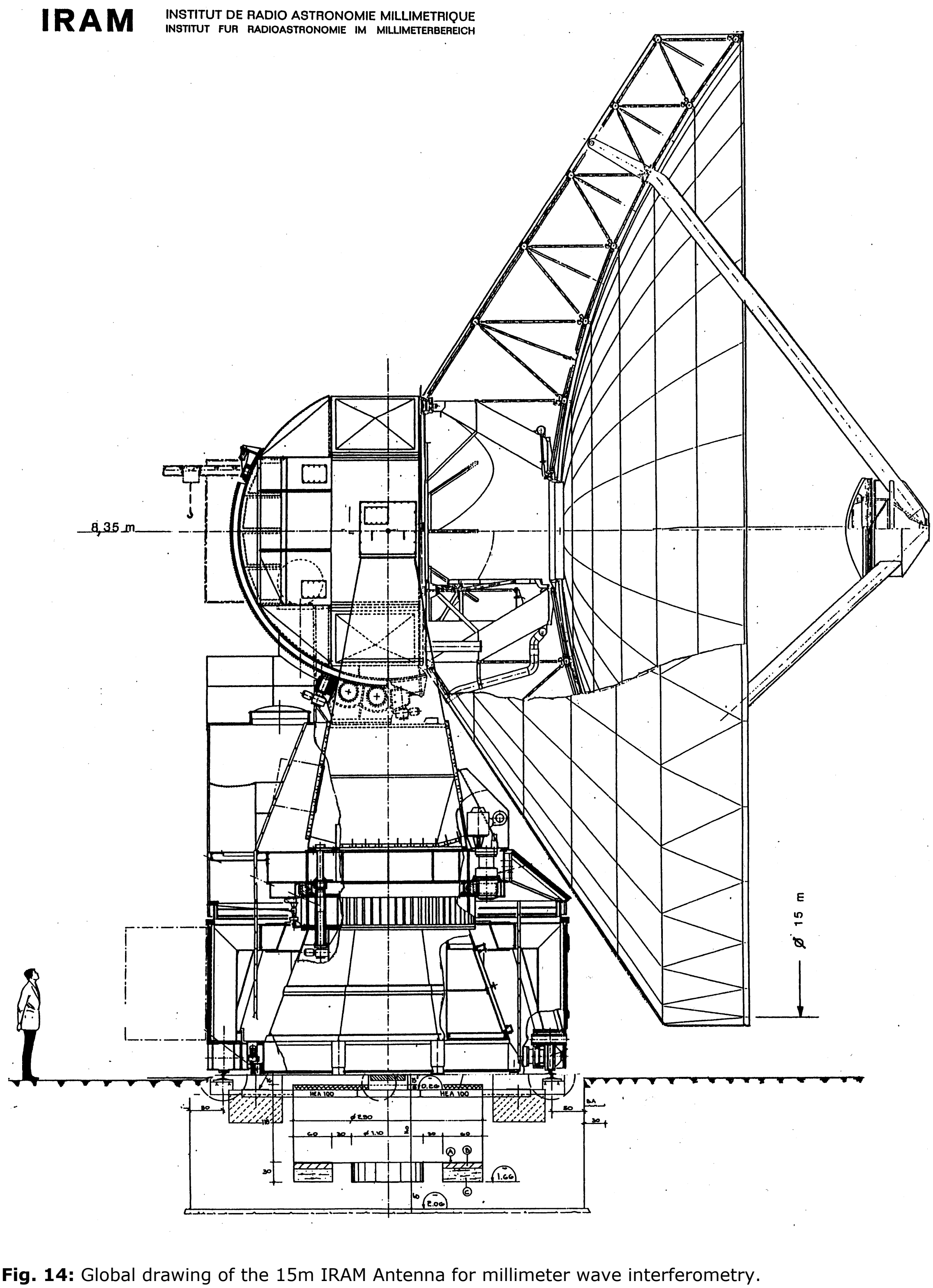

Fig. 14: Global drawing of the 15m IRAM Antenna for millimeter wave interferometry.

Fig. 15: Antenna 6 during assembly in the PdB maintenance hall.

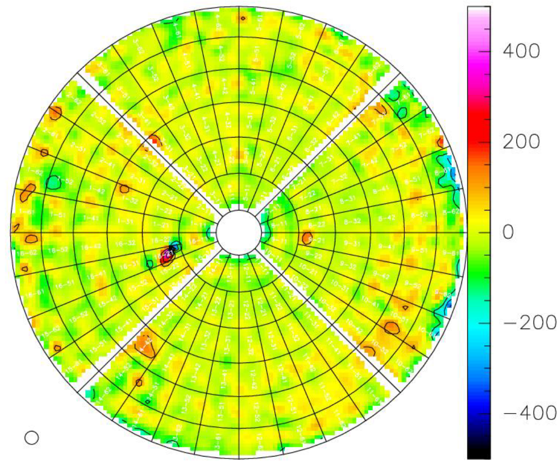

Fig. 16: Surface of antenna 5 as of 2006. Deviations from the ideal parabola were measured by holography observations. Wedge step values are in units of microns.

IRAM has the complete know-how to lead and organize the construction of the future antennas if an improved version of the current design is used (Fig. 15). This will have an important impact on the cost/antenna. Subcontracting of subsystems is foreseen for the quadrupod-secondary support design. External support might be used to speed up antenna assembling.

Current and Future Antenna Surface Accuracy

In preparation of the installation of the new-generation receivers, a campaign of surface adjustments was launched in early winter 2004 on the aluminium panels of antenna 5 to (1) investigate the precision to which the surface of the 15m antennas can be adjusted for operation at frequencies above 300 GHz and (2) evaluate the long-term stability of surface adjustments over a period of a few years. After a series of iterations the surface was found to present an accuracy of 35 microns (Fig. 16). This compares with typical rms values around 50 micrometers for antennas with carbon fibre panels. We are now in the 3rd year of monitoring the stability of the antenna 5 surface adjustments and have still no significant degradation in surface precision. Together with envisaged improvements in the surface metrology and thermal matching of the panel support points, a 35 microns rms surface accuracy for all antennas is therefore a very realistic goal.

Holographic measurements made over the last decade have shown that precision panel settings remain stable, in general over periods of typically ~2 years. The surface stability of the antennas is therefore sufficient, and makes unnecessary the initially implemented expensive and relatively fragile motor-actuator system for panel settings.

The high precision surface of antenna 5 requires only modest maintenance at present and ensures excellent aperture efficiencies for operation at frequencies up to Band 4 (Table 3). Work is in progress to optimise all six antennas to similar high surface precision.

Table 3: Antenna Performance Goals - 35 µm RMS

	RF coverage	η_A	Jy/K
Band 1	80 – 116	0.72	21.8
Band 2	129 – 174	0.71	22.2
Band 3	201 – 267	0.67	23.5
Band 4	267 – 371	0.62	25.4

Note: Aperture efficiencies and Jy/K conversion factors are for the center of each band. Values based on holographic measurements of the surface of antenna 5. Expected values are given for Band 4.

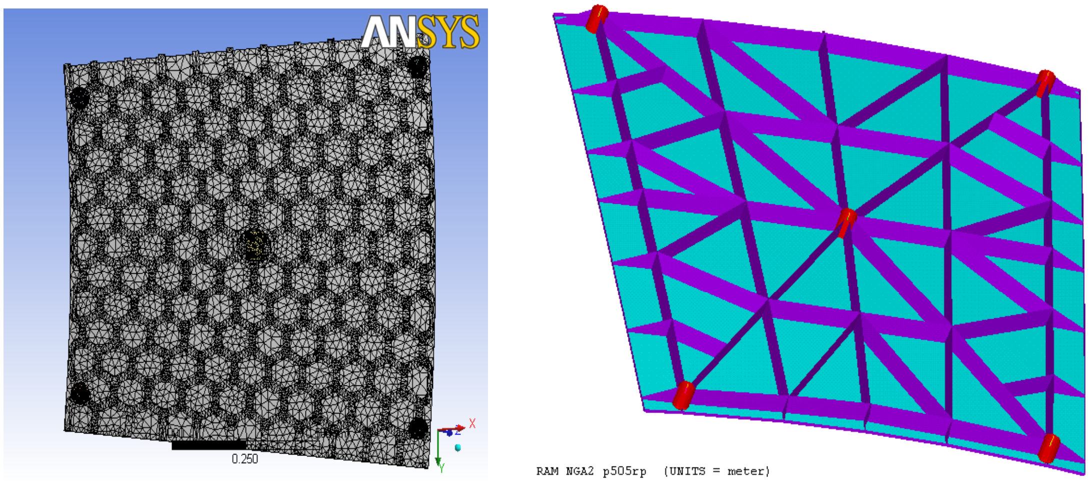

Fig. 17: First generation PdB aluminum panel with hexagonal backside reinforcements (left). Second generation PdB aluminum panel design with simplified backside reinforcements (right).

