White Paper:

ASAC recommendations for ALMA 2030

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This document summarizes the recommendations emerging from the ALMA 2030 process. The findings are discussed in three documents: 1) the Major Science Themes in the 2020-2030 decade, 2) the landscape of Major Facilities by 2030, and 3) the Pathways to Developing ALMA, which describes a number of possible developments.

After compiling this information, the ALMA Science Advisory Committee discussed together with the Regional Program Scientists and the JAO at its February 2015 face-to-face meeting the best avenues for mid- and long-term improvement of the observatory, arriving at the conclusions presented here. The purpose of these recommendations is to guide the regional ALMA Development process in a coherent fruitful direction, by presenting a list of broad themes we foresee as the highest priority among the developments considered. It is important to keep in mind, however, that the development process also includes a creative, bottom-up element. Innovative technical ideas well grounded in astronomy should also have space in the future development of ALMA, and in that sense this is not an exclusive list. It also assumes that completion of the baseline capabilities of ALMA (adding bands 1 and 2) will proceed.

Separately from these developments, the ASAC notes that a large single-dish telescope equipped with cameras capable of fast large-scale mapping would be an important scientific complement to the interferometer. Such an instrument is outside the scope of the envisioned ALMA development projects, but if built, it would have large potential scientific synergies with ALMA (for example, surveying for sources, or providing the larger source context).

Recommended development paths

1. **Improvements to the ALMA Archive**: enabling gains in usability and impact for the observatory.
2. **Larger bandwidths and better receiver sensitivity**: enabling gains in speed.
3. **Longer baselines**: enabling qualitatively new science.
4. **Increasing wide field mapping speed**: enabling efficient mapping.

Better usability and impact: ALMA Archive

The archive is an integral piece of the observatory. An archive that is easy to use for the non-expert, and goes beyond being simply a repository for PI data is a great potential multiplier for the impact of ALMA. Analysis of the productivity of mature facilities shows that publications using archival data can rapidly overtake the publications from the original proposers acquiring the dataset, as is the case for the Hubble Space Telescope and other facilities. Thus the archive may be what ultimately determines the productivity of ALMA.

In order for the archive to be productive, it needs to be public, searchable, easy to mine, and it needs to contain fully reduced science-grade data products. In addition, the archive should contain value-added products either automatically generated (for example, lists of “detected lines” in the target), or user submitted post publication. Ideally the archive should be fully compliant with the Virtual Observatory standards, to be able to interface across wavelengths. It is also crucial that it can be fully exploited by users outside the community of interferometry and mm-wave experts.

With high sensitivity, position, frequency information, and large bandwidth, ALMA data are intrinsically very rich. A common feature is “involuntary” line surveys of sources, where lines beyond the targeted transitions are detected and mapped. The archive developers are already working on a few features to make it more user-friendly, with the introduction of quick visualizations of datasets, for example. Regional funding is being used to develop the first efforts into archive “enrichment” toolkits in EU, EA, and NA (e.g., ADMIT, the Japanese Virtual Observatory ALMA interface). Developing the ALMA archive into a fully-fledged science-grade minable archive, however, requires significant further development into pipelines and automated analysis. Because it will be unlikely that the quality of an automated pipeline reaches what is possible with experienced user reduction, we think the archive should be designed to accommodate user-submitted products (a version of this has been done for legacy- or treasury-class projects in facilities such as *Spitzer*, *Herschel*, and HST).

Gains in speed: Larger Bandwidths and Improved Receivers

The ability to provide and process wider instantaneous bandwidths, together with continuous improvements in receiver sensitivity, can bring scientifically significant increases in observation speed. The ultimate goal is to correlate an entire receiver band in one go, with no loss of sensitivity. This requires improvements not just to the receivers themselves, but also to the digitizers, the IF transport, the correlator, and the archive.

Increasing the IF bandwidth of the receivers appears as eminently feasible technologically. ALMA currently features a 4 GHz bandwidth per sideband, except in Band 6 where it is 5 GHz. CARMA and NOEMA, by comparison, feature 1-9 GHz and 4-12 GHz IFs, providing 8 GHz of bandwidth per sideband (note that a bandwidth of at least 6 GHz would allow to fit simultaneously ^{12}CO and its common isotopologues in one sideband of Band 3, for example). Doubling the bandwidths of the digitizers, fiber-optics transmission, correlator, and archive seem, likewise, eminently possible with current technology. The expansion of the IF to include an entire band will require considerable research. Nonetheless, it looks like an achievable long-term goal that will bring gains of factors of ~4-6 in speed for many observations. Bandwidth expansions will, simultaneously, enormously increase the legacy value of the archive while increasing the likelihood of serendipitous discoveries.

Continuous improvement to receiver sensitivities will also result in significant gains in speed across all science. Besides improving receiver temperatures (through removal of warm optics, or improved devices), the dual sidebanding of the currently DSB Band 9 and Band 10 receivers would yield important gains in speed at the higher frequencies of ALMA operation. Long-term sustained research in better devices or new technologies (such as TKIP amplifiers) has the potential to yield significant breakthroughs that are equivalent to doubling or tripling the collecting area of the array with its present instrumentation.

New Science: Longer Baselines

ALMA just recently demonstrated the potential of 10 km baselines in mm-wave interferometry by producing breathtaking images of the HL Tau protostellar disk and the SDP81 gravitational lens, among other targets. The designed maximum baseline of ALMA is 16 km. Doubling it to 32 km will provide an angular resolution of ~8 mas at 230 GHz (reaching this resolution at optical wavelengths would necessitate a 16 m diameter telescope in space). This is the size of the photosphere of α Centaurus A, and it is equivalent to a resolution of 1 AU at the distance of the Taurus molecular cloud (140 pc), ~10 pc at 240 Mpc, or a resolution of ~60 pc in the high-z universe (the size of a large Giant Molecular Cloud in the Milky Way). With the current system the Rayleigh-Jeans 1-sigma noise equivalent in a 24-hour continuum integration would be ~1 K at that angular resolution. This means that it is certainly possible to image warm dust structures with a moderate optical depth ($\tau \geq 0.01$), and it is easy to detect stellar photospheres, which have resolved brightness temperatures of several thousand degrees.

A further doubling of the baseline to ~60 km would lower the sensitivity to 4 K (assuming no improvements to the system), which means that a wide range of structures can still be imaged (from warm dust in protoplanetary disks to AGN tori). This angular resolution corresponds approximately to the diameter of the main sequence B7 star Regulus, 20 pc away. High signal-to-noise imaging of stellar photospheres at high-resolution opens up the possibility of measuring star-spots, temperature gradients, and stellar shapes in nearby stars.

Longer baselines will also allow for very accurate astrometry of nearby solar-type stars, enabling the search for planetary companions through their orbital effects. A Jupiter-like companion of a solar mass star induces a wobble of ~0.01 AU (i.e., ~1 mas at 10 pc) on the primary: because high signal-to-noise measurements can centroid with very high precision, and because ALMA astrometry should be extremely stable over long periods of time, it is likely that ALMA can look for companion-induced wobbles in stars out to several tens of parsecs. The bottom line is that increasing the resolution of ALMA has the potential to lead to qualitatively new scientific insights about the universe, and even more so when coupled with the sensitivity/bandwidth increases that we recommend in the previous point.

An intrinsic advantage of an interferometer is that the increase in angular resolution can be done progressively, by adding new antenna stations at larger distances. It is possible to progressively increase the length of the maximum baseline over the designed 16 km to understand the technical and practical limits of the equipment (e.g., LO distribution noise, line-length correction, and ultimately correlator) and the normal coherent correlation technique.

Correlation on long baselines requires using atmospheric phase correction techniques, currently 183 GHz water vapor radiometry in combination with fast switching in ALMA. Devoting effort to perfecting the atmospheric phase correction is something that should proceed in parallel with the investigation of the longer baselines. This will likely pay off not only on long baselines, but also on the fraction of usable time at the highest frequencies.

Wide Field Mapping Speed: Multi-beam Receivers

One of the major limitations of ALMA is its relatively small field of view (~1 arcmin at Band 3 and inversely proportional to frequency), determined by the diameter of the antennas and their primary beam. There is considerable scientific interest in increasing the field of view to enable faster wide field mapping of extended objects. Survey and imaging science will benefit from this.

The primary way to attain potentially large gains in mapping speed is to develop multi-pixel array receivers for interferometry. Such receivers are likely to occupy a significant fraction of the (already tightly packed) available focal plane space, and are likely feasible for only one band at a time and with only modest pixel counts without major redesign of the antenna optics. Nonetheless, it makes a lot of sense to investigate the tradeoffs in replacing a high-demand band (e.g., band 6 or 7) single-element receiver with a multi-pixel receiver.

The technical and scientific tradeoffs involved in developing and using multi-pixel receivers in ALMA are complex and require investigation to evaluate feasibility. Upgrading even one band to a multi-pixel receiver requires a number of improvements in elements downstream (IF transport, correlator, archive), and possibly upstream (LO distribution). Some of these improvements may be parallel with improvements required by larger bandwidths. In particular, for many science projects that require mapping of one spectral line, it may be practical to share bandwidth among pixels (large scale mapping of continuum sources would not be practical with such a scheme).

Major Science Themes in the 2020-2030 Decade

Executive Summary

ALMA was designed to address many science questions in the broad area sometimes bundled under the umbrella question: “How does the Universe work?” This includes areas in which the submillimetre band has traditionally advanced knowledge, such as the physics and chemistry of the ISM, the formation of stars and disks, the structure and evolution of galaxies and AGN. ALMA also has the potential to contribute to the highest profile areas of astrophysics, namely the search for life elsewhere, and placing constraints on fundamental physics.

Introduction

The purpose of this document is to serve as a reference for future discussions of science priorities for the ALMA Development Plan. We examine the outstanding science questions in a number of sub-fields, and consider the landscape of likely advances from other observatories in the near future. The potential contribution of ALMA to each of these science areas is laid out. The emphasis is on the science questions to be addressed, rather than the details of how data can be utilized to answer those questions, i.e. there is no discussion of data volumes or visualization/analytic tools to use to answer the questions.

[The primary audience for this document is a set of future ALMA bodies faced with ranking options, in which science prioritization plays a role. However, it is expected that the document may be read more widely.]

There can be little doubt that two areas of modern astrophysics grab the most headlines: studies of extrasolar planetary systems, leading towards the goal of searching for signs of life elsewhere; and investigation of fundamental physics using astrophysics in order to understand the composition and origin of the Universe. ALMA can contribute to both of these areas.

However, a third research area is also highlighted in most planning exercises (see Appendix A), namely “How does the Universe work?” This is the “bread and butter” of a very large fraction of ALMA observations, directed towards understand the life cycles of stars, the evolution of galaxies and the relationship between stars and disks and between galaxies and black holes.

These research areas are directly linked to the “level one science goals” that motivated the construction of ALMA in the first place, namely:

- the ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation;
- the ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation;
- the ability to provide precise images at an angular resolution of 0.1″.

ALMA’s range of capabilities enables it to contribute to a wide range of the astronomical sub-fields within the general “how does the Universe work?” unifying theme.
We discuss each of these areas below, within separate sections in which are described: (1) outstanding science questions or goals; and (2) how ALMA can contribute. We divide astrophysics topics into the following areas, stepping generally from the largest scales of the universe down to the smallest ones:

- Cosmology
- High redshift galaxies
- AGN and Black holes
- Nearby galaxies
- Origin of stars and planets
- Astrochemistry and Astrobiology
- Stellar evolution
- Solar System

Cosmology

Outstanding Science Questions/Goals

1. Constrain theories of modified gravity and dark energy, measurement of H(t), w(z), BAO, growth rate, etc.
2. Constrain inhomogeneities as a function of scale and redshift.
3. Measure shift of absorption lines in real time.
5. Probe the re-ionization history of the Universe and find the first objects.
6. Investigate the SZ effect at high resolution in order to understand details of the physics of galaxy clusters.

How ALMA Can Contribute

ALMA can contribute to an improved understanding of Galactic dust polarization to help with foreground removal for detecting CMB primordial B-modes. ALMA's high angular resolution capabilities reveal small-scale CMB anisotropies, and high resolution observations of the SZ effect in clusters can be used to accurate derivations of cosmological parameters.

High redshift galaxies

Outstanding Science Questions/Goals

1. Examine cold gas and dust at high-z without optical/IR detection in proto-galaxies
2. Probe the role of molecules in galaxy evolution (and metallicity evolution) through constraints on cooling and star formation rates.
3. Examine galactic dynamics at high-z.
4. 'See' large scale structure (clusters) in formation between proto-galaxies
5. Quantify obscured star-formation through cosmic time.
6. Determine the progenitors of present day elliptical, red and dead galaxies.
7. Establish the molecular and dust properties of galaxies in the very high redshift Universe (z = 6 and above).
8. Measure the evolution of the galaxy gas fraction through cosmic time

How ALMA Can Contribute

The well-known negative K correction effect at mm/sub-mm wavelengths give this region of the electromagnetic spectrum an advantage to studying objects from the distant universe. Higher survey speeds with ALMA would provide valuable contributions. Spectroscopy provides redshift determination, given a wide enough bandwidth to capture at least two adjacent CO rotational transitions. Therefore fast coverage of large portions of the spectrum is important (large bandwidths, multi-frequency observations) as is high sensitivity receivers. This is particularly true for the higher frequency windows of ALMA, which provide access to FIR fine-structure transitions near the peak of star formation history of the universe. Focal Plane arrays (with good bandwidth per pixel) may be also advantageous for surveys of galaxy clusters or deep fields, but the degree to which this technology helps and the tradeoff between bandwidth and number of pixels depends on the particular shape of the source galaxy counts.

AGN and Black holes

Outstanding Science Questions/Goals

1. What are the size and dynamics of the black hole in our own Galaxy?
2. What are the physical properties of AGNs in the local group, and can they be used to extrapolate to higher redshifts?
3. How do relativistic jets form, and what controls the magnetic activity in the inner regions of the accretion disk?
4. Understand accretion in AGNs, the formation of non-relativistic outflows (BAL winds), extent, geometry, whether they are ubiquitous in all AGNs.
5. Prove black holes and the (non)existence of singularity.

How ALMA Can Contribute

VLBI with ALMA will probe the conditions around the event horizon of the black hole in our Galaxy. This is the equivalent of the study of our Sun to understand stellar physics/evolution. The combination of high angular resolution and spectroscopy with ALMA combine for a powerful probe of the kinematics of circumnuclear regions. The dynamics and physical state of the gas can be probed with a combination of spectral lines tracing different densities. Black hole masses can be measured from ALMA observations of nuclear molecular gas.

Nearby galaxies and the Galaxy

Outstanding Science Questions/Goals

1. What is the physics and chemistry of the lifecycle of baryonic matter in galaxies (including our own)?
2. How do baryons cycle in and out of galaxies, and what do they do while they're there?
3. What is the effect of metallicity on the evolution of early galaxies? Is the mode of star formation the same as on later galaxies?
4. How does large scale feedback occur?
5. What are the gas flows within galaxies?
6. What are the relative roles of star formation and AGN feedback? What is the relative importance of AGN feedback vs. (for example) stellar feedback on its AU/pc/kpc/Mpc scale environment?
7. How do black holes grow, radiate, and influence their surroundings?
8. How do Giant Molecular Clouds form and evolve?
9. What determines the efficiency of the star formation activity across galaxies?

How ALMA Can Contribute

ALMA can contribute to answering these science questions by adding to the detailed inventory of baryons in nearby galaxies: cold gas, dust, molecules (clouds, continuous). In the past, people compartmentalized in wavelength regimes, focusing on a single ISM phase. In the future, simultaneous multiphase and multiscale studies will be the manner in which such questions are addressed. What is necessary is to link the large scales where accretion is happening, with the small and intermediate scales where star formation and feedback occurs. Multi-scale, high angular resolution mapping of entire galaxies (or the MW plane) in spectral line and continuum is needed. The multi-scale approach is key to connect the gas from kpc scales down to Giant Molecular Cloud (~100 pc) scales down to clump (few pc), core (~0.1 pc) and accretion disk (<1000 AU) scales. Full ALMA can do this in relatively small areas in the 12m+ACA+TP mode (which avoids spatial filtering), but large area surveys at < 1" resolution, without spatial filtering and in multiple tracers (of different ionization state, densities, temperatures) would be a task for Focal Plane arrays.

Origin of stars and planets

Outstanding Science Questions/Goals

1. Is the IMF Universal?
2. What is the life cycle of the ISM?
3. What are the properties of disks that form planets?
4. When does planet formation first take place? How is it affected by the transition from proto-planetary disk to debris disk?
5. How do the structure and evolution of debris disks constrain the architectures and evolution of planetary systems at late stages of their formation and beyond?

How ALMA Can Contribute

ALMA can sample many well-studied disks, which will enable the diversity and similarities of disk properties to be explored. Studies which connect the large scales of molecular clouds and star forming regions to the smaller scales of single star+disk/planets systems will follow the flow of mass and energy and enable studies of turbulence. Large fields of view with high spatial resolution and multiple tracers (e.g., lines, dust emission etc.) are necessary. Multi-wavelength coordinated studies including diagnostics of the UV radiation field are important.

ALMA can detect stellar photospheres and track stellar positions with sub-mas accuracy. ALMA should demonstrate its capability to supplement radial velocity characterizations of exoplanets with barycentric motion characterization so that the planetary contingent of e.g. Pollux may be better defined.

Astrochemistry and Astrobiology

Outstanding Science Questions/Goals

1. How do pre-biotic molecules form?
2. When do the first complex organics form in the Early Universe?
3. What is the pathway from complex molecules to life?
4. How do early solar system dynamics shape planetary systems?
5. What is the chemical composition in (exo-)planetary atmospheres?
6. What molecules can be used to trace life in other planets/moons/asteroids?

How ALMA Can Contribute

ALMA enables the detection of complex organic molecules (COMs) with abundance levels down to <10^{-11} or even down to a few 10^{-12}. This applies to both pre-stellar cores and protoplanetary disks. The high angular resolution of ALMA will help protoplanetary disk chemistry studies because cold disks show typical sizes from some tens to hundred of AU (angular scales of <1” at distances of 100-200 pc). For pre-stellar cores, the development of Band 2 would be useful because the beam would match the region where the emission of complex organics (a few 1000 AU at a distance of 100-200 pc) is expected to be found. An increase in the sensitivity of ALMA would allow the detection of the simplest COMs in the Early Universe providing constraints on when COM chemistry becomes active and on how efficient this process is at high redshift. Radio Recombination Lines could be useful as well since they have the potential to probe the densest, and innermost regions of ionized winds.

Stellar evolution

Outstanding Science Questions/Goals

1. What drives stellar mass loss? What is its role in star formation, galactic enrichment, and feedback?
2. What is the contribution of dust from supernovae and evolved stars?
3. How do the extremes of matter constrain fundamental physics?
4. What is the role of binarity in stellar evolution?
5. How do stars interact with their environment?
6. What is the structure of the outer solar atmosphere? How important are shocks and dynamics to maintaining the observed temperature profiles?

How ALMA Can Contribute

ALMA can probe stars at differing evolutionary stages, from those which are forming to those which have already expired. ALMA’s ability to study the Sun and solar-like stars using essentially the same instrumentation makes it unique, and eliminates some of the instrumental issues surrounding solar/stellar studies. ALMA’s studies of the Sun can provide simultaneous constraints on the co-location of cool and hot gas above the visible solar surface. Stellar astrometry can be used for proper motion measurements, important for dynamical constraints on binarity. Line surveys of evolved stars (including the rich molecular diagnostics available in the mm and sub-mm) probe the conditions of mass loss at various stages of stellar evolution. Continuum measurements constrain dust production in different stellar sources. Pulsar observations with ALMA enable the possibility to probe strong gravity and provide tests of fundamental physics. Enabling

VLBI capabilities with ALMA can probe the influence of compact objects on their environments.

Time domain studies are important to several areas of study in stellar evolution, both periodic/stochastically occurring phenomena, and transient/triggered transient objects. Central to this theme is an examination of the time-varying millimeter sky, something probed only cursorily with previous generations of millimeter and sub-millimeter telescopes. This requires transient follow-up capabilities in general, both for something like gamma-ray burst follow-up as well as other transient phenomena. What ALMA needs is fast reaction time and flexible scheduling capabilities. ALMA could be an extremely powerful tool, if it were able to react to science alerts from other facilities (satellite or ground-based), autonomously and on the order of hours.

Solar System

Outstanding Science Questions/Goals

1. Is there life in the Solar System and how do we find it?
2. How did the Solar System form and evolve?
3. How does giant planet composition vary with altitude and latitude?
4. What are the dynamics of planetary and satellite atmospheres?
5. What do the composition of comets reveal about conditions in the primitive solar system?

How ALMA Can Contribute

ALMA’s ability to perform high resolution mapping in a number of spectral lines is key to making advances on several of these solar system questions. High resolution spectroscopy elucidates velocity fields, and the abundance of spectral lines present from molecular rotational transitions of these generally cold objects provides a wealth of information about the chemistry of solar system objects. Objects such as comets change in real time, requiring repeat observations, and non-sidereal tracking requirements.

Appendix A: Existing plans

The selected themes for the ESA Cosmic Vision 2015-2025 (http://sci.esa.int/cosmic-vision/38542-esa-br-247-cosmic-vision-space-science-for-europe-2015-2025/) were:
- What are the conditions for planet formation and the emergence of life?
- How does the Solar System work?
- What are the fundamental physical laws of the Universe
- How did the Universe originate and what is it made of?

The 2013 NASA "Astrophysics Roadmap" (http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf) lists three fundamental questions for the science-driven 30-year vision of space astronomy:

- *Are we alone?*
- *How did we get here?*
- *How does the Universe work?*

At the next level of detail in NASA's Roadmap, seven out of nine of the bullets in the report have relevance to ALMA:

- Probe the origin and ultimate fate of the Universe, and determine the forms of matter and energy that govern it, by mapping the growth of cosmic structure through its history.
- Unveil the chaotic flows of superheated gas swirling around black holes that fuel the most powerful engines in the Universe.
- Use telescopes as time machines to map the full history of galaxy formation and assembly, from the birth of the first stars through the turbulent epoch of rapid growth to the galaxies we see today.
- Make star-by-star maps of nearby galaxies across the full range of observed galaxy types to decode their histories and understand how and when they acquired their present-day forms.
- Characterize the evolution of planetary systems like our solar system by understanding the nature of newborn stars, the evolution of disk around protostars, the process of planet formation around them, and the crucial transport of water to inner planets. Study debris disks around main sequence stars to study the evolution of planetary systems in the late stages of their formation and beyond.
- Complete the reconnaissance of planets and planetary systems, including gas giants, rocky planets like Earth and Mars, ocean-covered water worlds, planets close to and far from their parent stars, and even free-floating planets that have been ejected to interstellar space by gravitational interactions with their siblings.
- Directly image the planets around nearby stars and search their atmospheres for signs of habitability, and perhaps even life. (define the signatures for life).

ALMA’s grasp of the cosmos extends from the solar system outward, and addresses key themes brought up in the recent planetary decadal survey (“Visions and Voyages”;http://www.nap.edu/download.php?record_id=13117). Three cross-cutting themes were identified:

Building new worlds – understanding solar system beginnings
Planetary habitats – searching for the requirements of life
Workings of solar systems – revealing planetary processes through time

Appendix B: Contributors to this document

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Appendix C: Brainstorming ideas

This is a very valuable list of ideas/questions contributed by several people to this document. Some are developed in the broader topics developed above, some are too specific to be included in those topics, except in the broadest sense. We list them here to preserve these ideas and individual questions.

* What is the astrochemistry of the universe?
    - how/when/where did the cosmos become populated with the heavy elements?
    - what is the pathway from simple molecules to complex molecules?
    - what is the pathway from complex molecules to life (e.g. astrobio, comets?)
    - How dust grains are formed?
    - how can molecular lines be used to constrain the physics of the cosmos?
    - how can the physical environments in the cosmos be used to inform chemical models (metallicity/alpha element dependant chemistry),

* What are the properties of proto solar systems (individual planets)?

* What physical conditions drive the most extreme star formation in the cosmos?

* What regulates star-formation? Is environment important?

* Better tracers of H2 and/or better understanding of the CO X-factor
    - improved tracers of non-molecular, non-ionized gas? ("CO-dark gas")

* Merger sequence (major and minor) over redshift and environment: tracing star formation etc.

* Galaxy centres- AGN fueling, black hole masses (w/ molecular gas at ALMA, stars/ion. gas and masers at other facilities), dusty torii (AGN unification), non-relativistic winds, link to megamasers, geometric distances, cosmology

* How does gas turbulence behave on many scales: Galaxy Disks/Centres, ISM, protoplanetary disks, our own atmosphere? [what questions will we be asking about turbulence in 20 years? Maybe all the same?] - on protoplanetary disks: which part of the disk is actually turbulent? (assuming we will have a good tracer for turbulence by that time). Also a relevant question is, what drives (replenish) turbulence in the ISM?.
    - turbulence in ISM requires large-area, multiscale: multi-beam receivers, OTF maps in the Galaxy

* What does the time-varying millimeter sky look like?

* Molecular outflows (SF or AGN driven, gas entrained or line driven, mass loading, extent, effect on environment). Maser proper motions may be observed in nearby Sf regions.

* Dust: Grain size distribution, grain shapes, different grain species. What effect do

these have on our inferences about mass of clumps? high redshift galaxies? What heats dust in different types of galaxies- star formation, old stars, AGN
* What drives "anomalous microwave emission"? (spinning dust? important at small scales?)
* Gas in galaxies of different types, spiral, starburst, early-type, dwarf - differences and similarities
* Is intra-cluster dust (in galaxy clusters) significant ?
*Biomarkers, is there an specific molecule that we could use to trace life in other planets/moons/asteroids.
*Gas kinematics in galaxies as a mass tracer - Tully Fisher, Dark Matter vs MOND (etc), maximal disks [CO as a high resolution and accessible tracer at all redshifts]
* Can we track infall into Sgr A*, e.g. if a G2-like event happens but *really* happens? What opportunities shouldn't we miss?
*Exoplanets in evolved stars. There are observations of planets around WD and also around NS, do they form in the PN/SN phase respectively? or are they captured? Observations of a second generation planet formation can open up a whole new window.
* Can ALMA detect globular clusters forming ? Proto globular cluster clouds. There are a few candidates of proto massive clusters in our own Galaxy. But the question here is whether we can really detect and characterize these at cosmological distances.
* We haven't found yet very young planetary systems - maybe a few? - RV surveys are hard on young stars due to activity (<100Myrs). The number of young stars hosting planets might increase thanks to a future NIR spectrograph (NTT or/and CRIRES+. added in proof :-) the number of transiting planets will increase by a lot thanks to the future missions/facilities. It is not clear the role of ALMA in characterising the planets themselves (not sure about the sensitivity to do direct imaging). For sure their circumstellar environment is of interest.
* Galaxy Clusters - evolution of molecular gas, fueling of stellar mass loss
* What is overall morphology of the magnetic field throughout the ISM? Its relevance for molecular cloud and star formation? How is magnetic flux lost during star formation? Magnetic field relevance to the ubiquitous filaments seen in the ISM? Does magnetic braking solves the star formation angular momentum problem?
Does the magnetic field collimate bipolar outflows from proto-stars?.
How is the magnetic field morphology in accretion disk around supermassive black holes? ALMA will require wide field mapping in full polarisation mode for some of these to happen, as well as very high angular resolution in full pol.
High sensitivity mapping of the CMB polarisation in bicep2 like fields.
Understanding of the sun magnetic field, specially magnetic reconnection in sun spots or/and coronal mass ejections, sun flares.
* Linking dynamics of the outer Solar System with composition and origin of TNOs: How

the primordial TransNeptunian disk formed and evolved to the current day? In particular, how dominant was dynamical instability versus smooth migration in moving Neptune from its formation location? How could the low-inclination/low-eccentricity TNOs population survive the planetary migration?
* Astrometry in the mm regime: relatively unexplored territory
* Study the origin of second generation gas in debris disks, is it related to late stages of planet formation? What about gas in Gyr old systems?
* Can ALMA contribute on the study of the Sun, Sun-Earth connection, climatology in planetary system and finally on global warming
* Mass measurements of multiple Trans-Neptunian systems through mutual orbit determination in order to constrain the origin of TNOs. (need for higher angular resolution ~5 mas, preferentially in band 7, in order to resolve ~25 known binary systems)
* Can ALMA help solving the Li puzzle in K-giant stars?

PATHWAYS TO DEVELOPING ALMA

A document to inform the scientific discussions leading to
the development of a roadmap for improvements in ALMA

ALMA DEVELOPMENT WORKING GROUP REPORT

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This document is part of a report initially commissioned by the ALMA Development Steering Committee, and subsequently the ALMA Board. The goal of the report is to provide guidelines for the long-term development of the array, and its continued and scientifically fruitful operation beyond 2030. The report is broken up in several documents, of which this is the one devoted to addressing the interface between was is technically possible (or possible to envision for this group of people) and its impact on the science performance and operations of the instrument.

To this end we have classified the possible developments in broad areas of improvement subdivided in smaller branches. The purpose has been to concisely discuss each development path, and whenever possible go beyond its description into a qualitative and quantitative evaluation of its scientific, technical, and operational impact including some very rough level of cost analysis. This document is intended to be informative for the general reader, and includes only broad technical concepts where necessary.

The table in the following pages classifies and summarizes each development in terms of the improvements it enables. It also contains a very rough estimation of the cost and the operational implications. The costing qualifier (very low, low, moderate, high, very high) corresponds roughly to estimated costs in millions of USD in the ranges < 0.1, 0.1-1, 1-10, 10-100, and >100 respectively.

No.	Improvement Area	Item	Degree	Speed/Difficulty	Fabrication Cost	Target Science	Note	Operation effects
01	Sensitivity	More 12m antennas	incremental	Known	High to Very High	All	Correlator, IF transfer	More power generation
02		More ACA	incremental	Known	High to Very High	Large scales	ACA correlator/IF	More power generation
03		New digital system	×2 bandwidth in some cases, otherwise needs new Rxs	Moderate, some research	Moderate to High	All	See also 33, 43	Some power, array downtime
04		2SB B9/B10	×2 for B9/B10	Research/Known	Moderate	High frequency	~20% of all observing time	Downtime for installation
05		Lower noise Rxs	20%-200%,	Moderate to long research	Moderate	All		Downtime for installation
06		New technology devices for Rxs	Potentially large	Long scale research	Moderate to High	All	Quantum-limited amps, ultra-wideband	
11	Resolution	Longer baselines	×2-3, or up to 300 km	Requires construction	Moderate to Very High	SMBHs, photospheres of stars, high-z BH	Need more experience with long baselines	Snow cleanup and recovery
12		Better phase correction	~10%-30%, more for high frequencies. Increasingly important for long baselines	Software, research, maybe some new hardware	Very low	Disks, exgal. All science fields that require high resolution.	Need statistics on current performance of WVR	
13		mmVLBI	VLBI operations for general users	Ongoing	Low to Moderate	High resolution/non-thermal	Need good operation model	Low Agreements with other observatories/networks
21	FOV	Multi-beam Rxs	×N	Extensive; modifications to cryostat, LO, potentially IF transport, correlator	Very high	Nearby galaxies, local SF regions, Galactic surveys	Biggest gain at higher frequencies	Downtime for deployment and testing. Data rate increase, archive cost. Software/pipeline/algorithms development needed

22		Under-illuminated feed	×a few for mapping of bright sources	Not clear how to share with normal system	Moderate	Solar science, GMC mapping	Easier to implement independent subarrays	Downtime for installation
31	Spectral Coverage	B2	New capability	Similar to other bands	Moderate to High	Disks, high-z, SZ, molecules	Could be combined with upgraded B3 and wide band	Downtime for installation
32		B11	New capability	Research, long commissioning	High	Very high-z H2, FIR, local NII 205 um	Very small fraction of time available	Downtime for installation
33		Extend IF for Rxs	×2-3, maybe more?	New Rx, new digital system/IF transport	Moderate to High	Simultaneous isotopologues, line surveys	More correlator to improve sensitivity and spectral coverage	Data rate/Volume increase
34		Correlator	×2 bandwidth in some cases, otherwise needs new Rxs	Moderate, some research	Moderate to High	line surveys	See also 03, 33	Data rate/Volume increase
41	Simultaneous frequency coverage	B2+3	New capability	Some research	Moderate	As B2	Saves a 4K cryo slot for B11	Downtime for installation
42		Multi freq. feeds	×2 ?	Research	Moderate	SLEDs, multi-transition studies	Requires system wide modifications	Data rate/Volume increase
43		Dual feed use?	×2 for large scale mapping	Quick?	Low to moderate?	Galactic GMCs, nearby galaxies	Requires system wide modifications	Data rate/Volume increase
51	Imaging quality and calibration	Deconvolution, combination software	Important for extended /complex srcs.	Quick, some research	Low	Complex sources	Need to understand the best way to add 12m array with ACA	None
52		Better phase calibration	~10-30%, maybe more at high freq.	Research	Low	High frequency, high resolution (e.g.,disks)		Data gathering
53		Better sidelobe calibration	Better image fidelity in mosaics	Measurements	Low	Large mosaics, bright sources		Data gathering