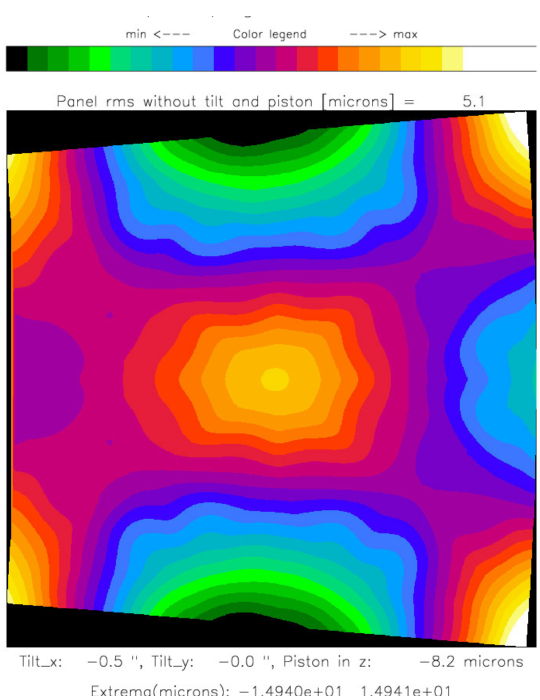

Fig. 18: Deformation of the 2nd generation aluminum panel (here ring 5) under horizontal gravitational load, the rms deviation is 5.1 µm.

As a complementary investigation to ongoing panel re-adjustment, a complete mechanical remodeling of the antenna has been made with state-of-the-art finite element software. Follow-up studies are currently underway to improve the thermal matching of the central panel support and to introduce a central support for panels of the innermost ring. A second third generation panel with improved weight and stability and at the same time reduced machining costs is also in work (Fig. 17 & 18).

At this point it still seems worthwhile to investigate alternative antenna designs with equivalent optical properties. In particular IRAM will investigate the possibility to make use of a modified design of the ALMA antennas.

Receivers

Present status

IRAM has a long standing know-how in the development and construction of state-of the-art millimeter wave SIS receivers. The specificity of IRAM consists in the institutes' complete infrastructure to support the receiver development. The various inhouse key components concern superconducting detectors and high precision micro-mechanics as well as cryogenic designs, complex control electronics and advanced quasioptical systems. Apart from significant cost reduction this setup allows to develop instruments with outstanding performance and within short timescales.
A major upgrade of the receivers of the PdBI was performed at the end of 2006 (Fig. 19 and 20). These new receivers are currently the most powerful mm-wave receivers in the world and provide several significant improvements in capabilities or performance over the previous receivers at PdB, which they replace:

- Four frequency bands (B1) 84-116 GHz, (B2) 129-174 GHz, (B3) 200-267 GHz, (B4) 277-371 GHz. At the time of writing (Jun-2008) the first three are in operation, while the fourth is scheduled to be implemented in 2009;
- Dual-polarization, i.e. each band allows simultaneous observing of the horizontal and vertical polarizations;
- Rejection of the image sideband, implemented either by single sideband (SSB) mixers, or dual sideband (2SB) mixers. This cuts out half of the atmosphere's contribution to the system noise, resulting in a gain of observing time of typically a factor 2.5.
- IF bandwidth 4 GHz versus 0.5 GHz for the previous generation.
- Closed cycle cryo-coolers, allowing continuous operation for months without maintenance and without any need for cryogenic fluids.

Altogether, the new receivers in their baseline configuration provide 8 IF bands of 4 GHz, of which two (one frequency band, both polarizations) can be observed simultaneously.

Fig. 19: Interior of the NGPdB receiver with none and one or three modules (out of four) installed.

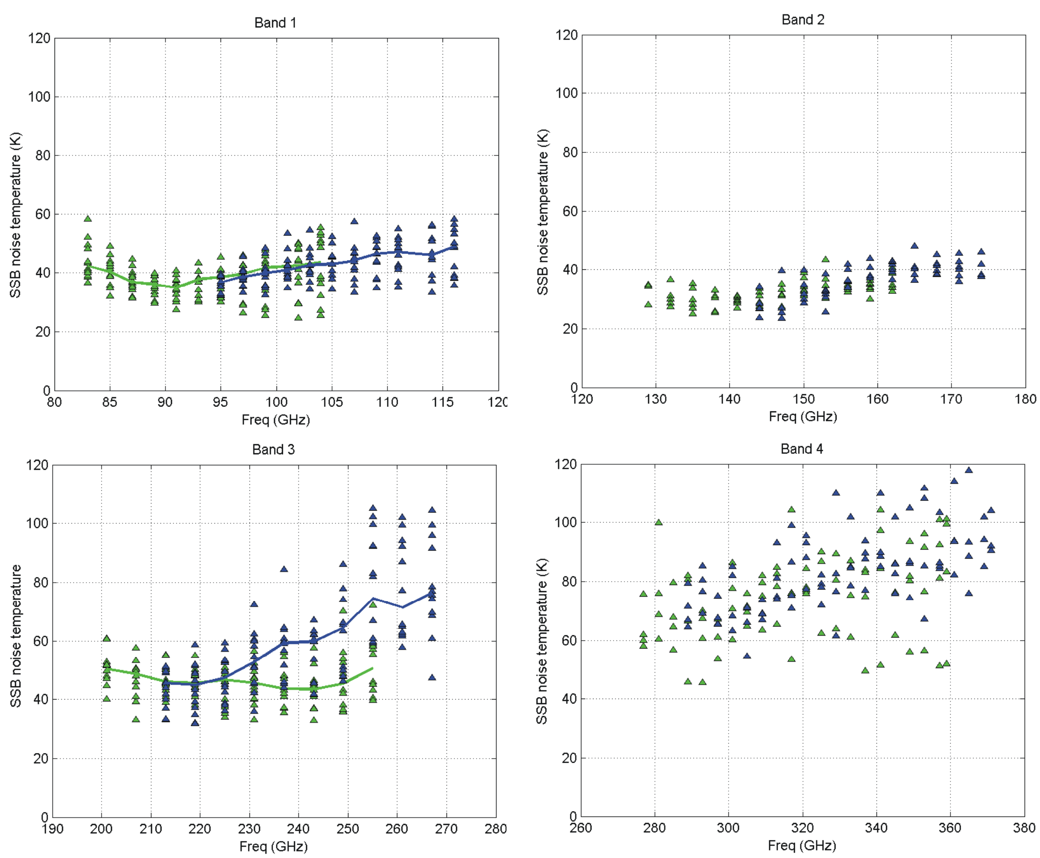

Fig. 20: SSB noise performance of the 3 IRAM receiver bands as implemented on PdB. The IF bandwidth is 4 GHz. The plot for IRAM band 4 gives performances of equivalent ALMA band 7 modules, this band will be commissioned at PdB in 2009.

Steps for NOEMA

IRAM has demonstrated its capability to exchange complete receivers on six antennas in a few months (autumn 2006) and to perform on-site upgrades with minimal loss of observing time (autumn 2007). Due to its ample internal space and available cooling power, the current receiver design presents a platform which will allow numerous future upgrades without changes in the fundamental setup of the cryostats. We are therefore well prepared for future additions and/or upgrades in the receivers of the PdBI.

- The modular scheme adopted for the assemblies of cold optics and mixers (one per frequency band) allows easy maintenance and upgrades as required.
- Full sideband separation operation. Sideband-separating (2SB) mixers have been successfully designed, built, and characterized: 275-373 GHz with 4 GHz IF bandwidth, developed for the ALMA project; and 80-116 GHz with 8 GHz IF bandwidth, developed within Radionet with the EU Framework Program 6 funding. IRAM will develop similar mixers for the other three bands, making possible a receiver with:
  (4 bands) × (2 polarizations) × (2 side bands) = 16 IF channels,
  with each IF channel 8 GHz wide. these receivers can be operated with two frequency bands simultaneously observable.
- On the existing receivers the envisaged upgrade requires an overhaul: to double the number of IF channels: low noise amplifiers, coaxial cables, and bias lines. With a adapted timing in receiver construction the increase in the number of antennas (and receivers) of the interferometer will open possibilities of refurbishing the existing receivers while new ones are swapped in.

The rapid development in the SIS mixer technology enables IRAM now to plan for the installation of a SIS mixer design which, in terms of bandwidth out-performs the one which will be implemented in ALMA. The new 8 GHz 2SB technology has recently been demonstrated with excellent performances in the 100 GHz band (see Fig. 21 and 22) and will be extended to the IRAM bands 2 to 4.