54		Better amplitude calibration	×2?	Calibration source	Low to moderate?	High precision line ratios, absolute calibration		Data gathering
55		Better passband calibration	Very high spectral resolution?	Noise injection device	Low	m/s velocity resolution		Data gathering
56		Better polarization calibration and purity		External wire grids, OMT development	Moderate	High precision/ dynamic range pol.		Data gathering
61	Flexibility	Subarrays	×2-3 speedup for shallow mapping or multifreq. or simultaneous multi-wl monitoring	More LO reference systems	Low	Galactic GMC, nearby galaxies, variable phenomena	Pretty much implemented	None
62		Increase in data rates	Resolution, archival value	Infrastructure	Moderate	Galactic, nearby gals., high time resolution	Increase in processing time, data transmission	Archive space and cost
71	Usability	Better automatic pipeline calibration and imaging heuristics	Better archival products, long term science value	Software	Low	All		None
72		Automatic Analysis and Enriched Archive	Added value products, cube descriptions	Software	Low to moderate	All		None
73		Visualization	Quick first look tools, better 3D visuals	Software	Low to moderate	Complex sources		None
74		Cube analysis tools (source finding, line ids, source decomposition, property measurements)	Better analysis for experts and non experts	Software	Low to moderate	All		None
81	Reliability & efficiency	Remote power recovery	Fast recovery from power or weather	Infrastructure	Low	All	Partially implemented	Increased efficiency, low cost
82		Upgrade of power delivery system	Increased reliability	Infrastructure	?	All		Increased efficiency
83		Cryo cooling improvements	Cheaper reliable cooling systems	Infrastructure	Moderate	All		Refurbish all antennas, downtime
84		Remote inspection for weather recovery	Fast recovery from weather	Infrastructure	Low to Moderate	All		Installing and maintaining cameras

00 Sensitivity Improvements

Lead author: Leonardo Testi

01 - More 12m Antennas

The third high-level ALMA science goal is to provide excellent imaging, which requires an optimized distribution of the antennas, a large number of baselines to effectively sample the Fourier plane and correction for imaging errors. Adding more antennas will improve the collective area of the array with two beneficial effects: improve the image fidelity and the overall sensitivity. This is a "brute force" approach, it would provide a very significant benefit only if we consider doubling the number of antennas (or use an even higher factor).

At the current stage, we would need to restart the antenna production lines, as well as all the hardware required to outfit the antennas. The array was designed for 64 12m antennas; the baseline correlator accommodates that number of antennas. The configuration was also designed for 64 antennas, differences with the current 50 antenna design are mainly in locations in the compact array, thirteen 64-antenna configuration pads were not built. The power consumption of the array will also scale linearly with the number of antennas. Owing to maintenance needs, only 47 of the 50 12m antennas in the main array will be available on average for high-resolution imaging. Two conclusions of an NRC committee[1] which investigated the effect of smaller numbers of antennas on ALMA performance were that (a) the Level One goal of high-contrast imaging of protostellar disks could not be met by an array of 50 operational antennas and (b) that image fidelity would be degraded by a factor of two with such an array compared to the planned 64 antenna array. An additional 4-6 12m antennas added to the current 50 antenna complement of the 12m Array would increase sensitivity for the 12m Array by 8-13%, decreasing integration time by 17-27% and increase high resolution imaging quality by as much as a factor of two in image fidelity. All considered, most likely this will involve a cost per additional antenna very similar to the original cost in the construction project. The overall cost of doubling the array could be of the same order of magnitude or the whole original bilateral ALMA project (infrastructure costs will not be needed, obviously, with the possible exception of upgrading the power plant).

The ballpark number for the cost of one array element (fully equipped telescope) in construction is of the order of 10M$, but this figure may very significantly change for a new production run, depending on the number of elements to be produced and possible design/production changes. Experience indicates that building systems designed several years ago frequently requires redesign, as several of the original components will not be available in the market anymore and/or there are small numbers of specially fabricated components. This adds increasing risk and cost to

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[1] The Atacama Large Millimeter Array (ALMA): Implications of a Potential Descope issued by the US Committee on Astronomy and Astrophysics (CAA) Board on Physics and Astronomy (BPA) Space Studies Board (SSB) (2005)

any future addition of antennas.

02 - More ACA antennas

The current number of ACA antennas (both 7m and 12m-TP) is based on the evaluation that approximately 25% of the projects would need zero-spacing data and it would typically take four times the time on the ACA to reach the required signal to noise level as compared to the main array (in the overlapping region of the (u,v) plane). These estimates were based on the analysis of the ALMA DRSP (see http://www.eso.org/sci/facilities/alma/documents/drsp.html) and on dedicated simulations. The current number of ACA antennas (both 7m and 12m-TP) is based on the evaluation that approximately 25% of the projects would need zero spacings and it would typically take four times the time on the ACA to reach the required signal to noise level as compared to the main array (in the overlapping region of the (u,v) plane). These estimates were based on the analysis of the ALMA DRSP (see http://www.eso.org/sci/facilities/alma/documents/drsp.html) and on dedicated simulations.

Increasing the number of ACA antennas would allow the ALMA observatory to speed up the short- and zero-spacing observations. Depending on the usage pattern for the ACA, this could be highly beneficial as the typical programs now require a factor 2-4 more time on the ACA than on the 12m array to reach the correct sensitivity level in the short spacings. The same cost considerations as in the expansion of the 12m array apply. Note that it would be likely necessary to expand the ACA infrastructure on the ground (pads and cabling). The ACA correlator will also need to be upgraded to handle the correlation of more stations, in addition to the current 16 inputs, designed to cover the simultaneous inputs of 12-7m and 4-12m antennas. The expected cost for each additional, fully equipped ACA antenna is expected to be approximately 8M$.

03 - New digital systems

One can envision different types of upgrades to the digital system, from the backend through the correlator. Sensitivity gains would be realized by reducing losses and improving digitization efficiency, allowing simultaneous correlation of more antennas (although the gain in this case would be limited to two additional array elements, including all 66 available antennas, unless the number of these is also increased), and allowing wider bandwidths to be used in connection with receiver upgrades. While the first two gains are incremental, the latter could be substantial. The scientific gain of significantly increasing the instantaneous bandwidth of ALMA by a factor N will be in improving the continuum sensitivity (~square root of N), allowing more efficient spectral surveys (~N), and enabling simultaneous observations of several combinations of molecular lines (this will depend on the exact IF arrangement of each new receiver bandwidth). These will all boost the science productivity for unit time on sky.

Note that the current ALMA Band 6 already offers a wider bandwidth (2x5GHz) than what the current ALMA backend system can digitize and transport. Bandwidth increases of factors 2-4 are technically possible in the receivers (and already studied and ready to be implemented in some cases, e.g. Band 9 upgrade to 2SB-16GHz/pol and Band 2-3 cartridge with 16 GHz/pol bandwidth).

ESO has done a very preliminary investigation of the cost required to improve the digitization and backend system to digitize and transport double the bandwidth. The cost is expected to be significantly lower than the original cost of the backends. In fact, considering that such an upgrade could occur on a timescale of ~5 yrs, there is scope for studying, prototyping, and possibly testing at the OSF on a 2-antenna interferometer a new digitization board that would provide better reliability, lower costs, and double the bandwidth. ESO is starting a study contract with Universite de Bordeaux to carry on a preliminary investigation and prototyping for these next generation digitizers. The impact on this upgrade on operations would be an increase in the data rate and data volume from the array (it the digitizer and transport upgrade is connected with wider bandwidths and a correlator upgrade). This is a significant consideration since the data rate is already limiting observations. A newly designed more modern system could have benefits in the maintenance area, the concept that Université de Bordeaux is developing could allow to replace several components of the current system with a new single electronics board, for example. Work is needed to study the impact and cost on the correlator of expanding the instantaneous bandwidth.

04 - 2SB B9/B10

The system temperature, which characterizes the sensitivity of the observations, is approximately (see ALMA memo 170 for a full treatment)

$T_{SYS} \cong f\,[T_{RX}+\eta_{SP}\,T_{SP}+(1-\eta_{SP})\,T_{SKY}\,(1-e^{-\tau})]\,e^{\tau}$

where f is 1 for a SSB and 2 for a DSB system, T_{RX} is the SSB receiver temperature, η_{SP} and T_{SP} are the spillover fraction and the corresponding temperature, T_{SKY} is the temperature of the sky, and τ is the optical depth of the atmosphere ($\tau=0$ is perfectly transparent). This is an approximation that assumes equal gain and T_{SKY} in both sidebands for a DSB system.

Bands 9 and 10 are the only DSB receiver cartridges in the ALMA system. This reduces the sensitivity in interferometric mode as noise from the image sideband contributes very significantly to the overall budget. Moreover, in single dish mode the signal from the two sidebands cannot be easily separated, which leads to a number of problems when combining with interferometric observations. A two-sideband (2SB) architecture would suppress the signal and noise contributions from the image sideband. The gain in sensitivity by eliminating the noise from the image sideband can be substantial for spectral lines: typically a factor approaching 2 as the brightness of the sky is significant at these high frequencies, but it can be much higher if the image sideband falls in an opaque region of the atmosphere. For continuum the corresponding factor is approximately sqrt(2). For single dish observing, the line overlap and confusion from the image sideband would be removed.

ESO contracted NOVA at the end of 2010 to study the feasibility of upgrading the Band 9 cartridge to 2SB operations with an option of delivering 2 full 4-12GHz IF sidebands per polarization for a total of 16 GHz/pol. Such an upgrade would significantly improve the sensitivity and the instantaneous frequency coverage of the receiver. The study concluded that the upgrade is technically feasible and we have a design ready for implementation. Detailed costing needs to be evaluated, but the proposed upgrade scheme involves an in-situ replacement of some of the modules, with minimal impact on the other cartridge systems, making this a very attractive option for the future. An NRAO-funded study focuses on Band 10, for which receivers employing balanced sideband-separating mixers based on new-technology promise reduction in Tsys by a factor as large as 4 along with higher dynamic range (and calibration accuracy) and flat gain and noise characteristics over a full 4-12 GHz IF band.

05 - Lower noise Rxs

At frequencies below ~100 GHz, the existing ALMA Band 3 receivers and the current designs for Band 1 and 2 are just meeting the ALMA requirements, which are a few times the theoretical quantum limits. In the Bands 4 to 7, the current receivers are performing very close to the theoretical noise levels. At higher frequencies, sensitivity gains could be substantial (possibly a factor of 2 or even larger) but difficult to quantify without a dedicated study. In the above-mentioned study for the B9 upgrade, it was shown that it is now possible to produce reliably mixers with significantly better noise specifications than the ones that populate the existing B9 cartridges. Replacing all the mixers is however a significant cost and likely this makes sense only in the framework of a more ambitious cartridge overhaul that would also deliver a 2SB mode and 16GHz/pol useable bandwidth.

In the lower frequency bands, the preliminary results from a B2-3 study indicate that significant gains are possible by using very good performance MMIC devices for the whole band with less stringent cooling constraints (compared to SIS junctions). The removal of the 4 K stage in the insert could allow enough space for cold reimaging optics. The combination of better devices, the removal of warm optics, and a wider IF bandwidth (16 GHz/pol) would result in significant performance gains even in the Band 3 range. The cost of such an upgrade would be the production of a full set of Band 2-3 receiver cartridges (plus upgrades to the IF transport and correlator in order to process the enhanced bandwidth). The current limitations are thought to be in the development of sufficiently wide band and low noise temperature active MMIC devices. There are few foundries in the world that could develop these, and a few development projects are currently being carried out in USA and in Europe (in the framework of the Radionet3 EC-FP7 project) with good prospects.

06 – New technology Rxs

New technologies may allow leaps in receiver bandwidth or noise temperature. These technologies are more experimental than the ones discussed in the previous section, and thus require investment in long-term research.

An ALMA/NA funded study (Woody 2013) investigated the use of JPL TKIP (traveling-wave kinetic inductance parameter[2]) amplifiers for ALMA at 55-175 GHz. These amplifiers hold the promise of significantly improving the system noise temperature, particularly in the lower bands that are not atmospheric noise limited while simultaneously increasing the instantaneously available bandwidth on the sky. The current Band 3 receiver noise temperature could be reduced from ~5h/k, ~25 K, to ~2h/k, ~10 K and the instantaneous bandwidth could be increased from 16 GHz to >32 GHz.

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[2] Eom et al, Nature Physics 8, 623 (2012)

Realizing these improvements, however, would require changes to some parts of the existing front-end cryogenics and receiver cartridges. A receiver based on TKIP technology has yet to be demonstrated.

A Band 6 NA study being extended investigates a redesigned superconducting mixer circuit in which the Nb/Al-AlOx/Nb SIS junctions are replaced with Nb/Al-AlN/Nb junctions. By using Nb/Al-AlN/Nb SIS junctions with a relatively high critical current density (JC), the junction capacitance can be reduced. With a modified mixer (embedding) circuit, this allows the RF bandwidth to be increased substantially if accompanied by increases in the IF transport system and eventually the correlator. For example, this can improve ALMA's speed for observing isotopic CO lines in B6 by a factor of 2-3 since they could be fit within the same observation. Improving the receiver noise temperature from 80 K to 40 K SSB would reduce Tsys by a factor greater than 1.4 over more than 88% of the observing time, and by a factor of ~1.8 under the best observing conditions. The corresponding improvements in observing time are factors of 2 and ~3, respectively.

10 Resolution Improvements

Lead author: Daisuke Iono

11 - Longer Baselines

Traditional VLBI measurements are so far limited to compact, non-thermal high-surface brightness emission such as synchrotron and maser. The addition of ~ 5 x 12m antennas within a 300km range of ALMA fills the gap between VLBI and the connected array, and it will realize angular resolution of < 1mas and with sensitivity to detect Tb < 1000K (i.e. the thermal universe). The baseline plan is to connect the pads through fiber-link and build five new 12m antennas equipped with the workhorse ALMA bands (e.g. band 3,6,7). Maximum delay (~ 1 msec) can be compensated within a buffer (~16 MB) of a new correlator.

The science case includes, for example, BH formation in SMGs, mass accretion processes onto AGN engines, imaging stellar photospheres, distance measurements to stars and exoplanet characterization through astrometric measurements of host star motion. The idea of the ALMA Extended Array is to add five additional 12-m antennas (or pads) within 300 km from the central cluster of ALMA. A completed concept study can be found at: Kameno, S., Nakai, N., and Honma, M. (2013), ASP Conf. Ser. 476, 409. See also http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/EA_Development_Meeting/Program_files/Kameno.pdf. Note however that the relevant ALMA continuum sensitivity for 1 hour is about 20 uJy: we use the correspondingly corrected numbers below.

Conventional VLBI measurements so far are limited to compact, non-thermal high-brightness sources such as synchrotron radiation from AGN jets or maser from star forming regions, evolved stars, and circumnuclear regions of AGNs. The intermediate-length baselines up to 300 km will allow us to study the lower surface brightness emission, namely emission that are thermal origin; for example accretion of matter onto the super-massive black holes (SMBHs) of AGNs, or photospheres of nearby giants/supergiant stars. The high-z universe can be studied at 10-pc scale, allowing us to search for SMBHs in forming galaxies, which is ultimately linked to the galaxy-BH co-evolution scenario. The 1 hour continuum sensitivity is 20 uJy, which corresponds to a detection limit of Tb ~ 3,000 K (5 sigma) with an angular resolution of 0.6 mas at Band 7. This will result in a factor of ~20 improvement in resolution compared to the 16 km baseline array. This, of course, relies on integrations of 1 hour being possible for these very long baselines without self-calibration.