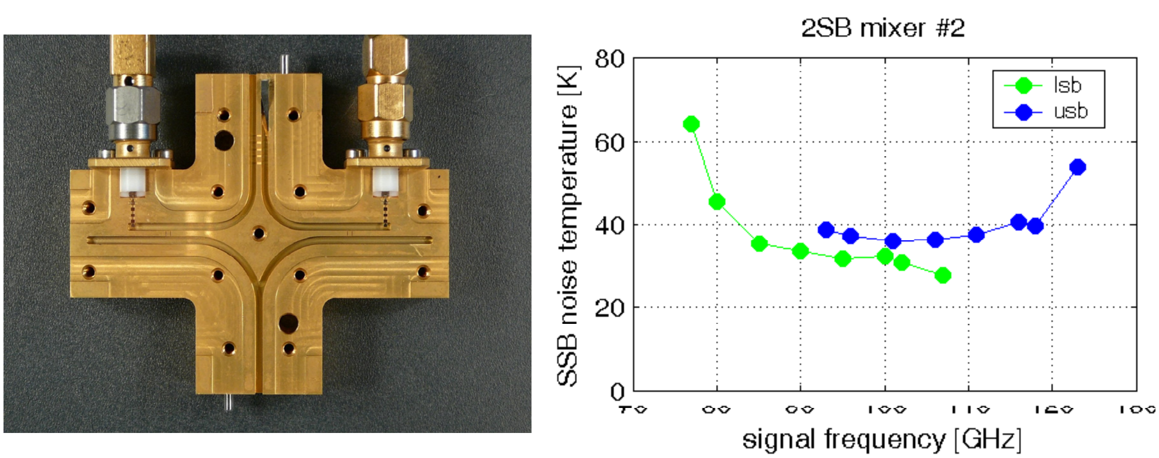

Fig. 21: Sideband separating SIS mixer block for the IRAM Band 1 (100GHz) and SSB noise performance of the **two separate IF bands with 8 GHz** width each. This development has been supported by the EU FP-6 RADIONET/Amstar program.

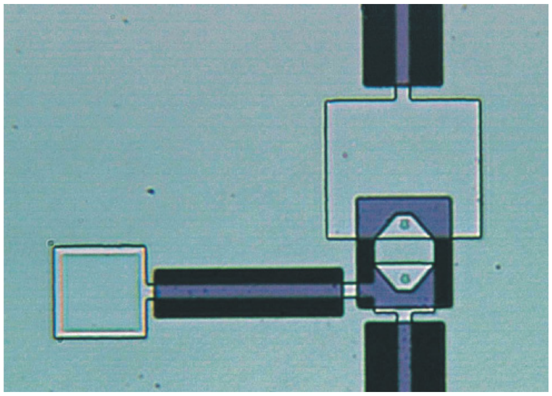

Fig. 22: 2-junction SIS circuit for wide band mixers in the 3mm window.

Phase reference and IF transport

Stable phase reference and IF transport is a key condition for the radio interferometry. In particular for the highest NOEMA frequencies (370 GHz) and the longest baseline lengths requirements will be demanding.
For the envisaged baseline extension the maximum distance between the correlator in the central building and antenna on PdB is 1.3 km. For such distances coaxial distribution of the phase reference signal is still practical. For distances beyond 800m a single fixed repeater is required. The phase control loop of coaxially distributed phase reference signals is used at PdB with great success. This scheme avoids the technically very demanding distribution of 100 GHz LO reference signals over optical fiber towards the antennas (actually a major risk factor and cost driver in the ALMA system) and allows for a compact and optimized design of samplers, correlators and calibration noise sources in the controlled environment of the central building. A price to pay for this scheme is the use of relatively costly low loss coaxial cables, however this is not a critical factor for the relatively low number of new stations required for the configurations with 12 antennas. PdB currently operates 12 round trip controls, a design which has initially been used to supply phase reference control for two simultaneous frequency bands for 6 antennas. For single frequency observations as recently implemented with the new receiver generation the existing scheme can be retrofitted to serve 12 antennas. The next generation LO's and receivers without mechanical tuning elements will enable to operate time-sharing dual frequency operation even with a single phase-reference per antenna.

In 2006 IRAM has successfully introduced the open loop transmission of an IF band width of 4 GHz by means of optical fiber transmission in analog technology. The glass fibers are installed in trenches similar to the on of the reference coaxial cables. A special compensation scheme is not required for stable observations. The connectors have shown sufficient reliability for conditions on PdB. Connectors with further improvements in handling are currently investigated. The 12 optical transceivers in use have shown reliable operation since their introduction 2 years ago.
Meanwhile commercial analog fiber transceivers offer 8GHz bandwidth (4-12 GHz) with sufficient stability and dynamic range. Therefore the foreseen BW enhancement in the receiver technology is well covered by existing commercial equipment. For NOEMA ultimately a scheme of 4 times 8 GHz transmission BW is foreseen per antenna.

Backends

With the fast progress in receiver performance notably bandwidth, generating enough correlation power for the NOEMA project will be one of the major challenges of the coming years. We argue that IRAM's backend group is ideally placed to cope with this challenge and to provide a well-focused and suitable solution to the needs of the project.
The development of new backends will be strongly supported by recent new industrial developments in the area of fast digital to analog converters and the availability of FPGA devices with rapidly increasing performance.

The current correlators on PdB are among the most powerful and flexible devices which have been built for millimeter interferometry. The current narrow band correlator allows for very high flexibility and high resolution (min 40 kHz) with a maximum total correlation bandwidth of 2 GHz per baseline. A large part of the flexibility in this correlator is generated by analog IF processing.
The currently built WIDEX correlator will be ideally suited for continuum and extragalactic line search with a fixed frequency setting and channels spacing of 2 MHz. The total IF bandwidth per baseline will be 8 GHz with a maximum of 28 baselines (8 Antennas). This design will therefore help to cover part of the needs during the future extension phase. The design is of ultra-compact nature and very energy efficient.

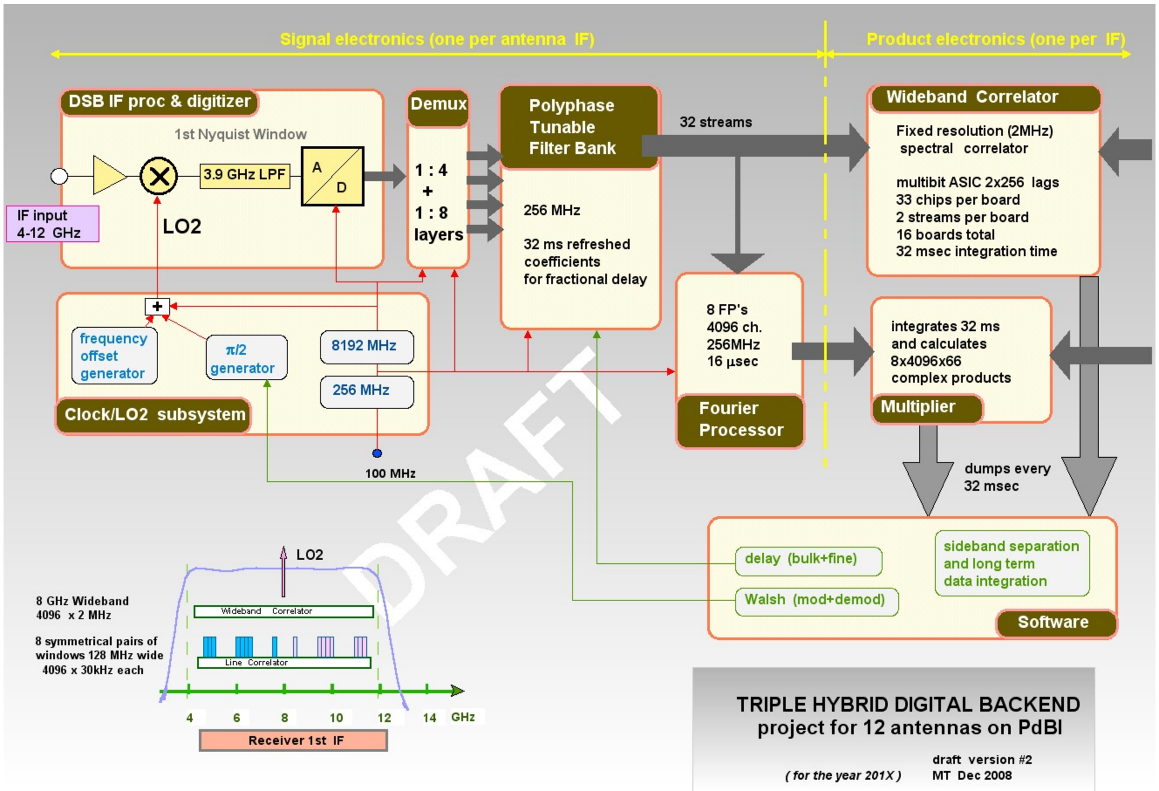

Fig. 23: Circuit diagram of a preliminary design study for a NOEMA backend. The represented scheme processes an 8 GHz IF band. 4 identical units are required to process the full dual polarization 2SB signals from the NOEMA receivers. The design relies on fast sampling and DSP with use of FPGA technology.

The design of new and more complex backends for an extended number of baselines will make the step from analog to digital IF processing and make extended use of

PGA technology. Figure 23 shows a preliminary design study for a NOEMA correlator. In this design Walsh switching for RF sideband separation is replaced by a frequency offset scheme with fringe cancellation in the rejected sideband. The 90° Walsh switching is instead applied to separate sidebands within the IF band. This allows to treat the signal in the following stages by a single 4 GHz sampler unit. In the same way the size of all following backend parts is also reduced by a factor of 2. Sideband separation by frequency offset fringe cancellation has recently been successfully demonstrated by IRAM at the PdB interferometer. Following the current design study a total of 8 flexible high resolution windows, each covering 128 MHz with 4096 channels or a 30 kHz channel separation can be set for each RF sideband (0.1 km/s at 3mm and a coverage of 140 km/s at 270 GHz). A fixed resolution full bandwidth module will cover the 8 GHz RF-sideband with a 2MHz resolution for continuum and extragalactic line studies.

Polarization work will be covered by Walsh switching of IF inputs. This scheme sacrifices √2 in sensitivity but reduces digital complexity of the backend and avoids restrictions on its capabilities.

Technically, all building blocks are thus available as of today or within the very near future. This means that design risk is low and is located more in the global system design than in key components. In turn detailed design studies can be started very soon and the difficult situation of parallel and anticipating system design and technology development can largely be avoided.

Water Vapor Phase Correction

Correcting atmospheric phase fluctuations at (sub)millimeter waves to recover the astronomical phase is one of the challenges to realize the full potential of the NOEMA array. The atmospheric phase calibration scheme implemented since 2004 at the PdBI is based on a three-channel discriminating system to detect emission from water vapor at 22 GHz and reject spurious emission from cloudlets and water droplets. The PdBI system is the most sensitive, fully operational system on a millimeter-wave array. With its exceptional gain stability it has proven to perform with excellent precision and reliability for regular astronomical operation.

The WV radiometric phase correction system provides an increase of coherent integration time. The resulting increase, not only translates into a sensitivity gain and an improved calibration precision, but is also of paramount importance for astronomical observations at short millimeter waves. The NOEMA radiometer system will not only benefit from planned improvements in the PdBI system but also gain from valuable knowledge currently developed at IRAM.

IRAM is heading towards transforming the current calibration scheme into an even more powerful absolute atmospheric phase correction. Such a scheme will provide crucial means to extend the winter period for high resolution mapping at all frequencies in NOEMA’s extended array configuration. Similarly it will ensure summer observations at lower frequencies with optimum sensitivity and phase precision to the most remote stations in the array’s compact configuration. Finally the improved coherence length due to phase correction will allow to make full use of the increased sensitivity of NOEMA due to the increased number of antennas in order to proceed self-calibration on weaker sources.

Software and Data Management

IRAM, together with numerous collaborators in the IRAM community, has created in the 80s the powerful GILDAS package. Since then the package has received far-reaching extensions and has been kept up to modern programming standards. It is also a key tool to prepare and simulate ALMA. GILDAS will provide interfacing with CASA, the ALMA software package, and therefore offer the IRAM user community the possibility to profit from developments in both packages as well as easy exchange and combination of data from both NOEMA and ALMA.
In detail the NOEMA project imposes three different kinds of constraints on software: The number of antenna doubles from 6 to 12, implying a change in the number of baselines from 15 to 66; The bandwidth increases from 8 GHz (4 GHz dual polarization SSB receivers) to 32 GHz (8 GHz dual polarization 2SB receivers); The largest baseline length will double. While not strictly requested by the NOEMA instrumental upgrades, other software modifications will increase the overall throughput and efficiency of the interferometer. The GILDAS package will have to be upgraded and adapted to the new requirements and a scheme for efficient management of the greatly increased data quantity has to be developed.

Data rates

The typical NOEMA project size will significantly increase as compared to the PdB interferometer (today 0.5 to 5 Gbytes for NOEMA). This is the result of both, a 4-fold increase of number of baselines and the total number of spectral channels as provided by the backend over the increased IF bandwidth. These figures apply to standard integrations and result in a yearly data quantity of about 4 Terabyte. Currently available computing and storage technology already provides solutions to such data rates.
On-The-Fly (OTF) techniques, as currently developed at IRAM for larger scale mapping, will boost the data rate by at least another factor of 20 if full backend power is used. This mode therefore will need a particular effort to handle the related data rates.

Required Software Developments

For NOEMA a number of upgrade in the current core software as used for PdB will be necessary. The most prominent points are:

- The increase of the baseline number from 15 to 66 implies a modification of the user interface for visualization and interaction with the successive calibration steps.
- The software for a fully automatic calibration pipeline must be adapted to the increased number of baselines and spectral windows. More features of data quality assessment and flagging will have to be included.
- The increased sensitivity and the increased number of baselines of NOEMA make self-calibration techniques useful. Flux limits for self-calibration are currently 100 mJy which will shift to < 25 mJy for NOEMA. These techniques will improve the calibration consistency in addition to the current antenna-base calibration scheme.

- The increase of the IF bandwidth implies a frequency dependence of the atmospheric calibration due to atmospheric and hardware chromaticity. The treatment of the calibrator spectral index will improve the accuracy of the RF bandpass and flux calibration.
- The large data sets generated by NOEMA will generate the request for software to "cut out" subsets from the calibrated data in an efficient way.
- In principle the increased number of baselines will make OTF technics more powerful, however the principle, which has been laid out by Ekers & Rots in 1979, have not yet given birth to practical algorithms of imaging and deconvolution. In the framework of the FP6 ``ALMA Enhancements'' program, IRAM currently leads an effort to develops such algorithms.
- With the large relative bandwidth of the future SIS receivers and for sources with well known spectral indices multi-band synthesis will be of high interest.

Due to the increased complexity of NOEMA a number of additional software tools in the area of scheduling, observatory management will have to be developed in order to maximize efficiency and throughput:

- Software to support project preparation and flexible scheduling.
- A database to monitor the instrument and atmospheric conditions.
- This database will be connected to another input concerning regular specific instrument and antenna characterizations as well as maintenance and repair.

As a conclusion all basic key elements of the required operation software for NOEMA are available, however a continuous development has to be foreseen to obtain an efficient ensemble of software sub-packages. Data storage and housekeeping should be in combined with the requirements for the ALMA support at IRAM.

Future NOEMA Enhancement Options

It is important to emphasize the possibilities of future enhancements for NOEMA. The envisaged number of antennas (12) will allow such enhancements with the available expertise and manpower at IRAM and within well-defined and limited cost envelops. NOEMA will therefore offer long-term perspectives of a dynamical instrumental development platform with very high impact in the field.

A relatively straight-forward enhancement can be envisaged by the inclusion of the frequency range from 70 to 80 GHz. This frequency window, which will not be covered by ALMA, has lately received great attention through the detection of many deuterated molecular species. Such species are unique tracers of very dense and cold environments such as found in pre- and protostellar cores. An additional benefit from the increased frequency range would be the increased low frequency window for high redshift CO lines. Current developments in SIS mixer and HEMT amplifier technology indicate that coverage of the frequency range from 70 to 116 GHz is not unrealistic. Dedicated developments have to be foreseen in the area of horns and quasi-optics.

NOEMA will be an interferometer which relies on earth rotation synthesis, therefore imaging integration time is quantized by tracks of roughly 8 h durations. In this context simultaneous observations in different bands are very advantageous.

Powerful quasi-optical dichroic elements have recently become available for the millimeter wavelength range. Such dichroic elements will be used for the first time in the new generation receiver for the IRAM 30m telescope (EMIR). The relatively large space in front of the NOEMA receivers can be used to host re-designed beam combination optics. In particular for signal to noise limited observations in the higher atmospheric windows such dichroic setups will be of great benefit. If combined with adapted (split) or additional correlation power the multiband observations will be of very high interest to significantly increase observatory throughput, improve relative calibration between bands and relax scheduling constraints.