Some of the technical issues to be investigated are; (1) study of the feasibility of long coherent integrations on long baselines without self-calibrations (the data for 10 km baselines would provide a good starting point for understanding the properties of the atmosphere at the site. Further testing with specially purposed small remote antennas may be desirable), (2) understanding sub-mm coherence at long baselines (e.g. is the current central LO distribution accurate enough? how do we calibrate the phase?), (3) a detailed site survey for the additional pads, and (4) fiber connection at distance of > 100 km, (5) next generation correlator. The construction of the new pads could be done parallel to normal ALMA operation and should not interfere with it, but commissioning tests using the ALMA correlator must be done and will require some CSV time, once the new antennas and pads are installed. In addition, acceptance tests must be performed once the new antennas are delivered to JAO.

The estimated cost for installing 5 new antennas with baseline lengths of 300 km is shown below. The largest expenditure will likely be the new antennas, although infrastructure (e.g., roads) and fiber optics is also likely to be expensive. A mitigation plan could be to use the existing ALMA antennas and only build new pads, although in practical terms it means that the distant antennas will be removed from the usual configurations. To use existing ALMA antennas likely requires disassembling them for transportation and rebuilding at the new pads, rather than moving the antennas via the transporter. The best model for powering, maintaining, and servicing the distant antennas and the associated infrastructure will have to be studied. Another option to reduce the cost is to use VLBI-type recording to replace fiber connectivity. Fiber optics cabling to distant pads is likely an expensive item. Note that the planned LLAMA (the Large Latin-American Millimeter Array) antenna in the north of Argentina with a baseline of ~180 km to the ALMA site is essentially a step in this direction.

New Stations and antennas	19.7 MUSD/station x 5 = 98.5 MUSD
Fiber line/data transport	?? MUSD
New infrastructure	?? MUSD
Computing	2 MUSD/5 years
AIV/CSV/SE	6 MUSD
Management	2 MUSD

12 - Better Phase Correction

Accurate phase correction is a key part of interferometric calibration and imaging, as imperfect phase calibration will lead to poor image quality and affect the science interpretation. Better phase correction will result in higher fidelity imaging, and this affects all science. Based on the results from the latest CSV tests (Asaki, Matsushita et al.), the longest baseline that achieves the ALMA RMS spec [10(1+PWV) microns] is up to ~ 400m, even after WVR correction. A 2 km baseline currently achieves 70 micron RMS (PWV=1.3 mm, 333 GHz), which is still x3 worse than the ALMA spec. This is equivalent to saying that the observed visibility amplitude is reduced to ~90% of the true value, as the coherence is proportional to $\exp(-\sigma^2/2)$ where σ is the phase rms in radians (Thompson, Moran, & Swenson 2001).

Another finding is that the current WVR correction does not improve the phase RMS when the PWV is high (> 3 mm) or very low (< 0.5 mm). For high PWV conditions, this failure is probably due to the increasing optical depth of the 183 GHz water line monitored by the system. In low PWV conditions the atmospheric phase perturbations are probably dominated by the dry air component, to which the current system is not sensitive. The good news, however, are that the outer scale turnover of the structure function (e.g., Carilli & Holdaway 1999) appears to be at ~ 500 - 1500m, which means that the phase RMS will not increase significantly for baselines longer than ~ 2km (Matsushita et al.).

A simple mitigation scheme is to use fast-switching (with cycles of 10s), for which tests indicate that the RMS phase of baselines longer than 3 km meets the ALMA spec. The current baseline plan is to use both the WVR and fast switching.

There are several limitations to the current phase calibration system;

- The WVR system assumes uniform weather conditions among all antennas. That is, the coefficients derived for the WVR correction assume the same weather conditions for all antennas. This may introduce errors. A possible mitigation plan is to install new weather stations near the longer baseline antennas.
- The WVR only looks at the water vapor component of the atmosphere and the dry component is not taken into account. First and foremost, an evaluation of the oxygen sounder data is necessary. See http://www.mrao.cam.ac.uk/~bn204/publications/2010/2010-08-General.pdf
- We do not have a phase monitor at the site. Thus it is difficult to evaluate the phase condition before/during the science observation. An installation of a phase monitor system will allow us to characterize the phase screen (and possibly use the data for real time phase correction), and it will also help us in the decision making process of dynamical scheduling. Installation of 50 BS/CS antennas and associated equipment will cost ~0.1 MUSD.

13 - mmVLBI

The science case with the mmVLBI ranges from Galactic to extragalactic science and fundamental physics. Science cases include;

- Nearby supermassive black holes -- produce the first Schwarzschild-radius scale images of nuclear black hole accretion disks and jets, allowing astronomers to perform new tests of general relativity in a strong-field environment,
- High-resolution imaging of AGN jets -- understand the internal jet structure, the role of magnetic fields in jet launch and collimation, and connections with very-high-energy photon emission.
- Spectral-line VLBI of absorbing systems -- measure the chemical evolution of the universe over cosmic time and test whether the fundamental constants of nature are variable. In some cases VLBI may be key to separate a complex absorber into smaller systems, for example in the case of material in a gravitational lens absorbing against images of a background source.
- VLBI observations of masers -- refine estimates of the physical conditions and dynamics in the circum-stellar gas around young stellar objects as well as in the circumnuclear

environment of AGN.
- Astrometry -- clarify the structure of the Milky Way and obtain geometric distances to Galactic and extragalactic objects.

Phasing all the ALMA dishes together to allow ALMA to act as a single large VLBI aperture requires the array to operate in a specialized mode. This mode, however, will likely be commissioned soon as part of the APP (ALMA Phasing Project). Note that although the APP makes VLBI possible, it is not sufficient. In particular, the observatory would need to develop a VLBI network and an operations model that enables such observations. In particular, the ALMA paradigm of delivering "science ready" images to the user community would require developing a VLBI pipeline.

Associated developments also include new monitor and control software as well as low-level software for sub-system tasks necessary while doing VLBI, including post-processing software to calculate the antenna-based phases and delays to create a coherent sum of all antenna signals. An entirely new digital sub-system will accept the phased sum output from the ALMA correlator and process the data for recording on the new generation of hard-disk based VLBI recorders. These recorders will be located at the OSF and linked to the AOS by optical fibers via the planned AOS-OSF fiber bundle.

References:

"High Angular Resolution and High Sensitivity Science with a Beamformed ALMA" Fish et al.
"Phasing ALMA for (sub)mm-VLBI Observations" Doeleman et al.

20 Field of View

Lead author: Daisuke Iono

21 - Multi-beam Rx

One of the main weaknesses of ALMA is its small FOV (21" at 300 GHz). This is a limitation for surveys requiring large area mapping, such as galactic star formation regions, nearby galaxies, high-z surveys, Magellanic Cloud studies, and solar observations. For example, roughly 100 pointings are required to map the Hubble Ultra Deep Field at band 6. According to studies done by Y. Tamura (U. Tokyo), the expected number of mm/submm sources is ~600 after spending 500 hours on-source with the full array. This observing time will decrease by N_{pixel} for a fixed sensitivity, assuming the continuum bandwidth is maintained. Wide field of view will also be important in terms of synergetic studies with future instruments such as e.g. SKA, TMT, EELT. Hence the attraction to develop a multi-pixel array to obtain an instantaneous sky coverage increase by N_{pixel}.

A number of additional developments are necessary to realize the multi-beam receiver on the ALMA antennas. For example, wide-field high-z mapping for continuum or for line detection when the redshift is unknown need to use the full bandwidth of the correlator. A N pixel receiver also needs a N times bigger IF transport system and correlator behind to take full advantage of it for high-z mapping, since exchanging area for depth does not work: there are many more faint sources. For low-z molecular cloud mapping, by contrast, a strategy could be to do only a few lines at a time (or just one) and split the correlator among several pixels. Multi-beam heterodyne receivers have been developed in order to achieve fast mapping and high spectral resolution on single-dish telescopes. SuperCam, developed by the University of Arizona, has 8 by 8 pixels, is largest of such receivers so far [J. Kloostermana, SPIE, 2012].

ALMA has tight technical specifications based on scientific requirements and many engineering constraints (weight, size, thermal load, etc). A multi-beam receiver based on current heterodyne technologies faces a number of technical challenges. For example: design of optics, development and packaging of RF devices such as superconducting-based low-noise mixer or semiconductor-based low-noise amplifier, powerful and efficient local oscillator, thermal load reduction, and on-chip integration. These developments are band-dependent.

Some of the foreseen challenges are:

- Fitting the multi-beam optics though the cryostat window while keeping the polarization and aberration constraints.
- Fitting multiple sideband-separating SIS mixers on a 4 K stage within the thermal load allowances, or else developing low-noise RF amplifiers operating at the frequency of interest.
- Developing an LO source that can power the multiple mixers while preserving the phase noise requirements.

- Miniaturization and integration of the components to fit within the available real state.

Some of these challenges are discussed in detail in Appendix A. The discussion is based on studies done by T. Kojima (NAOJ), see
http://alma-intweb.mtk.nao.ac.jp/~diono/meetings/EA_Development_Meeting/Program_files/Kojima.pdf.
The offshoot is that considerable development work is necessary before multi-beam receivers are viable for ALMA. In addition to the technical challenges of building a multi-beam receiver, installation of this system in ALMA will require major upgrades in the sub-systems downstream, such as the IF/LO, ACD, Correlator, Data storage, and Software (online, and data reduction).

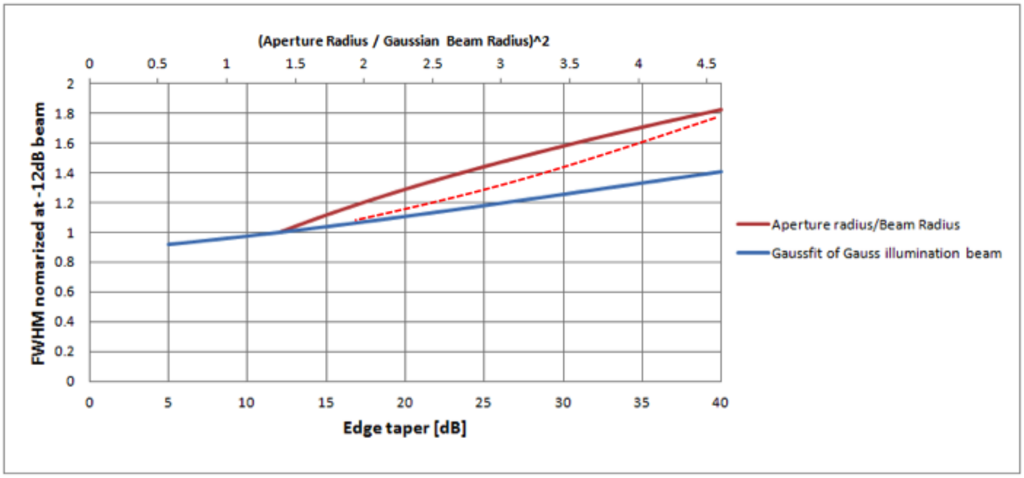
There are major operational implications to consider too. A major reconstruction will be required. A carefully designed plan is necessary in order to keep the array operation going but at the same time install the new system in parallel. It may be possible to keep 2/3 of the array operational while commissioning 1/3 of the antennas, spending ~ 1 year for implementation and testing (per 1/3 of the array) for a total of 3 years. The renovation of the correlator could occur simultaneously.

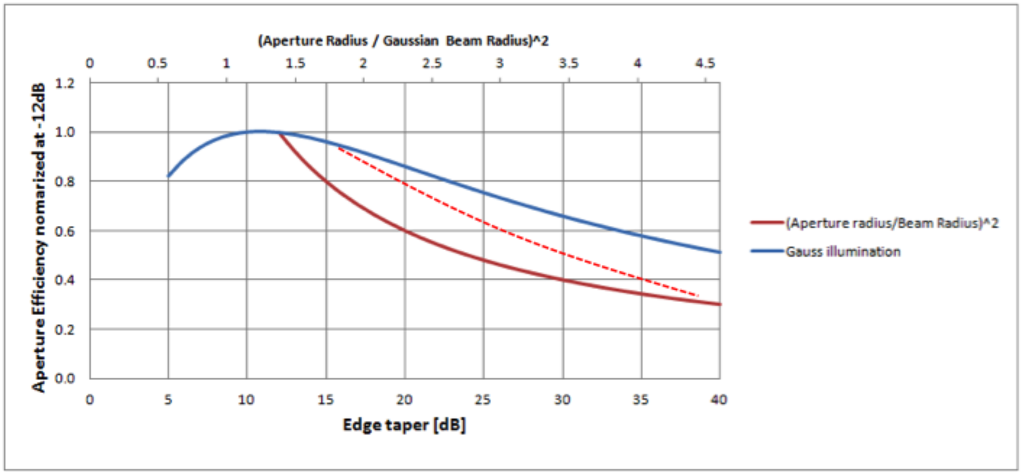
The precise estimation of the cost of a multi-pixel receiver is very hard, as it depends on the band, the technology, and the implementation (e.g., the number of pixels). A study that may shed some light on these topics is currently funded under NA and be complete in a year, but clearly further study is warranted. We can venture a very “order of magnitude” estimate by looking at the cost of a new ALMA band. The band 5 receivers cost approximately 30 MUSD, which is split approximately equally among development, components, and fabrication/integration. To first order, a multi-pixel system may require twice as much development, and the cost for components would be multiplied by the number of pixels. For example, a simplistic order-of magnitude estimate for a 9-pixel receiver in each antenna may be ~120 MUSD for receivers alone. Precise estimates require studies.

22 - Under-illuminated Feed

Another way to increase the FOV of the array is to introduce a lens in the system to under-illuminate the primary dish. The advantage of this method is in the low effort/cost required for its development. The disadvantage is the loss in sensitivity. Because of the loss in sensitivity, science cases will be limited to instances where the tradeoff between sensitivity and survey area is meaningful. Possible examples are large scale mapping of bright lines in Galactic molecular clouds, or observations of our Sun.

An under illuminated feed can produce a beam that is larger than a fully illuminated surface, at the cost of reducing collecting area (aperture efficiency) and sensitivity. Note that there is no gain in “short spacings” covered, since the antennas cannot be pushed closed together. The following plots and figures fome from a study by M. Sugimoto (JAO/NAOJ). Figure on the left shows the expected FWHM (normalized to the -12 dB beam) as a function of the edge taper [in dB], and the figure on the right is the corresponding sensitivity loss. Note that the real curve depends on the actual illumination pattern of the receivers, and it is likely close to the dotted line. For example, if we were to decide to increase the FOV to 1.8 times the current diameter, we have to change the illumination taper to 40 dB (in terms of Gaussian optics). In this case, the efficiency drops to 0.3 with respect to the current efficiency (which is ~0.7). Further discussion of the increased noise due to the insertion of a lens in the system can be found in Appendix B.





In terms of impact on the system, there would be some impact to the operation/CSV/control-software because the insertion of the lens will certainly change the focus. It may also affect the pointing, baseline, beam shape, and phase stability. Finally, we would also need to accommodate the loss of sensitivity in the sensitivity calculator and CASA.

The estimated cost for different design concepts is ~ 0.4-1.5 MUSD total. This includes components, labor, commissioning for pre-production studies, and production for 50 antennas

A variation on this idea is a combination of under-illumination and multi-pixel receivers. In principle it is possible to subdivide the collecting surface into patches illuminated by different pixels in the receiver. If cross-correlations were performed between the patches, this would also increase the short spacings coverage and the sensitivity to large angular scales. Unfortunately, this approach suffers from a number of drawbacks, including the large cost and complexity of multi-pixel receivers, the need for a very large correlator, and the unknown stability of the illumination patterns among others.

30 Spectral coverage

Lead author: Leonardo Testi

31 - Band 2

This is the last of the original ALMA Bands that is missing from the complement (considering that B1 and B5 are being developed/produced now). Completing this band will cover the full range of transparent windows at Chajnantor from 35 GHz through 1THz. The key science goals will be complex organic molecules and deuterated molecules in the Local Universe, high redshift low-excitation molecular gas and spectral surveys at high redshift. Design and prototyping of critical components and an overall design for this band, which could possibly end up covering the entire range from 67 through 116GHz with an instantaneous bandwidth of 16GHz per polarization, is actively being studied in North America and Europe. The cost for production would be roughly comparable to that of any other ALMA band (few tens of MUSD). The most critical item for such a broad band would be the performance of active devices, optics, waveguide and OMT. All these are actively studied and some of the risks on the passive components have been retired as part of a design/prototyping study carried over by a consortium of European institutes. More work is needed on developing the active and passive components for such a broadband system. In the meantime, NA has funded a 2014 development project with the goal of producing a traditional Band 2 receiver prototype, which will allow a determination of the costing and performance attainable for a Band 2-only receiver.