Multibeam imaging for radio interferometers has been discussed on several occasions and has become realistic through the successful development of millimeter wave multibeam receivers for single dish observatories. NOEMA as a homogeneous array with 12 antennas will be ideally suited for multibeam interferometry within a longer-term perspective. The mapping capabilities of such an upgrade, together with the availability of 30m telescope short spacing data, will be extremely powerful.
The receiver cabins of the PdB/NOEMA antennas are designed with an additional mechanical interface for future multibeam receivers. Mechanical finite element simulations have confirmed that the additional gravitational charge of a multibeam receiver on the central hub is tolerable.
A number of important technical developments are linked to the introduction of multibeam interferometry. The most demanding ones are: IF transport, correlation power and finally on-the-fly (OTF) observing and related calibration and data reduction methods. The OTF requirement is due to the resulting field rotation of arrays in modern Az-El antenna mounts, while a mechanical derotation of receivers is not practical due to the related mechanical vibrations and resulting path lengths variations.
In the framework of advanced developments for ALMA IRAM is leading the effort to develop interferometric OTF procedures and is therefore well placed to prepare the required modes for interferometric multibeam observations. IRAM is also leading the European FP7 program Radionet/AMSTAR+ which specifically addresses the development of high performance, compact mm-wave array receiver elements.

Phasing up all NOEMA antennas will be of high interest for global mm VLBI. IRAM has established the first successful phased-array operation at 1 GBit/sec bandwidths, and holds the 3mm VLBI sensitivity world record on its PdBI-Pico Veleta baseline. IRAM has also pioneered VLBI at a wavelength of 1.3 mm.
So far PdBI phasing has been achieved over a relatively narrow bandwidth (max. 16x16 MHz = 256 MHz = 12.8% of the cross-correlator band) in dedicated adder modules of the current NB correlator, which corresponds to a raw data stream of 1 GBit/sec (256 MHz 2-bit Nyquist sampled). This limitation was set in the past by the available VLBI recording speeds and storage medium capacities, but recent technical breakthroughs have pushed back those limits. Experimental tests have shown the possibility to record up to speeds of 4 Gbit/s using two Mark5B+ systems in parallel /station and geodetic VLBI projects try to push recording bandwidth towards 32Gbit/sec recorded in “burst mode”.
Phasing of more antennas and wider bandwidth will require a substantial dedicated investment and clearly collaborations with other phased array developments (SMA, CARMA). For the time being IRAM will pursue the NOEMA project with the phased array option supported by an interface requirement of the IF/backend system.

Infrastructure

The NOEMA project requires a limited number of changes and upgrades of the Plateau de Bure infrastructure.

The most significant upgrades are required in the electrical power supply and distribution. The power cable to the station has to be upgraded in capacity by a factor of 2. To comply new legislation the central transformer has to be replaced by a transformer without Pyralene. In contrast to the existing low voltage power distribution the most remote antenna stations of NOEMA have to be supplied over 20KV lines using a single transformer station at about 2/3 of the maximum baseline distance to avoid excessive voltage drop and ground return problems.

Four of the existing antenna platforms have to be modified into a displaced configuration with respect to the main tracks. This upgrade is required to enable efficient configuration changes and maintenance movements of the antennas.

The current correlator room is relatively limited in space and available cooling power. Its location below the operating room has also been identified as non-ideal by the safety audit of IRAM's insurance company. The NOEMA project therefore foresees the construction of enlarged correlator room including reorganized cable distribution. The new correlator room will be equipped with energy efficient air conditioning and IRAM will also work on a recovery scheme for heat from the correlator room in order to support heating of the maintenance hall.

The current data-connection from the IRAM headquarter in Grenoble to PdB uses a dedicated radio link (rented from France Telecom) with a fairly limited bandwidth (100 kb/s). For a number of situations this bandwidth is insufficient and therefore IRAM plans to connect NOEMA over an optical fiber. There are two alternative paths for a possible future fiber connection. On one side it is now possible to include optical fibers in the carrier cables of modern cable cars. This would bring the fiber connection down to the lower station of the cable car near Devoluy village. On the other side it would be possible to include the optical fiber layout into the upgrade of the power supply running towards the Super-Devoluy ski station. Both options are currently under study and will be matter of negotiations with the local authorities.

Operation

Operation of NOEMA will be comparable to that of the current PdBI. With the closed cycled cryo-coolers and fully remote receiver tuning the required operator staff does not depend on the number of antennas and can be kept on the current level (7 p. on-site). With all antennas equipped with aluminum panels and the currently implemented improvements in antenna sealing, heavy maintenance in the PdB hall (2 weeks/antenna) can be restricted to a biannual frequency. Antennas remaining outside will undergo minimum check and maintenance on antenna mechanics (1 week per antenna).
Maintenance will be done during summer period. With the described scheme the array will therefore operate for 18 weeks during summer with 11 antennas. The maintenance will be coordinated with the configuration changes (2/year) and therefore minimize antenna movements. In this scheme it is foreseen to bring the 6

antennas that are foreseen for the next heavy maintenance into the 6 closest positions. Due to the generally increased number of equipment we foresee an increase of technical staff for trouble-shooting and maintenance by 1 person (technician level).

Budget (in EU 2008)

Investment:

The cost of NOEMA is dominated by the cost of the six antennas (Tab. 4). The costs per antenna will be optimized by: combined orders of subcomponents of all new antennas together, design of panels with simplified machining and if possible by reduction of complexity of electrical interconnections.
Due to the construction of the last PdBI antenna (completion 2002) under IRAM lead, IRAM has precise information about the market of suppliers, possible improvements areas and therefore total costs. Uncertainties are only related to rapid fluctuations of raw materials like aluminum and steel as well as possible shifts in suppliers' internal politics. In terms of total costs and cost risks it is best to place as much grouped orders as technically and logistically possible. However this generates a spending peak in the early phase of the project which might be difficult to be covered (see Fig 24). Details of possible cost equalizations over time will be evaluated as soon as specific negotiations with suppliers have started.

Antennas (6)	30
Frontend	1.6
Backend (incl. IF transport)	6
Infrastructure and Baselines	4
Others	2
Total	43.6

Table 4: Basic cost break down of the NOEMA project (MEu)

A best estimate of costs for the 6 antennas ordered with an optimum setup is 5 MEu per antenna. This figure includes the full costs of required supplementary personal for mounting and assembly at PdB.
The project foresees also supplementary men power for the backend group (2 positions for 6 years) and for the reflector area and project management (2 positions for 6 years).

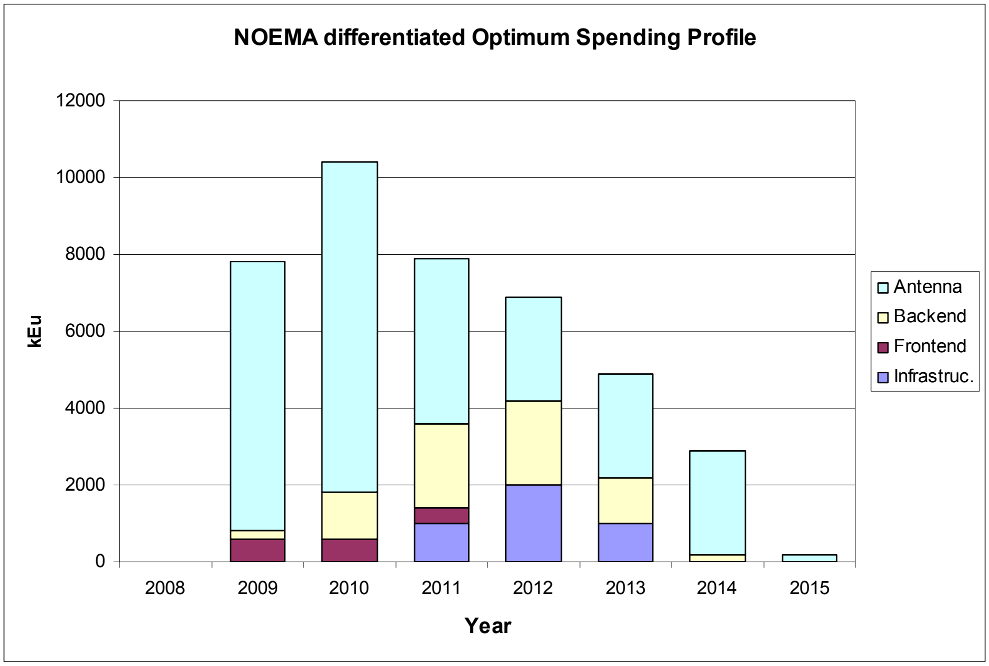

Fig. 24: Preliminary differentiated optimum spending profile if a maximum number of grouped orders are placed at the beginning of the project.

Operation

Operation costs of NOEMA can also be forecasted with high accuracy (Tab. 5). The operation of NOEMA will not differ substantially from that of PdBI in that the mode of service operation will be maintained with the same number of operators. Energy requirements are mainly increased due to the required additional electrical power for deicing. Maintenance of 12 antennas will be accounted for with 1-2 additional technical staff positions and the required software and data management is accounted for with 1 supplementary staff position. Here we list the additional operation costs as compared to the normal PdB operation. With a total plus of 350 kEu/y the operation costs of NOEMA will be increased by only 20% as compared to the current operation costs of PdBI.

Electrical Power	100
Suppl. technical staff (1)	50
Suppl. Software staff (1)	80
Suppl. Astronomer (1)	80
Spare parts	150
Total	460

Table 5: Additional operation cost of NOEMA as compared to PdBI (kEu/year)

Schedule

The schedule is dominated by the preparation of subcomponents and the construction of the antennas. Without interrupting the operation of the existing interferometer it will be possible to complete 1 antenna every 10 months. Except for the last two antennas a construction of antennas in parallel is not considered realistic. However it will be possible and practical to have construction of one antenna going on in parallel with commissioning and fine-tuning of a recently completed antenna.
Considering that during 2009 IRAM will rebuild the PdB cable car, transport of subcomponents to PdB and construction of antennas will start early 2010. This matches with the need to prepare the contracts.
Other time critical items are backend developments and IF transport. The WIDEX backend, commissioned in early 2009, will allow partial coverage of the backend needs with 8 antennas until the arrival of the 9th antenna end 2013.
Baseline extensions are shifted towards the end of the project when the increasing number of antennas allows efficient use of such an extension.
Receivers construction is relatively uncritical, however careful planning has to be made to integrate the envisaged 30m upgrades into the global scheme.

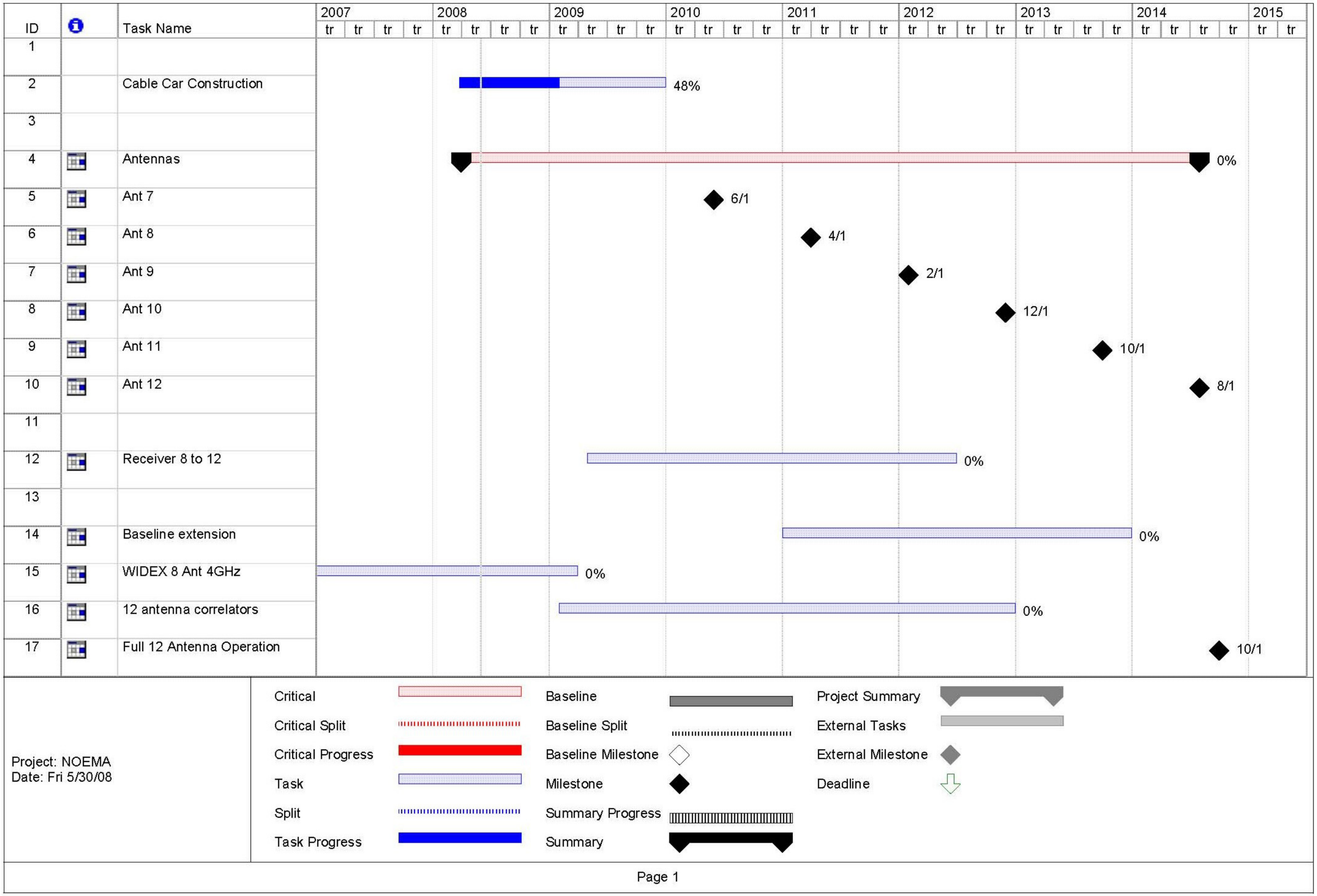

Fig. 25: Schedule Overview for NOEMA.

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With contributions from: J. Boissier, M. Bremer, B. Gautier, S. Guilloteau, B. Lazareff, J. Pety, J.L. Pollet, P. Raffin, M. Torres,

v16

References:

Boissier, J. and R. Neri,, IRAM Working report 2008

Cesaroni et al., 2008, Proceedings in Astrophysics and Space Science Vol 313, Nos, 1-3.

Downes, D. & Eckart, A., 2007, A&A 468, L57-L61

Garcia-Burillo, S. et al, 2003, A&A 407, 485-502

GILDAS : see http://www.iram.fr/IRAMFR/GILDAS/

Gueth et al, 2008 in prep.

Karastergiou, A., 2007, IRAM working report

Krichbaum, T. P. et al, 1997, A&A V 323, p.L17-L20

Maier, D. et al, 2008, Proceedings of 19th ISSTT, Groningen

Pietu, V., Dutrey, A., Guilloteau, S., Chapillon, E., & Pety, J., 2006, A&A, 460, L43

Pietu, V., Dutrey, A., Guilloteau, 2007, A&A, 467, 163

Pietu et et al. 2008, in prep.

Tacconi, L. et al, 2008, ApJ, 680:246-262

- Annexe 1 –
Millimeter-Wave Arrays – A Comparison

Table 1 Key parameter of existing and future millimeter/submillimeter interferometers.

	Altitude (m)	N_{ANT}	Diameter (m)	Coll.Area (m^2)
IRAM PDBI	2550	6	15	1060
CARMA	2200	15	6/10	772
SMA+CSO+JCMT	4080	10	6/10/15	481
NMA	1340	6	10	471
IRAM NOEMA	2550	12	15	2120
ALMA	5060	50	12	5652

Table 2 Sensitivity comparisons among current and future millimeter-wave arrays. The calculations assume a mean target elevation of 45^o, 8 hrs of integration, receiver temperatures as published on the web sites, and conditions corresponding to a 1mm column of water vapor at 345 GHz, 3mm at 230 GHz and 5mm at 90 GHz.

Point Source Sensitivities at 90 GHz

	η_A	NPOL	BW (MHz)	Continuum (μJy)	Line (mJy/1MHz)
IRAM PDBI	0.72	2	4000	29	1.8
CARMA	0.62	1	1500	290	18
NMA	0.64	1	1000	890	28
IRAM NOEMA	0.72	2	16000	6.5	0.8
ALMA	0.80	2	8000	2.9	0.3

Point Source Sensitivities at 230 GHz

	η_A	NPOL	BW (MHz)	Continuum (μJy)	Line (mJy/1MHz)
IRAM PDBI	0.60	2	4000	67	4.3
CARMA	0.60	1	1500	549	27
eSMA	0.77	1	2000	376	31
IRAM NOEMA	0.67	2	16000	14	1.7
ALMA	0.80	2	8000	5.2	0.5

Point Source Sensitivites at 345 GHz

	η_A	NPOL	BW (MHz)	Continuum (μJy)	Line (mJy/1MHz)
IRAM PDBI	0.50	2	4000	117	7.4
eSMA	0.72	1	2000	948	60
IRAM NOEMA	0.62	2	16000	21.3	2.7
ALMA	0.70	2	8000	12.4	1.1

- **Annexe 2 –**
-

Preliminary Results and Conclusions of geological Expertise on PdB Baseline extensions (Geolith, Crolles).