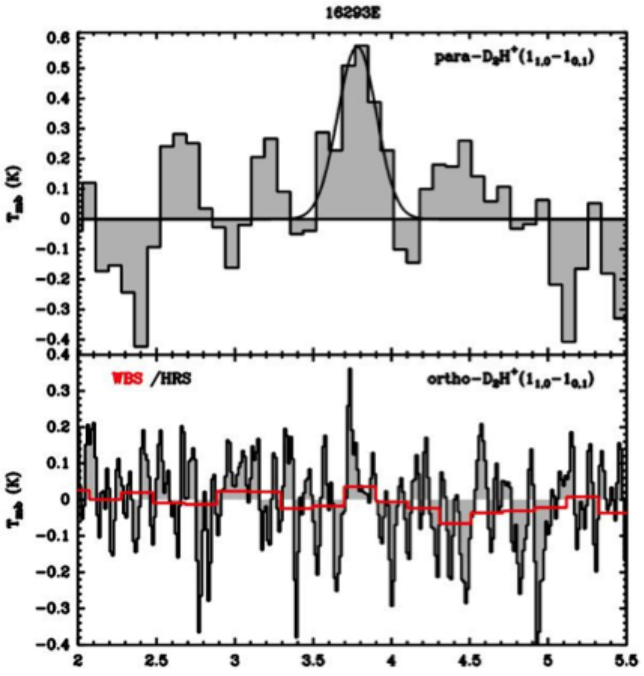
ALMA's two highest-level science goals are directly related to Band 2 science. The first is that ALMA should have 'the ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.' In the Milky Way at z~3, CO excitation and ALMA's frequency coverage identify the target line as the J=3-2 line at 86 GHz, in Band 2. In fact, ALMA covers this line through a late-construction expansion of the Band 3 frequency range. Since the enshrinement of this goal, the role of Dark Energy in the expansion of the Universe has become evident and the distance of a galaxy at z~3 has increased, making the 37 μJy line more difficult to detect (Baker et al. 2009). A receiver meeting the Band 2 specification of T_{rx}~30K will bring detection within reach. In 1 day of integration it would attain ΔS~15μJy, yielding 2σ per 100 km/s channel; in a galaxy with Δv=300 km/s it would achieve a 4σ detection in integrated intensity.

The second high level goal is that ALMA should possess 'The ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.' Disk midplanes are the sites of planet formation, the main reservoirs of mass and probable sources of complex organics which may be incorporated into those planets. Furthermore, disk midplanes are cold—ices form and as ices are sticky good larger body seeds are available. To characterize disk midplanes requires access to range of low-energy lines of ions, deuterated molecules, isotopologues and organics. These lines are found in ALMA Band 2, making it a band of primary interest for investigation. With the 2SB dual 8 GHz windows provided by the prototypes currently being developed in both North America and Europe, both the deuterated lines and their ^{13}C counterparts would be accessible for study in a single science goal, subject to correlator constraints.

32 - Band 11

The original ALMA project had foreseen 10 frequency bands covering the millimeter and submillimeter windows up to ~1THz. Just above the ALMA original limit there are three transparency windows in the region 1.1-1.6THz that have reasonable transparency (up to 40%-50%) under the best conditions at Chajnantor. The APEX telescope has a receiver operating at 1.3THz demonstrating the feasibility of observing at these wavelengths, albeit only for a very limited number of hours per year. The key science goals of a Supra-THz receiver for ALMA cover galactic and high redshift astrophysics, two examples from the Science Case document by Rigopoulou et al. (2014) are briefly summarized below.

An ALMA Band 11 could allow, in combination with ALMA Band 9, the study of para/ortho ratio of the doubly deuterated of H_3^+, the key ion in the interstellar medium chemistry. The figure below shows measurements of the two forms of D_2H^+ in the IRAS 163296 protostar with the CSO and Herschel (Vastel et al. 2012).

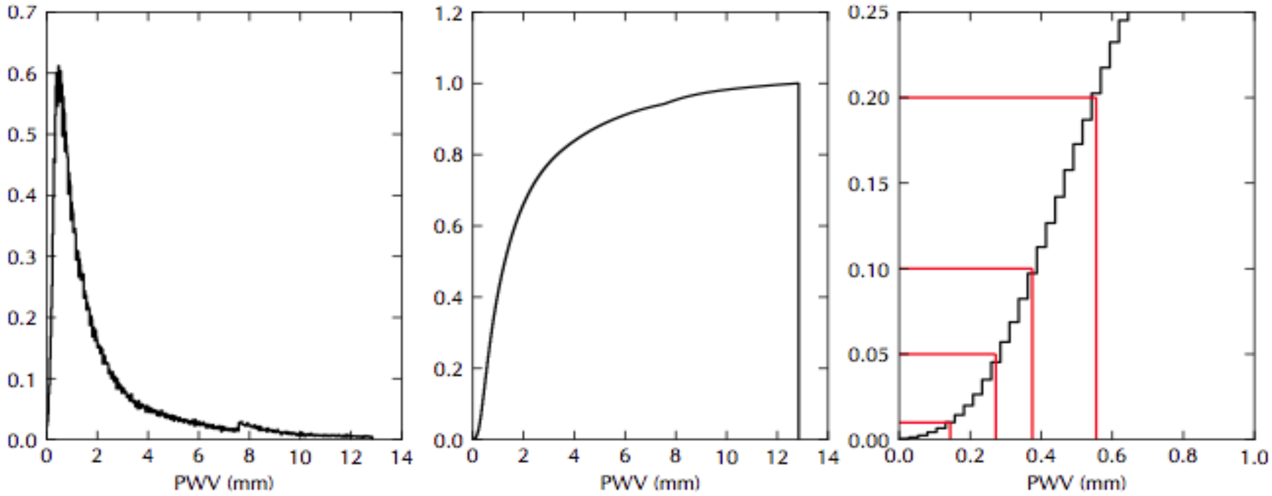


Band 11 will also allow us to investigate the [CII] line emission in intermediate redshift galaxies. This line, the major coolant of the cool ISM of local galaxies, has been proposed as a major probe of the star forming medium at high redshift. Band 11 will allow us to trace the [CII] emission in galaxies from redshifts 0.2 to 0.9, a critical phase in galaxy evolution when global activity winds down to present-day values. Band 11 will also allow us to cover the mid-infrared molecular hydrogen quadrupole lines (J=2-0 at 28.22 um, J=3-1 at 17.04 um) at very high redshift (z≥6), opening the possibility of probing directly the bulk of the warm molecular gas forming the first generations of stars.

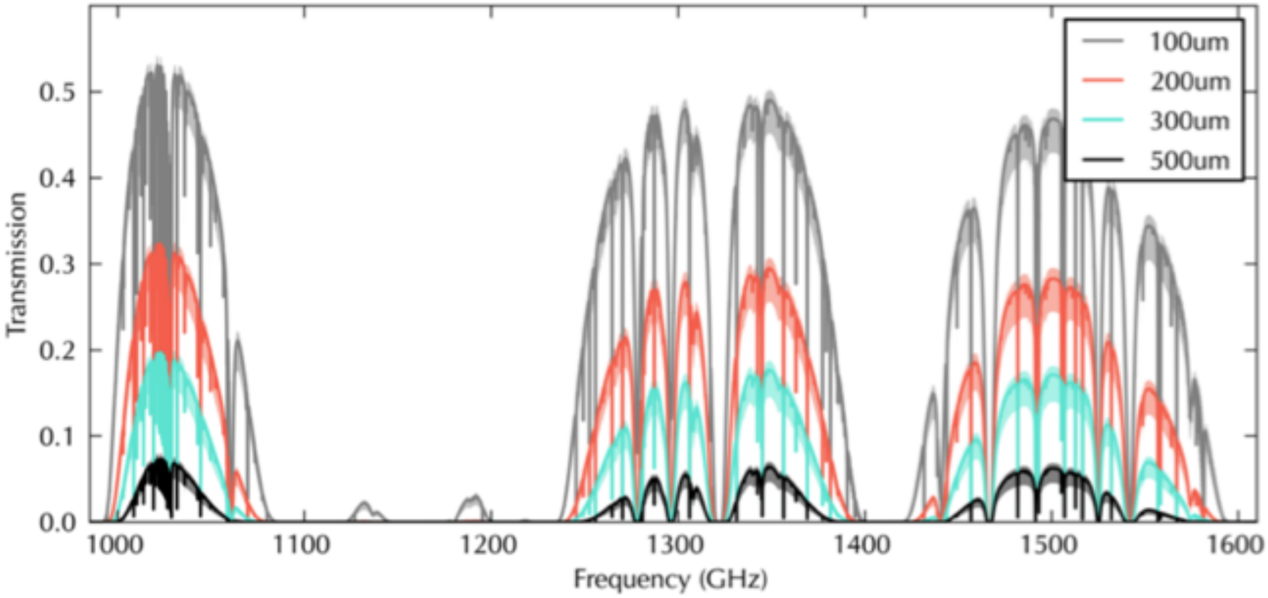
Initial studies are being carried over and the receiver cartridge appears to be technologically feasible. Such cartridge would require a space in the cryostat close to the optical axis of the system that is currently unavailable, but several options have been discussed. One possibility could be to see a development of a Band 11 receiver in the framework of a new focal plane system for ALMA. A second possibility is to replace one of the existing cartridges. For example, the combination of bands 2-3 into one cartridge powered by LNAs occupying the band 2 slot (see section 41) will leave the current band 3 slot available, which is connected to the 4 K stage and could be used for a high frequency cartridge (the currently open band 2 slot is not connected to the 4 K stage and cannot be used for an SIS system). This position, however, may be too far off-axis and introduce aberrations. A third option would be to develop a Band 11 receiver as part of a dual frequency cartridge. For example combining an upgraded Band 9 with Band 11 has been mentioned as an option. Although attractive in principle, such option would need to be studied in detail, due to the likely trade offs with other receiver performances (e.g., polarizations, bandwidth, power consumption). The cost of a Band 11 cartridge per-se would be probably at least similar to the full production run of either Band 9 or Band 10 (several tens MUSD).

Science cases for a Supra-THz band for ALMA and the required environmental and instrumental conditions for productive observing have been investigated in the framework of an ALMA Upgrade Study. The final reports are currently being written and will soon be available. These will also include some preliminary figures for the sensitivity that may be reached by a Supra-THz receiver for the ALMA array.

An analysis of the expected transparency conditions at Chajnantor was performed as part of the ESO funded European study on the opportunities for Supra-THz interferometry with ALMA. Analysis of precipitable water vapor at the site suggest that precipitable water vapor columns of less than 100um and 270um, should be achieved in 1% and 5% of the time respectively (averaged over the whole year). Experience with APEX operations at Chajnantor at 1.3 THz, show that these conditions are usually available during the June-August months. The histograms of water vapor content measured in the 1995-2004 period are shown in the figure below, no information exists about phase stability. The three panels show the normalized histogram, the total cumulative histogram and a zoom of the cumulative histogram on the best conditions. The availability of adequate observing conditions for a given array configuration will not only determine the time available for observations at this band, but also the pace of commissioning operations and the ability to appropriately calibrate the data.



The computed atmospheric transparencies in the Supra-THz region using various assumptions on the precipitable water vapour are shown in the figure below. High transparency in the 1-1.6THz windows is expected for pwv<200um (Graves et al. 2014).



33 – Extend Rx IF

The current 2SB receivers have an IF of 4 GHz in each sideband and polarization. This is a limitation of both the receiver design and the digital IF transport system. Extending the Rx IF would, when coupled to a new IF transport system, yield large improvements in accessible bandwidth. This instantaneously accessible bandwidth would permit, for example, simultaneous isotopologue observations (e.g., ^{12}CO and ^{13}CO are currently not simultaneously observable in B3, and only for very limited setups and narrow lines in B6) and a more intelligent placement of spectral windows. With an expansion of the correlator, these improvements would translate into factors of a few faster line surveys, line searches, and better continuum sensitivity.

The expansion of the available bandwidth can be done progressively. The first step is to plan for receivers with a broader IF. This is already the case for the Band 6, which provides 5GHz per polarization in each sideband. The Band 2(+3) prototype receiver prototypes being developed in Europe and North America will be capable of delivering 16GHz per polarization. Similarly, among the options that are being investigated for the Band 9 2SB upgrades, there is the possibility of broadening their instantaneous bandwidth while supressing the image sideband.

Wider IF bandwidth will immediately allow more flexibility in spectral line observing, without the need of upgrading the current backend and correlator systems. The full benefit of the wider IF will be obtained by upgrading the backend and correlator systems in order to fully use the available instantaneous bandwidth for continuum and spectral line use.

34 – Correlator

The current ALMA correlators are very versatile and capable of handling very complex low (continuum) and high spectral resolution modes. The full flexibility of the main array correlator with the tunable filter boards has not yet been fully exploited, and the ACA correlator is in principle capable of delivering even more complex modes. The main limitations in the medium-long term from the current correlator capabilities are in the ability to process all antennas together (although the current baseline correlator is in principle capable of correlating 64 out of the full set of 66 antennas), and the ability of processing completely more than 8 GHz per polarization, although linearity limitations have also been an issue in the testing of the single-dish capabilities.

Requirement SCI-90.00.00.00-00030-00 of the ALMA Scientific Specifications and Requirements document (ALMA-90.00.00.00-001-B SPE) requires resolution of a self-absorbed Gaussian line in gas at 10K, to measure infall motions in a prestellar core. The linewidth corresponding to this is 0.1 km/s. With a correlator mode (mode 31; ALMA Memo 556) providing a bandwidth of 31.25 MHz and 3840 effective channels, ALMA should achieve a resolution of 0.046 km/s at 3mm, using the as-yet unimplemented double Nyquist mode. In Band 7, one could achieve the goal but with the baseline correlator, ALMA falls short of meeting this target in Bands 1,2,3,4,5 and 6. Advances in digital electronics since the design of the baseline correlator may make higher resolution modes achievable through an upgrade in the correlator circuitry. It may also be possible to achieve faster dump time for the data--implementation of the correlator Frequency Division modes slowed dump times relative to those in the Time Division mode for some configurations. Investigation of this correlator upgrade should also be investigated through a dedicated study.

In the long term it would be interesting to investigate the possibility of upgrading the correlator to make use of the wider bandwidth receivers that are being developed. Possible options for upgrades of the correlator merit dedicated studies. Obviously the correlator is a major expense and it cannot be replaced on a short timescale. On the other hand, experience suggests that major correlator developments require a long timescale from conception to inception (~10 years), so it is never too early to start thinking about what the next generation may be like.

40 Simultaneous frequency coverage

Lead author: Alwyn Wootten

ALMA's cryostat will include ten receiver cartridges. Owing to its thermal budget, only three may be operated at one time. Changing to a new band that is not among those thermally 'ready' may involve tens of minutes, though switching to one of the 'ready' bands may involve only seconds. Simultaneous coverage is important to follow spectral energy distribution changes in, for instance, solar flares. For flares, one may configure ALMA into two (currently implemented) different subarrays, each observing at different frequencies. Other rapidly changing sources, from comets to AGN, may also benefit from simultaneous or near simultaneous observation.

There are several ways to extend simultaneous frequency coverage—one may extend the boundaries of an existing band or one may combine bands into a single cartridge in such a way as to effect simultaneous observations. Splitting the array into pieces to achieve simultaneous coverage means that each subarray will have fewer antennas, and hence poorer sensitivity and imaging quality for a given integration time. Furthermore, since the spatial frequency sensitivity is different for each array, the measurement of spectral index through comparison of images made with different subarrays is subject to uncertainty.

41 – Dual-band Receivers

Achieving a broader spectral reach through extending the boundaries of a specific band does not really achieve simultaneous frequency coverage. It may, however, allow the incorporation of different cartridges covering different frequencies into the dewar.

For instance, by combining ALMA Bands 2 and 3 and using a MMIC or other receiver, one could, possibly, cover the band 67-116 GHz in the Band 2 15K cartridge slot. This would free the 4K slot currently housing the B3 receiver for another band. One might, for instance, devote that position to a receiver covering some portion of the spectrum above the current upper receiver complement cutoff of ALMA at 950 GHz (Band 11). A disadvantage of this approach could be that the very broad coverage of the B2/3 receiver would pose challenges for polarization separation using ortho-mode transducers, this risk has however been retired by the ESO study which demonstrated two separate designs and prototype OMT and horns with excellent performances over the full B2/3 bandwidth. Current devices are also unable to achieve the superb performance required by ALMA in the limited Band 2 range, achieving the performance on the full B2/3 range will be even more difficult. This is important as some key science lies at the opposite ends of the B23 coverage—CO at the high end and deuterated molecules at the low end. Research would be needed in mixer technology and in polarization separation to design this broadband receiver. These possible limitations and tradeoffs are currently being studied as part of the activities in North America and Europe. Furthermore, performance for a high frequency cartridge using the current Band 3 slot might be compromised by its off-axis position—some coma may be present. Again, research would be needed into the technology of the high frequency cartridge as well as into the imaging characteristics of the off-axis receiver. While one would achieve broader frequency coverage, no single band in this proposal would likely be as sensitive as would be achieved in the lesser coverage achieved with receivers deployed as they are currently.

42 – Multi-frequency Feeds

An alternative method by which one could achieve simultaneous frequency coverage would be to employ two or more receivers within one package. One might, for instance, develop nested horns that could address harmonically related frequencies simultaneously—such as Bands 9 and 11 or Bands 7 and 9 for instance. NA received a proposal to study this but it did not get selected owing to referee skepticism.

Scientific advantages include the coverage of multiple frequencies, though the beam sizes would differ. Quite often molecular transitions are also harmonically related—one might observe several transitions of a given molecule, at quite different energies, with a single integration.

There would be some penalty in flexibility. The agility of placing windows in frequency might be compromised without careful consideration to design. Weather conditions suitable for one band might be marginal for another, restricting observation to the best weather in the most atmospherically compromised band.

43 – Dual-feed Use

One might double the sky coverage at a given frequency by deploying one of more feeds in the same cartridge. While this may provide little advantage for point sources, wide field imaging experiments would gain by approximately the number of feeds deployed. This development could provide throughput advantages for imaging of extended objects in our galaxy or in nearby galaxies. One possibility would be to allow independent tuning of the two feeds so that the target field could be imaged in two sets of frequency windows at once. Alternatively, one could achieve rapid spectral scanning by tuning the two feeds to cover contiguous bands. While there was a multibeam study proposal submitted to NA it was not approved over higher ranked studies. The cost of this development would intermediate between that of adding a new cartridge and the single cartridge itself.

50 Imaging Quality and Calibration

Lead author: Daisuke Iono

51 – Deconvolution and Combination Software

Radio synthesis imaging was revolutionized by the invention of the CLEAN algorithm, enabling synthesis imaging of complex objects even with relatively poor Fourier plane coverage. There are many different deconvolution algorithms in use but one aspect that is common to many of the best algorithms is the use of the multiscale approach. Examples of multiscale methods are as follows.

- Multiresolution CLEAN: The dirty image and point-spread-function are smoothed and decimated to emphasize the broad emission. The image resulting from CLEANing this dirty image is then used as an initial model for a CLEAN deconvolution of the full resolution image. An experimental version of this algorithm is already implemented in CASA.
- Multiscale Maximum Entropy: The performance of Maximum Entropy deconvolution could be improved by decomposing the image to be estimated into several channels of different resolutions. A hierarchy of scale sizes is specified and an image reconstructed by estimating pixels in the combined space such that the convolution equation is satisfied.
- Wavelets: Numerous authors have described the virtues of wavelet analysis and its application to deconvolution. Various authors have described an extension of the Maximum Entropy Method to wavelets as basis functions.
- Pixons: The Pixon method has been extended considerably, and the original algorithm drastically improved. Performance is extremely good, especially as measured by the statistical whiteness of the residuals. However, there has been no published success in applying the algorithm to synthesis observations because a key assumption, that the PSF is compact, does not hold for Fourier synthesis.
- Adaptive Scale Pixels: This has good deconvolution performance but is computationally expensive.
- Compressive Sampling: Compressive Sampling theory shows that under quite general conditions, a sparse signal can be reconstructed from a relatively small number of random projections (See Wiaux et al. 2009).

Possible developments would investigate implementation of these and other methods, with priorities assigned according to science demand. Research is required for understanding the basic theory, the application, and the algorithm.

Combining the data from the ACA and the 12m array: The feathering technique, which is already implemented in CASA, is being adopted for cycle 1 and 2. The feathering technique adds the single dish and (the CLEANed) interferometer data in the uv domain and Fourier transforms back to the image plane for the final image construction. Other techniques that are commonly used are (1) linear addition of two images in the image domain, (2) non-linear algorithms (e.g. Maximum entropy method). The former is available in CASA as a Toolkit, the later is currently in an experimental phase and requires more testing with real ALMA/ACA data.

Reference: Cornwell, 2008, IEEE, 2, 5, p793
Stanimirovic, 2002, ASPC, 278, 375

52 – Better Phase Calibration

Accurate phase correction is a key part of interferometric calibration and imaging, as imperfect phase calibration will lead to poor image quality and affect the science interpretation. Better phase correction will result in higher fidelity imaging, and this affects all science. Observations at the high frequency bands often suffer from lack of nearby bright, unresolved calibrators. The idea at ALMA is to transfer the phase measured at band 3 to higher frequency bands measured (almost) simultaneously. Current limitations are, for example, (1) it takes ~1.5 seconds to switch between bands, which can be a significant overhead, (2) lack of the general understanding of the phase screen and atmosphere. Another limiting factor could be the accuracy of the antenna positions. The accuracy of the baseline determination is currently xx microns, and the ALMA spec for baseline accuracy is 65 microns. Improving the calibrator database in terms of sky coverage and flux monitoring is also a long-term goal of the project, especially at the high frequencies.

53 – Better Sidelobe Calibration

Even if phase calibration were perfect and atmospheric effects were completely removed, image fidelity (defined as the difference between the “true” intensity distribution and the result of the imaging process) would quickly hit the limitation imposed by the imperfect knowledge of the telescope primary beam. This is a particularly key limitation for sources that are extended with respect to the primary beam and thus require mosaicing. Given the size of the ALMA field-of-view at high frequencies, this is a potentially important limitation for a wide range of observations.

There exist computational approaches that allow the inclusion of information about fully sampled voltage patterns for each antenna into the imaging process, but they are not yet fully implemented and tested in CASA. These approaches are anyway computationally intensive, besides requiring good measurements of the voltage pattern for each antenna far away from the primary beam. A way to improve this situation is, for example, to more accurately measure the voltage pattern for each antenna. Another path is to pursue new algorithmic development to better and/or more quickly include the voltage pattern information into the inversion and imaging process, for example developing adequate approximations to simplify the calculations, or perhaps to develop specialized hardware to speed up the calculations. The relative costs and benefits of a better treatment of the antenna pattern need to be evaluated in detail.

54 – Better Amplitude Calibration

Accurate amplitude calibration at millimeter and submillimeter wavelengths is a difficult goal to achieve due to the temporal variability of the emissive and absorptive properties of the Earth’s atmosphere and the lack of accurate astronomical flux standards at these wavelengths. ALMA Scientific Specifications and Requirements state 5% absolute and 1% (3% above 370GHz) relative flux uncertainties. Accurate amplitude calibration is essential in all science topics of ALMA, but it is particularly important in the areas of flux monitoring, and measuring of SEDs and SLEDs. The purpose of this development is to improve the accuracy of the amplitude calibration.

Bright sources with known model flux (e.g., planets and asteroids) are used for primary flux calibration. Quasars can be used as secondary calibrators. While this is defined as an observatory task, all cycle 0 projects had a primary flux calibration observation within each scheduling block. According to the CSV tests the repeatability of the current flux calibration measurement is of order few percent.

The current single dish (ACA TP) calibration scheme uses the 2-temperature load calibration device (ALMA Calibration Device). This yields the system temperature, and allows us to convert the correlator units to Ta*. (See "ALMA Cycle 2 Technical Handbook v1.1" page 152 for equations). It then uses the "amplitude calibration observation" to derive the main beam efficiency and the size of the primary beam, which are both necessary to derive the Kelvin to Jansky conversion factor.

The system is reasonably good although it involves a large number of assumptions. (1) Planets/asteroids/moons are resolved on long baselines (or even in short baselines at high frequencies), and the accuracy of the planetary models limit the overall flux accuracy. (2) Quasars are time-variable and good models do not exist for high frequency. (3) Line emission and absorption (e.g., Neptune, Titan) needs a well-understood atmospheric model. (4) The accuracy of the flux calibration is also be limited by the primary beam shape and pointing accuracy.

Several developments for improving the amplitude calibration could be considered:

1. Better primary calibrator (planetary) models
   This is a research topic, and does not involve new instrumental development. Software development for implementing the new models may be needed.
2. More frequent flux monitoring of the secondary calibrators (probably not the best solution: lower priority). This also does not involve new hardware development, but requires more CSV (or "observatory calibration" time). Constructing an easy-to-use database may require a small-scale software development.
3. Atmospheric monitoring and modeling in order to correct for the atmospheric variation between the primary (secondary) calibrator and the target source. Better modeling may also require the addition of more weather stations, and an improve connection between the models and the parameters monitored.
4. Noise source calibration strategies and the associated hardware.

55 – Better Passband Calibration

For observations that require high spectral resolution, one runs into the problem of low signal-to-noise in the traditional use of an astronomical source for bandpass calibration. For wide-band observations, the knowledge of the calibrator spectral indices can be a limiting factor. Thus an immediate improvement may be possible by compiling a better calibrator database that contains a list of compact sources with known spectral indices. Characterization of the long-term variation and stability of the bandpass will also be beneficial. In addition, the bandpass calibration requires longer integration time for the ACA 7m array, which has smaller collecting area (currently, the 7m array uses ~ 10min for bandpass calibration, as a rule of thumb). One way to overcome this problem is to inject (early in the data stream) a common noise source that is well characterized to all correlations, which will possibly mitigate this problem. A similar method has been implemented and tested at the CARMA array. For the 7m array, another possibility is to implement the combined array mode, which cross correlates the 7m and the 12m arrays.

ALMA Memo 505 “Bandpass Calibration for ALMA” A. Bacmann (ESO) and S. Guilloteau (IRAM/ESO)
CARMA Memo Series 55 “Bandpass Calibration and Stability” Melvyn Wright

56 – Better Polarization Calibration and Purity

The role of magnetic field in various astrophysical phenomena is often not clearly understood. This is in part due to the limited sensitivities and polarization capabilities of the current instruments. ALMA will probe deeper into the strength and the alignment of the magnetic fields, and although the capabilities are limited, polarization observations are offered in the cycle 2 call for proposals.

Polarization information from dust particles, Zeeman splitting, Goldreich-Kylafis effect, Masers, YSOs, etc, can provide extremely valuable insights into the strength and the orientation of the magnetic field entangled with the interstellar medium. This kind of measurement allows us to investigate, for example, the role of magnetic fields in star forming GMCs (the rapid or slow star formation scenario), starburst winds, nucleus of dusty active galaxies, and the Galactic Center.

Polarization calibration is currently done using an astronomical source, and already achieving ~0.1% accuracy on-axis which is satisfying the ALMA spec. Characterization of the polarization calibration accuracy at the 3dB edge of the primary beam is ongoing. One way to improve the calibration accuracy is to use an artificial noise source with well-characterized polarization properties. However, the polarization accuracy of the current noise source is unknown and improvements to its characteristics (including stability) may be necessary. Another way forward is to improve the performance of the wire grids (bands 7, 9, 10) and OMT (for other bands), or install an external wire grid common to all frequency bands.

Possibilities for further developments are

1. Properly evaluate the characteristics of the AOS artificial noise source. Initial studies are needed, and evaluate if better components are deemed to improve the characteristics. CASA development may be needed.
2. Component developments of better wire grids (B7,9,10) and OMT (other bands) will be needed. In such cases the initial research and development will be done at the lab. It is important to understand how the precision of the laboratory measurements translates into the polarization calibration.
3. Applying the off-axis D-term to the map (CASA development)

60 Flexibility

Lead author: Leonardo Testi

61 – Subarrays

The subarray capability is a means of obtaining simultaneous observations of different targets or at different frequencies. The number of subarrays available for ALMA is limited. Increasing the number of subarrays would open a number of interesting options for simultaneous observations. The sensitivity and image fidelity drops much faster than the gain in time by simultaneous observations. There are however interesting use cases of subarraying. A few potentially interesting cases could be to observe the Sun (e.g., providing simultaneous imaging of more than one FOV) or maser sources (if detailed, high-fidelity imaging is not required) with a very limited set of antennas and use most of the array for another program. Another use case would be simultaneous multi-frequency observations of highly variable sources (but these would need to be sufficiently bright). Finally an interesting application could be the use of a subset of the array elements as a phased array for pulsar observing or to participate in a VLBI session while the rest of the system continues standard observing. There could also be interesting technical and/or calibration use cases for additional subarrays. The cost of adding subarrays is relatively modest (assuming that no impact is expected on software and operations).

There is currently an NA approved project aimed to reinstate the full subarraying capabilities that were reduced as part of the rebaselining. The outlook at the moment is to be able to use 2 subarrays for ACA operations (total power and interferometry) and up to four subarrays with the main array.

62 – Increase in Data Rates

As it has been investigated in a number of ALMA memos, the current data rate is a limiting factor for the scientific throughput of the array. Data rates limit the spectral resolution of the observations, for example, and directly impact the use of archival observations for spectral line research (since the fall-back position is to limit the data rate by reducing the spectral resolution of spectral windows that do not contain the proposed main lines). These limitations will become more severe with long baselines operations and in some fast dump rate observing modes (like on-the-fly single dish and interferometry mosaicing) or high spectra resolution modes. This may become an even more critical limitation in the future if the system is upgraded to process wider bandwidths. It will be extremely important to perform a detailed study on the possibility of increasing the average and maximum data rates from the observatory and its implications for the software and archive systems.

70 Usability

Lead author: Alwyn Wootten

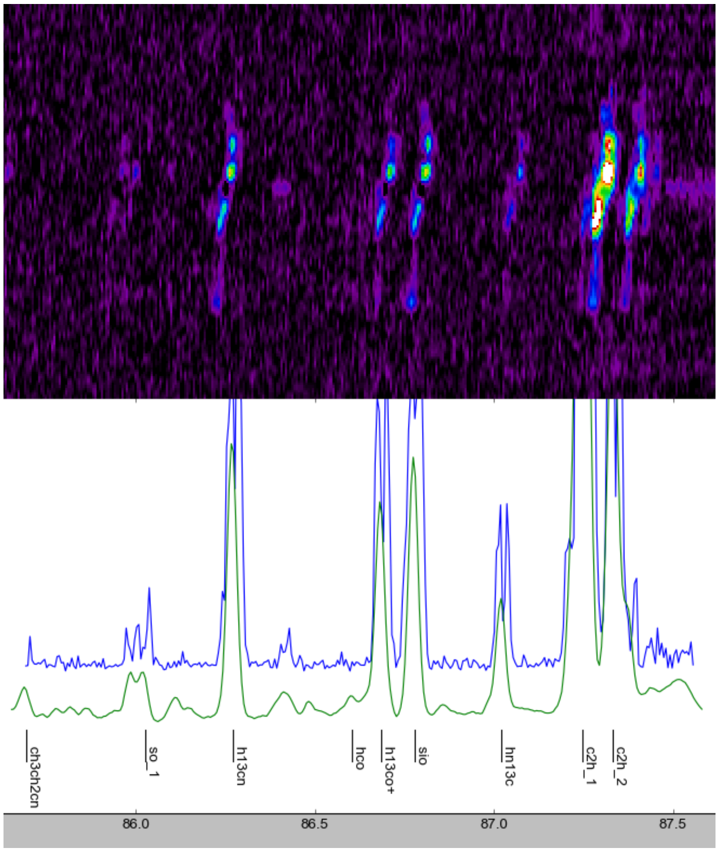
ALMA need provide the tools to find data of interest in an enriched, and forever expanding, data and software archive. These tools can either be operated remotely, if the size of the dataset is too overwhelming (but perhaps at the cost of limited interactivity or less flexible computing), or locally on a users “desktop”. For more control, the user may use CASA packages and toolkits for analysis and modeling (pipelines), to explore the robustness of science results. Ideally these toolkits can be expanded on by the astronomer to create new analysis tools for the a wider audience.