Goal:

GEOLITHE has been charged by IRAM to investigate the geological and geophysical situation on Plateau de Bure along possible east and west extensions of the existing baselines and along a possible track extension to the south-east. The main investigations were done in fall 2007 with some measurements currently ongoing (spring 2008). The report is therefore of preliminary nature and a final report will be available in July 2008. Here the plots of the measurements and the preliminary conclusions are presented.

Preliminary Conclusions (translation from original document):

On the request of IRAM the company GEOLITHE has undertaken a preliminary geological and geophysical study of the Plateau de Bure site (mission G11 following the normalized procedure NF P94-500). The study is made as part of preparation of a project which intents to extend existing baselines on Plateau de Bure.

The site exploration was done along the following lines:

-Analysis and interpretation of airborne photos of the specified zones and their surroundings.

-Investigation and inspection of the complete project area by a geological engineer.

-Realization of geophysical measurements (electrical and seismic) along all defined possible future extension lines.

The preliminary interpretation of the measurements allow to the following conclusions:

- Presence of at least 4 faults (with resulting zones of important karstification) crossing the base lines close to the current limits of the tracks.
- Zones with moderate or profound alterations on the western and eastern limits of the projected baseline extensions.
- Good rock homogeneity and generally good ground quality on the possible track to the south-east.

This results may be subject to changes according to future measurements which still have to be done.

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38920 CROLLES
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Fax: 04 76 92 22 33
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Dossier : 07-209-I

LOCALISATION DE LA ZONE D'ETUDE

Date : Avril 2008

Observatoire de Bure (05)
Projet d'extension des voies Est et Ouest - Création d'une voie Sud-Est
Etude géologique et géophysique préliminaire de site

ZONE D'ETUDE

Echelle 1 / 200 000

Légende :

⊕ : Point GPS
— : Profil Geophysique

OBSERVATOIRE DU PLATEAU DE BURE (05)
PROLONGEMENT DES PISTES EXISTANTES

GÉOLITHE

ETUDE GEOTECHNIQUE

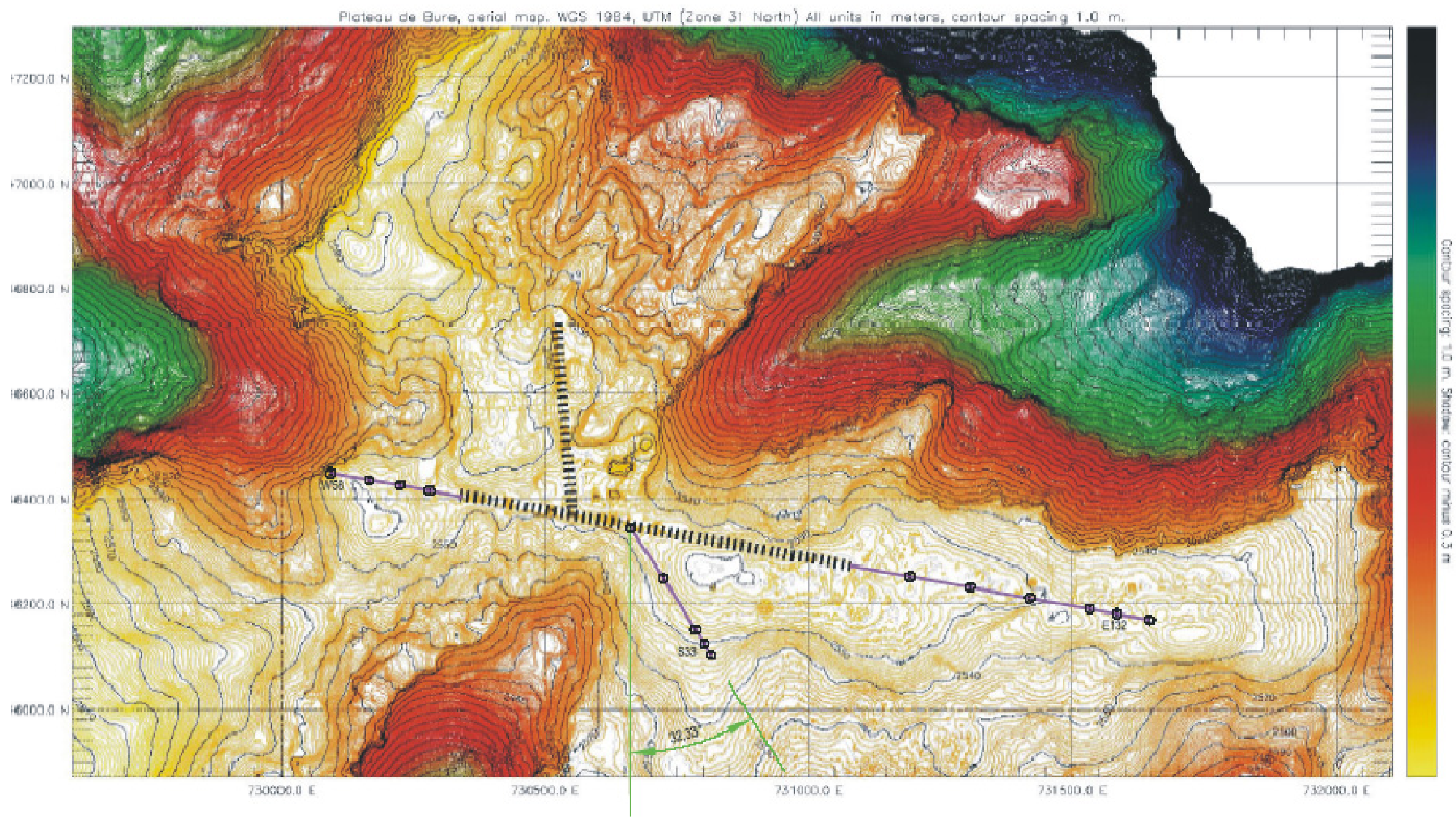
PHASE AVANT-PROJET

VUE EN PLAN

IMPLANTATION DES RECONNAISSANCES

07-288 [1	Date : 07/04/08	N° Plan : 01	ECH. : 1/10000	Indice 0

0 50 100 200 500m



LEGENDE

- Couche n°1 : Terrains superficiels issus de la gélifraction Vp < 1250m/s
- Couche n°2 : Rocher très altéré et/ou fracturé à disloqué 1600 < Vp < 2100m/s
- Couche n°3 : Substratum rocheux sain à moyennement altéré / fracturé 3700 > Vp > 2300m/s
- 970 m/s Vitesse de propagation des ondes sismiques
- W56 ★ Positionnement du projet
- Espacement intergéophone = 5,00m