71 – Better Pipeline Calibration and Imaging Heuristics

The Calibration and Imaging Pipeline is under active development, with calibration heuristics approaching levels suitable for initial deployment. Imaging heuristics will be improved substantially during development. It is envisioned that as pipeline heuristics improve, reprocessing of archived data is essential and will be supported. The content of the archive will therefore improve as heuristics improve. While eventually, for instance, all of the spectral lines in an ALMA data cube will be imaged and archived, in the pre-pipeline era only the lines specifically requested in a proposal Science Goals will be imaged, archived and delivered to the investigator. It is anticipated that pipeline improvements to perfect imaging and calibration and to add new observing modes will be ongoing throughout the lifetime of the observatory. Experience with observatories such as *Spitzer* and *Herschel* shows that external effort and expertise can be very synergistic to the internal pipeline development. The role of Analysis Pipelines should not be underestimated. Ideally there would be a method to feed their results back into the archive, for example, detection of unidentifed lines.

72 – Automatic Analysis and Enriching the Archive

Each dataset may be characterized by its spectral content. Chief among these are the names of the spectral lines targeted by the PI. But ALMA’s sensitivity and spectral grasp normally allow the inclusion of many other lines in the dataset, awaiting serendipitous discovery: a typical dataset for a bright source will contains tens to hundreds of lines that have not been specifically targeted in an observation but just happen to be detected. An automated program may hunt through the archival cubes, discovering other lines, and identifying them from a comparison to a catalogue such as that provided by Splatalogue. For the sub-cube containing the spectral line, image statistics could be calculated and attached to the line name. Small images of derived quantities such as spectral line peak profile parameters, moment images and other characterizing products could all be stored in the archive to provide fast access to information on the content of the data product cube. More complex (and interesting) descriptions of the dataset can be envisioned; for example a PCA-like data product pointing out which lines have similar distributions, an automatic source extractor and catalog, kinematic data products, etc. Thus the richness of the archival datasets can be made available easily. The key elements of this automated program are that it provides easy, organized, immediate access to the science data in the cubes, as well as tools for discovering and mining science from the data and efficient access to the science in archival data for data reuse.



Automatic line identification in an extragalactic datacube. The data are ALMA observations of NGC 253. The p-v diagram spectrum is shown in blue. The results of a cross-correlation algorithm based on the p-v diagram correspond to the green trace. High cross-correlation corresponds to identifiable spectral features, correspondingly labeled (from ADMIT toolbox).

To accomplish this, one might envision a post-reduction pipeline or toolkit that would create a detailed data overview including spectral search, line identification, moment maps, spectra, overlap integrals, and other images and browsable tables. These data overviews would be served from the ALMA archive. To explore these overview products software would be provided from the science portal or other repository. We envision this to be a python-based toolkit distributed with CASA for the user to examine, re-compute, and expand on the detailed data overview, or perhaps a client-server system. This would be the same toolkit that produced the archive data, but users can now improve on their results from their own workstation if data size allows this. Similar data products might be spread through the archive, related to different observing proposals. The post reduction pipeline toolkit should provide the structured environment needed to bring together archival datasets from multiple projects, analyzing and comparing them in uniform ways. In case of python, the astronomical community has already organized itself (e.g. astropy), and with a CASA interface in python an environment can be created to cover the whole range from basic analysis to sophisticated data mining. This Analysis Toolkit should also engender new analysis ideas by astronomers, which could later be adopted by the ALMA pipeline version. Thus not only data, but also software would be donated back to the archive. It is accurate to say that the richness of ALMA datasets opens a new dimension in the realm of archival value that radio astronomy needs to exploit to realize the full potential of the instrument. Projects and studies along these lines have been funded in NA (e.g., ADMIT) and EU.

73 – Visualization

The volume of data produced by modern astronomical instruments can be enormous. The process described above can begin to parse the dataset into individual components, each destined for analysis. Proper analysis of these data products begins with visualization of their content. The visualization stage is an important element to bridging the gap between the raw images and the scientific result. That visualization may be limited by available hardware, or by fundamentals of the software architecture. Given potential image data sizes of 50 GB to 1 TB (ALMA Memo 501), the current visualization solutions (e.g., the CASA Viewer, kvis, ds9, etc.) will be performance-limited by the hardware used to explore the data and many are fundamentally design-limited in their software architecture. One appealing way to visualize the data would involve dedicated servers running software optimized for the purpose. To address the need for exploring large data sets, an attractive approach is one where the visualization of the data is mediated through the ALMA science portal, and the computation required for visualizing the data takes place on dedicated servers using optimized software. Scientists may examine data anytime, any place, on any platform, in concert with one another simultaneously discovering hidden aspects of the data. Adaptive mesh imaging (e.g. voronoid tesselations) to deal with large data or VR (Oculus, Google Glass) environments could also address needs not met otherwise.

This suggests the development of a modular, plug-in architecture for a new viewer application, fusing the full feature set of the CASA viewer with a high performance independent viewer, capable of upgrade with fewer overheads. Using a web-based server located, for instance, at the archive site would enable fast visualization without the need to move large datasets over the net. NA has funded development along these lines. The software we contemplate would foster development of community plug-ins, increasing the depth of the available viewing options. Some form of interoperability with the aforementioned toolkit would seem an important feature to provide interactive components to this toolkit to empower the user during the re-analysis stages.

74 – Cube Analysis Tools

Astronomical imaging provides two-dimensional views of emission projected on the celestial sphere. ALMA’s independently tunable spectral windows can provide a suite of image cubes each of which contains velocity information as its third dimension. Comparison of adjacent pixels and velocity channels allows software to identify structures within the data that may not be apparent when viewed in two-dimensional subsets of the data. Emission regions could be characterized by their chemistry --- identification of certain sets of lines that follow similar traces of position and velocity for instance. A viewer/analyzer could also predict, via excitation and radiative transfer software, the complete spectra of a suite of molecules for comparison to the data in order to characterize the physical conditions in the parcel of gas imaged. This argues for integration between the visualization and analysis tools, where each can utilize functions in the other. These tools need be flexible enough for an astronomer to write additional modules that will benefit others.

80 Reliability and Efficiency

Lead author: Stuartt Corder

81 – Remote Power Recovery

Even in circumstances when power generation is extremely reliable, occasional partial or complete power interruptions are likely to affect the array. Even a relatively short power interruption can result in weeks of lost time if cryostats warm up, particularly in the extended configurations which typically occur during the Winter months coupled with possible snow conditions. Temperature cycling of cryostats can also produce failures related to thermal stress and reduce the reliability of the system, and therefore it is best avoided. The payoff in terms of reduced system downtime and increased reliability can be very significant.

Remote start capabilities can provide the ability to recover power to the array elements in the event of a short power interruption (less than 2 hours). Most critically, the cryostats of the healthy array elements will keep vacuum and be capable of cool down in less than 24 hours (warming up causes gas particles that were trapped on cold surfaces by cryo-pumping to be released, degrading the vacuum of the dewar). Power outages of over two hours, due to the dependence on UPS systems, are likely to cause extended recovery efforts, although refinements could allow for intelligent detection and potential response to power events thus allowing a slightly extended lifetime for rapid remote recovery. These refinements, and potential reduction in the time to recover the compressor post power outage, may result in less lost time due to power events.

The basic remote start capability is currently being implemented. The potential impact of further upgrades is unclear and will depend on the combined performance of the initial implementation of the remote power recovery and work to enhance the stability and robustness of the entire power network. It is expected that in 2015 it will become clear how frequent failures are and how often these potential extensions would impact operations.

82 – Upgrade of Power Delivery System

ALMA generates power through turbines operating at 3,000 m of altitude. The power is sent to the 5,000 m plateau through high-voltage underground cables and distributed to the antennas and correlator through a network of underground cables, switches, and step-down transformers. Reliable power is crucial for the long-term health and stability of the observatory. Significant power failures mean destabilization of the receiver cryogenics and the controlled environment of the correlator, with the consequent increase in component failures. Furthermore, transients during power failure, or caused by bringing back the power, may damage electronic components. The operation of restarting the observatory after a major power failure is long and complex, and requires a very significant investment of time (a week or longer).

Several upgrades are being explored regarding the power system. The speed at which the power can be returned following an outage could be improved by including automatic starting of the start-up generator, which is required to restart the turbine power system. External monitoring of the turbines is also a potential way to improve reliability, perhaps providing a means to address problems before they become outright power failures. The need for such improvements will depend sensitively on the performance and understanding of the power system. Significant experience is being gained with the operation of the system and these gains have resulted in some solved problems, suggesting that the steady state performance is yet to be reached. Once steady state is reached a cost assessment would be required to handle residual problems and determine if there is a clear need for upgrades.

83 –Cryogenic Cooling Improvements

The cryogenic coolers of the ALMA front ends can in principle be upgraded with more modern equipment that could allow for operational cost savings (for example lower power consumption), increased reliability, and/or higher cooling power. There is an ongoing European study that is investigating the possible operational gains that could be achieved by upgrading the front-end cryostats.

84 –Remote Inspection for Weather Recovery

One of the greatest challenges to array recovery after weather events is the requirement to physically inspect each antenna. After the antennas have been shut down or stowed in the event of a weather emergency they need to be inspected for condensation, snow blockage, etc, before moving them away from the survival position. Detailed inspection is mandated in the warranty conditions and, as experience develops, some of it may not be ultimately necessary. Nonetheless there is a level of inspection that is reasonable and unavoidable. Because the antennas will eventually be spread over the entire plateau and transportation between them following weather events will be likely slow if at all possible, there is a clear need for a remote inspection system. This will become necessary once extended configurations (~separations of a few km or more) are scheduled during periods of probable weather events (June-August). Such scenario is planned starting in 2016, and remote inspection capabilities are thought to be critical for the long-term health of the observatory.

Remote inspection requires the use of a distributed camera network, possibly mounted at several critical locations in, on, and around the antennas. At a bare minimum remote inspection will require, high definition, steerable cameras mounted on the weather station masts (seven in total), and additional cameras on varying locations along the arms and around the central cluster to allow visibility to each antenna from two sides. These cameras would need to be weather proof with quality zoom performance. If critical areas of the antennas and power infrastructure cannot be reliably secured from moisture and/or effectively imaged from remote stations, antenna mounted cameras may be needed. Additionally one or more cameras would be placed in every antenna, but these cameras could be of lower quality. It is advantageous to also install microphones in key portions of the antenna, for example close to the drives and the cold heads. They are inexpensive and low bandwidth, yet they can be used to quickly pinpoint problems such as a degrading drive. Automatic software can also be used to detect human voices or vehicles near far out antennas that may need additional security.

Detailed costing and benefit of this approach will depend on data currently being collected regarding the performance of the antennas in adverse weather conditions and the speed at which visual inspections can currently be done. Efforts to improve the latter are being made and tested, which will enable a definitive cost-benefit analysis for this improvement. Regardless of the outcome, antennas will continue to require visual inspection following adverse weather until the end of the antenna warranty period.

Appendix A: Multi-beam Receivers

1. Optics

There are several challenges for multi-beam optics in order to satisfy the current ALMA specifications:

1-1. Cross-polarization < -23 dBc
1-2. Defocus and distortion of off-axis beams
1-3. Small diameter of the cryostat window

In order to provide polarization separation capabilities, one of the two components must be used: wire grid or an OMT. Since a multipixel array horn aperture plane could potentially be quite large, the required wire grids are also expected to be too large, which makes the fabrication difficult and increases the cost. Using an OMT is a better solution, but the XsP performance of the receiver will be problematic. For example, the XsP in the current ALMA band 10 design is low because of the fact that the wire grid is blocking the cross-polarization of the feed horns. If an OMT is used, such as in band 4, there will be two new terms in the total XsP equation: XsP OMT and XsP horn.

$$XsP = XsP_{horn} + XsP_{OMT} + XsP_{mirrors} + XsP_{IRfilters/window}$$

This will increase the total system XsP, which will require the use of very good feed horns (a new design may be necessary). Moreover, there are currently no OMTs that are demonstrated at frequencies approaching 1 THz or beyond.

Another problem for a multi-pixel design is the small size of the cryostat window and the IR filter opening. The aperture is designed to avoid the truncation of a single beam. Avoiding the truncation of the off-axis beams will therefore be challenging. A possible solution might be the use of individual mirrors for each beam to slightly change the beam direction. This could allow all the beams to pass close to the center of the window. Proper illumination of the secondary would then be challenging.

2. Superconductor-based mixer or semiconductor-based RF amplifier

In radio astronomy, SIS mixers have been used because of the quantum-limited low noise performance. The problem of the current heterodyne receiver using the SIS mixer is that the size of the front-end system is too large to put multiple receivers on the 4-K stage of the ALMA cartridge. The ALMA receiver needs a sideband-separating mixer which consists of a number of cryogenic IF components such as a 90-degree hybrid, an isolator, and a low noise amplifier with wideband and low power consumption.

On the other hand, technologies of semiconductor-based RF amplifier, recently, are rapidly growing. RF amplifiers make the receiver system on the 4-K stage very simple because we can install the IF components at the other stages. Moreover, the semiconductor-based amplifier allows the operating temperature to be around 20 K. This reduces the thermal load to the refrigerator. By improving the fabrication process, Heterojunction bipolar transistor (HBT) and High electron mobility transistor (HEMT) in several currently available models exceed f_t(cut-off frequency) and f_{max}(maximum frequency) of 500 GHz. Using InP HEMT, comparable performance of low noise amplifier up to G-band (140-220 GHz) with SIS mixers was reported [Lorene A. Samoska, ISSTT, 2011]. For excellent and stable performance, finding the right manufacturer or a collaborator is needed.

3. Local oscillator power

For the multi-beam SIS receiver, the LO power required to drive each beam is proportional to the number of beams. If using a solid-state LO source for all beams, the power has to be efficiently divided and distributed to each device, because it is difficult to amplify signal that is higher than 200 GHz. Table 1 summarizes the required LO power per beam and the maximum number of pixels driven by the currently-used LO power P_{LO} in ALMA. The estimation reveals the number of operable receiver by the LO power is only 1 beam for frequencies higher than 500 GHz. Improvement of multiplier output power and increase of upper frequency limit of a power amplifier are needed. On the other hand, photomixing, quantum cascade laser (QCL) and Josephson oscillator technologies might be promising candidates as LO sources for the multi-beam receiver.

The photomixer can generate terahertz wave that corresponds to the difference of the frequency of two (short wavelength) lasers. The power of the lasers can be amplified using an Erbium-doped fiber amplifier (EDFA), which provides signal to each photomixer with enough power and low loss. Astronomical observation has been demonstrated at 1.05 THz for a single pixel receiver [I. C. Mayorga, et al., IEEE, 2012]. While this approach is promising, we will need to develop a more stable system for the interferometry in the future.

Radio emission by the QCL is based on the inter-subband transitions in the conduction band of the semiconductor hetero-structures. The important features are; powerful output power (over 100 mW), stable frequency, narrow linewidth, and in CW mode, which meet the conditions as an LO oscillator source for heterodyne receivers. One technical challenge which we need to solve for a multibeam receiver is developing the QCL with lower cut-off frequency. According to the paper by B. S. Williams [Nature photonics, 2007], the lowest output frequency remains at 0.85 THz at an operating temperature of 40 K by applying magnetic field.

Element		Frequency Band					
		150 GHz		500 GHz		900 GHz	
		2SB	2SB-BM	2SB	2SB-BM	DSB	BM
Junctions	(uW)	0.10		0.13		0.3	
Mixer chip	(dB)	-0.5		-0.5		-2.0	
Quasioptical Coupling		0		0		-3	
Coupler		-17	-3	-17	-3	-13	-3
3dB coupler (2SB)		-3		-3		0	
Waveguide		-6		-6		-2	
Subtotal	(mW)	44.2	0.9	57.5	1.1	29.7	3.0
Available LO power P_{LC}	(uW)	630		100		30	
Number of elements		14	714	1	87	1	10

Table 1 Required LO power for each frequency and mixer configuration
2SB: Sideband separating mixer, BM: Balanced mixer, DSB: Double sideband mixer

Josephson junction oscillator also directly generates submillimeter power by applying voltage (0.4836 THz/mV). This means that no low frequency power source is needed. In addition, it would be easy to integrate the oscillator with a superconducting mixer V. P. Kochelets, et al [SPIE, 2010] and it is also possible to individually supply LO power to the mixer. In order to apply this technique to a multi-beam receiver for ALMA, this system stability and the linewidth needs to be improved

4. Thermal Loads

Thermal loads in the ALMA cartridge on 4, 15, and 110-K stages are limited to within 41, 162, 850 mW. Table 2 summarizes the estimated thermal loads for each band. The largest heat load on 4-K stage is the low noise amplifiers (LNAs), and no more pixels can be added. The most important task is to reduce the power consumption of the LNA, and/or to move the LNA to the other stages. In this estimation, excluding the heat load from wirings, if the power consumed in the LNA is less than 1 mW, more than 10 LNAs can be added.