GÉOLITHE

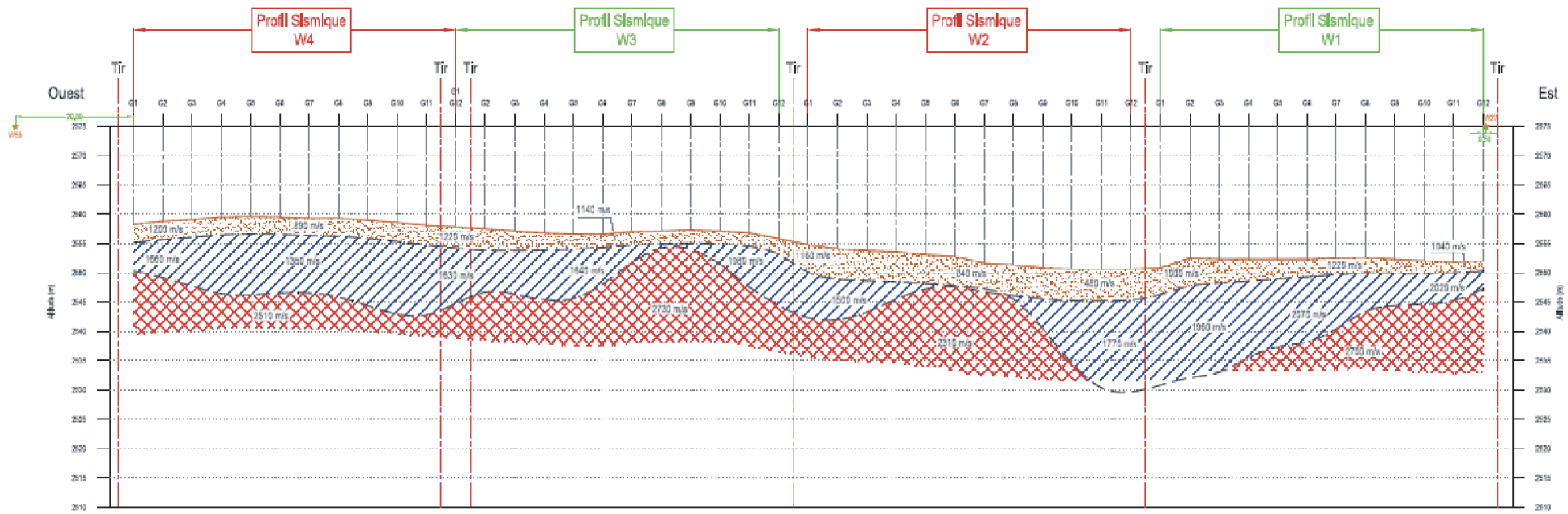
ETUDE GEOTECHNIQUE

SISMIQUE REFRACTION

TRONCON W

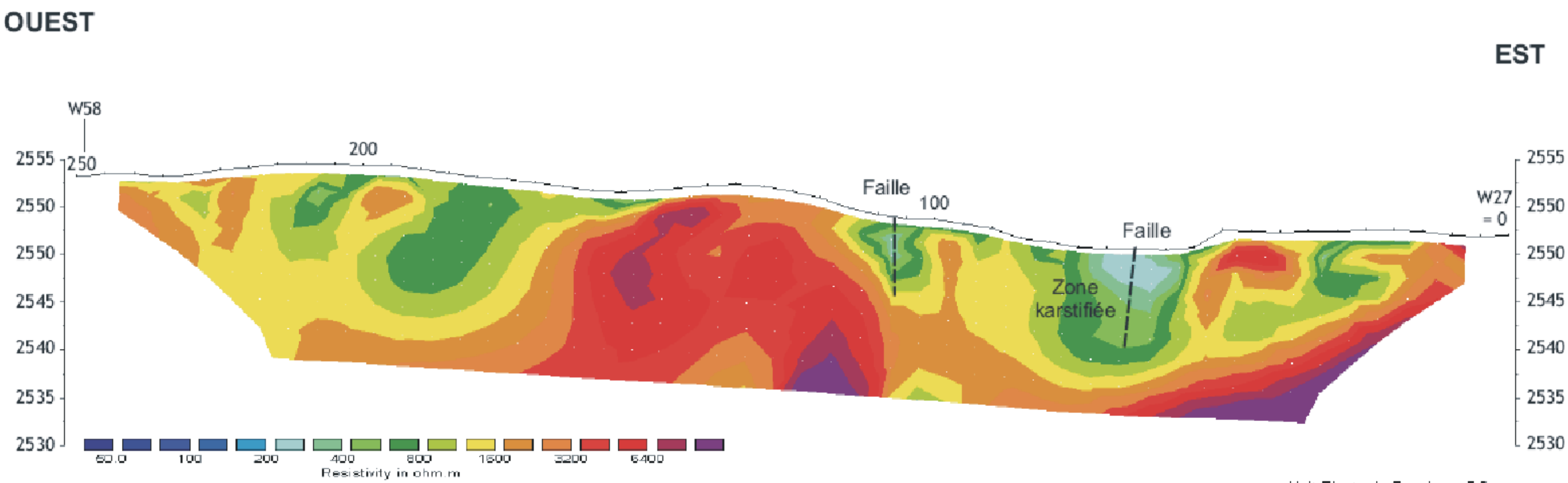
Indice 0

0 5 10 25m



Tronçon OUEST

Panneaux électriques



Echelle horizontale : 1/1000e
Echelle verticale : 1/500e

Date : 05-08 / 11 2007	Observatoire de Bure (05) Projet d'extension des voies Est et Ouest - Création d'une voie Sud-Est Etude géologique et géophysique préliminaire de site	Dossier 07-289

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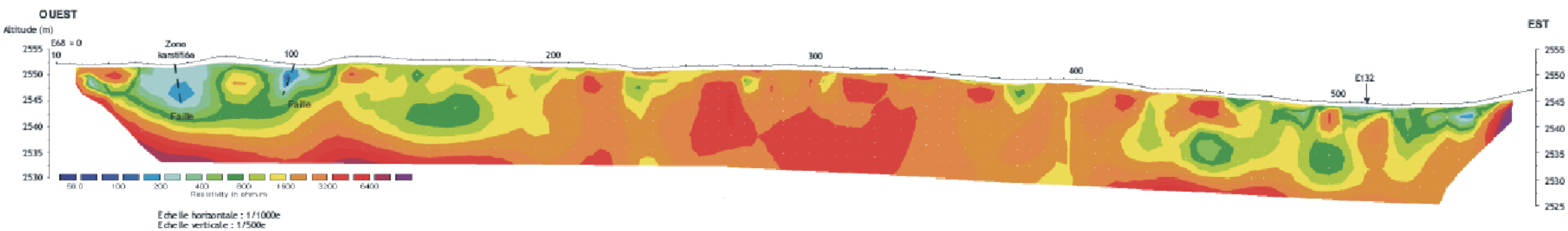
Fax : 04.76.92.22.23
geolithe@geolithe.com

A la demande et pour le compte de l'I.R.A.M.

Tronçon EST

Panneaux électriques



Date : 05-08 / 11 2007	Observatoire de Bure (05) Projet d'extension des voies Est et Ouest - Création d'une voie Sud-Est Etude géologique et géophysique préliminaire de site	Dossier 07-289

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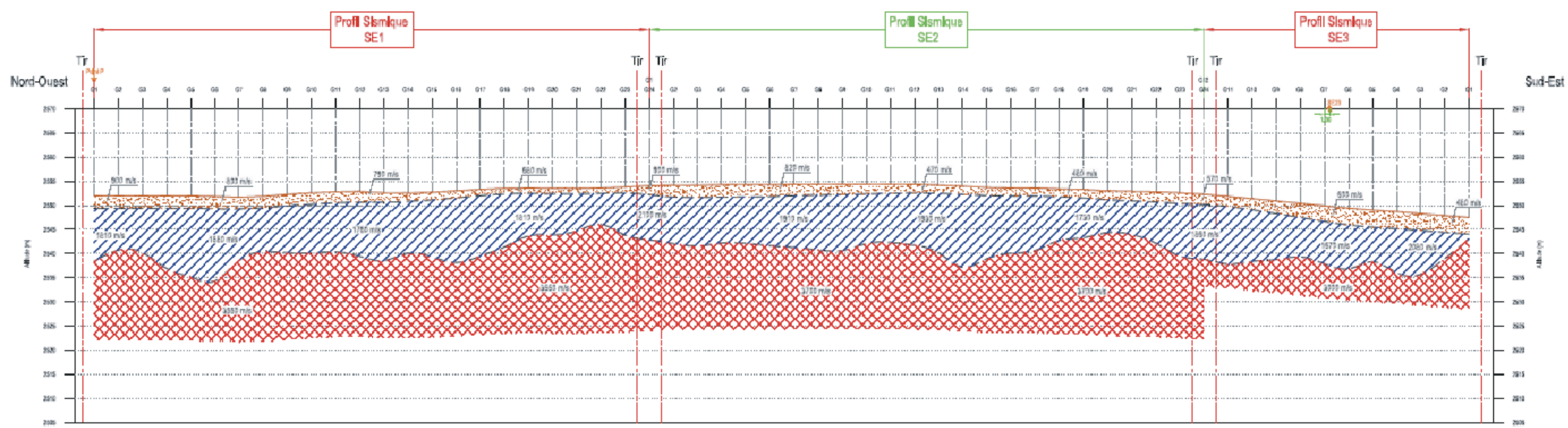

LEGENDE

Couche n°1 :
Terrains superficiels
issus de la gélifraction
Vp < 1250m/s

Couche n°2 :
Rocher très altéré et/ou fracturé
à disloqué
1600 < Vp < 2100m/s

Couche n°3 :
Substratum rocheux sain à
moyennement altéré / fracturé
3700 > Vp > 2350m/s

575 m/s Vitesse de propagation
des ondes sismiques

Positionnement du projet

Espacement intergéophone = 5.00m

GEOLITHE

ETUDE GEOTECHNIQUE

SISMIQUE REFRACTION
TRONCON SE

0 5 10 25m

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x12

NOEMA

project

NOrthern Extended Millimeter Array

iram

Institut de
Radioastronomie
Millimétrique

cnrs

advancing the frontiers

IGN España

MAX-PLANCK-GESELLSCHAFT