One of the approaches to reduce thermal loads on 4-K stage is to use a single stage as a preamplifier of IF signal. Since it would be difficult to control the gain for the single stage amplifier, two or three stage LNA to equalize the frequency dependence of gain should be put on the 110 K stage. In our estimation of the noise budget, the preamplifier with gain of more than 10 dB and noise temperature of less than 5 K on the 4 K stage, and the LNA with gain of more than 20 dB and the noise temperature of less than 20 K on the 110 K stage are necessary to keep the current cartridge performance.

The research and development on ultra-low power consumption and ultra-low noise LNA using semiconductor-based technologies is moving ahead and feasibilities of such LNA development for the multi-beam receiver have been shown. Chalmers University of Technology in Sweden has already demonstrated an InP-HEMT amplifier with power consumption of below 5 mW for three stages and noise temperature of 1 K [J. Schleeh, et al, IEEE, 2012]. California Institute of Technology has established and accumulated technologies as regard to development of cryogenic LNA. Recently they showed results of noise measurements of 1-20-GHz LNAs [Ahmed H. Akgiray, et al, IEEE, 2013].

Source of heat load	Band 4			Band 8			Band 10		
	4 K	15 K	110 K	4 K	15 K	110 K	4 K	15 K	110 K
Wiring Heat Load	3.1	16.6	32	3.1	10.2	17.3	6.4	21	28
LO waveguide	0.2	21	90	0.4	24	94			298
IF coax	1.1	44.5	132	1.4	27	102	0.5	22	70
HEMT amplifiers	8 x 4			8 x 4			17 x 2		
Multiplier			20			100			200
Summary (mW)	36.2	82.1	174	36.9	61.2	313.3	41	43	596
Dewar ICD (mW)	41	162	850	41	162	850	41	162	850

Table 2 Thermal loads in the ALMA cartridge

In addition to the semiconductor-based technologies, research on a superconducting amplifier is going forward. Recently, superconducting travelling wave parametric amplifier was demonstrated, which has features of quantum-limited low noise, low power consumption, wide-bandwidth with several gigahertz and high dynamic range [B.H. Eom, et al, Nature Physics, 2012]. This amplifier uses the nonlinearity of kinetic inductance of superconducting thin film. This makes it easier to integrate with a superconducting mixer. They also mention that the concept of this amplifier design can potentially be used for frequencies up to terahertz. On the other hand, operating temperature at 80 mK in the paper should be higher for the practical application such as ALMA.

5. Integration of devices and receivers

In the ALMA cartridge, a horn antenna, mixer blocks and other components occupy large area of 4-K stage. This is one of the critical issues which makes it difficult to increase the number of beams. In order to put more devices, the size of these components must be smaller. To this end, system optimization between devices and building of on-chip technologies would be needed, and then devices should be integrated.

One of the problems is the 50-Ω interface. For example, IF signals from the superconducting mixer unit are generally output to the 50-Ω transmission line and then input to LNA through SMA connectors. However, output impedance of the superconducting mixer is not always 50 Ω. In addition, input impedance and noise optimum impedance of the LNA are quite different and not 50 Ω. An isolator is usually used to match between them, but should be removed for integration. Therefore, an optimized design which is not limited by the 50-Ω interface would be needed.

An on-chip RF circuit takes advantages of the compact, low interconection and transition loss, and easy handing. Recently, an increasing number of studies on waveguide technology based on microwave and lightwave circuits, and application to submillimeter-wave exists. For instance, a substrate integrated waveguide (SIW) and photonic crystal waveguide are becoming available for (sub-)millimeter wave circuits. The SIW makes it possible to propagate the waves in the same propagation mode as a rectangular waveguide (M. Bozzi, 2009). Photonic crystal waveguide, which is basically lightwave technology, has no metallic loss. The device size and structure can be fabricated by applying microelectromechanical system (MEMS) technologies [A. L. Bingham, 2008). Even a corrugated horn array can be fabricated on Silicon [J. W. Brittona, 2010]. These technologies help receiver to integrate and reduce the size.

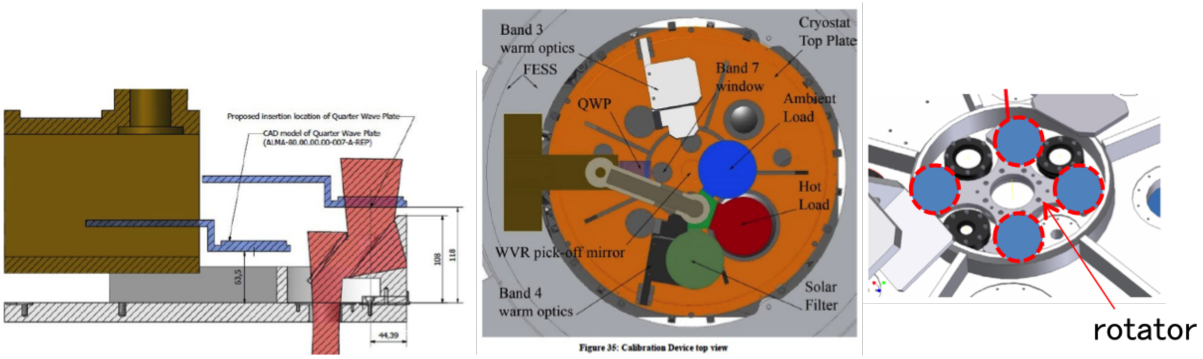
In summary, in order to construct the multi-beam receivers, significant modification to the current cartridge design is needed. Considerations not only from the engineering point of view but also from the research point of view are important. In terms of thermal loads, size and LO power, innovative improvements of component and device are needed. New technologies or adopting technologies developed in other fields will help. Discussion in different fields from radio astronomy, e.g. superconductor, semiconductor, MEMS, terahertz, telecommunication and photonics, will be important.

Appendix B: Under-illuminating Feed

Another factor that we need to consider is the sensitivity loss due to the insertion of lenses. The estimate is given in the following table (assuming a lens reflection of 1% and insertion loss of 2%). For example, the Tsys increases by 7% at band 7. Coupled with the sensitivity loss due to the under-illuminated feed, the sensitivity (AP_eff/T) will drop to 0.3*0.93 = 0.28.

Band	1	2	3	4	5	6	7	8	9	10
Tau0	0.01	0.0285	0.0261	0.03	0.0398	0.06	0.09	0.35	0.99	0.9
Trx no lens [K]	17	30	37	51	65	83	147	196	175	230
Eant	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
El [deg]	45	45	45	45	45	45	45	45	45	45
Tamb [K]	270	270	270	270	270	270	270	270	270	270
Tsys no lens [K]	53.4	77.0	83.9	102.1	123.8	157.0	256.2	579.4	1735.2	1713.8
lens eff	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Troom [K]	295	295	295	295	295	295	295	295	295	295
Trx with lens [K]	26.6	40.1	47.3	61.7	76.1	94.7	160.7	211.2	189.5	246.2
Tsys with lens [K]	64.3	88.7	95.8	114.5	136.9	171.1	273.5	607.1	1800.7	1778.2
Tsys(lens)/Tsys(noLens)	1.20	1.15	1.14	1.12	1.11	1.09	1.07	1.05	1.04	1.04

There are several ways to implement the lenses into the current ALMA receiving system; (1) using the quarter wave plate arm, (2) use the solar filter area of the ACD, (3) use a lens installer attached to a rotator. The advantage of (1) or (2) is that it only has a small impact on control. The disadvantage of (1) is that it can only be used for band 7. The disadvantage of (2) is that the solar filter will not be available. The advantage of (3) is that it can be used (for example) for four bands (e.g. bands 7,8,9,10), and the disadvantage is that it requires a new ICD to control, and additional costs to implement the stepping motors etc. A few examples of the Gaussian optics design are being considered.



[from left to right; (1) quarter wave plate arm, (2) solar filter area of the ACD, (3) lens installer attached to a rotator]

Major facilities by 2030

Table 1 Summary of operational and planned facilities

Wavelength		Ground based			Space missions		
	In operations	Under construction	Under study	In operation	Under construction	Under study	Proposals
Radio (m to mm)	GMRT, WSRT, J-VLA, eMerlin, VLBI arrays, Effelsberg, GBT, Arecibo, LOFAR, MWA, LWA, PAPER	SKA-P(MeerKAT, ASKAP), FAST, SKA1, SKA2,	SKA1, SKA2,?	RadioAstron		Millimetron	Low-frequency arrays 10-50 MHz
mm/submm/FIR	SMA, NOEMA, APEX, IRAM-30m, mm-VLBI, GMVA, BICEP3,..	CCAT, ASTE-2, LST	mmVLBI-LLAMA, Dome A	SOFIA		SPICA, Millimetron	Far-IR interferometers (FIRI), PRISMA,
IR/optical/UV	2-6.5 m telescopes, VLTs, GTC, VLTI, LBTi, Subaru, Kecks, Geminis	TAO, LSST, EELT, GMT, TMT		HST, Gaia,	JWST, Euclid, TESS, CHEOPS,	WFIRST-AFTA, HDST,	PFI Large apertures (>8 m): ATLAST
X-rays/Gamma rays	MAGIC,HESS, VERITAS	CTA		INTEGRAl,Swift, FGST, AGILE, Chandra, XMM-Newton, Suzaku, NuSTAR	Astro-H, eRosita, Athena, NICER		SMART-X GRAVITAS LOFT, ..
Solar System				Chang'e, LRO, Messenger Venus express, DAWN, ROSETTA, JUNO CASSINI, NEW HORIZON Mars Odissey Mars exploration rover Mars Express MRO, MSL/Curiosity MAVEN, MOM	Bepi Colombo Hayabusa II OSIRIS-REX JUICE INSIGHT Exomars Mars2020	MarcoPolo Europaclipper	LABSR ARM Comethopper TSSM Saturn Uranus

Connection between facilities 2030 and science themes

By 2030 it is expected that ALMA could be contributing to the main scientific topics to be addressed by the operational and planned facilities summarised in table 1:

Radio (m to cm)	ALMA
Dark ages: HI at z=30-50	Primordial chemistry?: HD, H2,.
End of Reionization: z=6-20	Dust + lines
Prebiotic chemistry	Lines?
Structure evolution of the Universe through HI	? Multibeams?
Exoplanets: Magnetospheres	Time variability?
Polarization: Cosmic magnetism	Continuum
Fundamental Gravity through pulsar timing	Time variability, Band 1?
Census of Galactic star formation through astrometry	Continuum
Zooming in on Black Holes and the onsets of jets	mm-VLBI (Continuum)

mm/submm/FIR	
Planet formation and evolution	Continuum +(lines?)
Star formation	Continuum +(lines?)
Large scale structure	**?Multibeams**
Galaxy formation and evolution (z = 0 to 10?)	Continuum+lines
Prebiotic chemistry??	??
Primordial B-mode (CMB)	Continuum ??
Astrometry (relative)? Exoplanet detection?	Continuum??
…	

UV/optical/IR	
Exoplanets: transits: detection of earth type at the Habitable Zone	**??**
Exoplanets: transits: characterization of atmospheres of super-earths at the Habitable Zone?	**??**
Exoplanets: direct image and characterization of super-earths	**??**
Exoplanets: microlensing detections	**?? Continuum**
Astrometry at µas, sub-µas and nas?.	**Continuum**
Exoplanet detection…	**Continnum**
Star formation	**Continuum+lines?**
Dark energy and matter	**??**
Large scale structure	**Multibeams??**
…..	

X-rays/Gamma rays	
Growth of SMBH up to z ~6	**Continuum + lines**
First population of stars through GRB at high z	**Continuum + lines**
Strong gravity	**??**
Black hole spin determinations	**??**
Equation of state of neutron stars	**??**

Evolution of large scale structure	Lines??
Detection of the WHIM	No
AGN feedback	Lines+ continuum
…..	

Brief description of facilities by 2030

Radio (m to cm)

Ground based

In operations

- **VLA: Jansky Very Large Array.** Likely to remain the most capable radio interferometer through to ~2020, possibly a little later depending on progress with SKA1 (see later). Offers full coverage across 1 to 50GHz and a powerful high-bandwidth correlator (WIDAR). Ultimately, an array covering New Mexico is envisaged. About to entering a new phase, conducting legacy surveys, following up NVSS and FIRST.
- **VLBI arrays:** A number of continent sized arrays with different characteristics in operation and construction. A recognized science case for high frequency and long global baselines in synergy with the SKA pathfinders.
- **LOFAR:** low frequency array with long baselines, looking for EOR signature, pulsars, transients.
- **eMERLIN:** niche imaging, at a spatial resolution between those possible with JVLA/Westerbork/etc. and VLBI, at 1.4 and 5 GHz. Probably retired by 2030.
- **GMRT, WSRT.** Possibly developing more fast survey capabilities with multi-pixel arrays. Studying galaxies through HI over large redshift ranges
- Other current cm single-dish facilities: GBT, Effelsberg-100m and Arecibo likely will not be operational by 2030.

Under construction

- SKA Precursors: MeerKAT, ASKAP - ought to be part of SKA by 2030
  The MeerKAT array is an international collaboration led by and based in South Africa, and expected to reach completion in 2017. It will be composed of 64 antennas, with a maximum baseline of 8 km, and receivers operating in UHF (0.6 to 1 GHz), L band (1 to 1.75 GHz) and X band (8 to 14.5 GHz). MeerKAT will likely be used mainly for large surveys and VLBI. The current top science science goals for MeerKAT are geared for L band. Two top priority projects focus on pulsar timing, and high-z HI. A list of 8 other MeerKAT science projects are planned, mainly on extragalactic and transient science.
  ASKAP timescale: early science in end 2015, full surveys starting mid-2017, focus on fast HI surveys with focal plane array receivers.

- **FAST:** Five-hundred-meter Aperture Spherical radio Telescope, first light expected in 2016. 500m dish, 300m illuminated aperture at a given time, 70 MHz to 3GHz.
- **Low-frequency arrays:** LOFAR, MWA, LWA, PAPER, etc. Evolving to HERA and SKA-Low (- 350 MHz) Emphasis on EoR. By 2030 might have EoR imaging leading to potential synergy with ALMA.

Under study

- **SKA1**: Phase 1 has 3 parts - SKA1-MID (250 dishes, 350 MHz - (maybe) 14 GHz; SKA1-Survey 64 dishes each with 36 beams, 700 - 1600 MHz; SKA1-low (see later). Should be fully operational before 2030. Synergies: Galaxy HI, evolution of SFR, protoplanetary disks (large pebbles - need high freqs), magnetic fields. Currently being re-baselined to fit within funding envelope of ~600ME.
- SKA2: operational at earliest in mid 2020's, which probably means around 2030, depending on speed of relevant technology development. Note: no frequencies above 14 GHz approved yet: up to at least 22GHz would give better synergy with ALMA. Compared with SKA1: longer baselines by a factor of 10; ten times the number of dish antennas; mid-frequency aperture arrays. Factor of 10 increase in sensitivity at least.

mm/submm/Far-IR

Ground based

Operating facilities

- Current mm/submm telescopes: IRAM 30m, IRAM NOEMA, APEX, SPT, LMT, ARO, JCMT, Nobeyama, Onsala, CARMA, SMA, NANTEN2, ASTE, .. It unclear how many of these will be operating in 2030. These deserve a global mention, but not going into the details, with the exception of NOEMA that will reach full upgrade in the second half of this decade and most likely will run at full capacity at least through the 2020-2030 decade. All others is unclear how long or in what model they will be operating long term. Many of these are capable of fast shallow mapping in the continuum and/or spectral lines, and we need to keep that in mind when recommending what capabilities to develop in ALMA. It is likely that some of these will still be very relevant in ~2030, e.g. LMT may be providing wide ~1-mm imaging at relatively high spatial resolution and competitive 3-mm spectroscopy.

- APEX instrumentation is now being upgraded with the next generation of multi-band bolometer cameras (thousands of bolometers e.g, ArTeMiS, A-MKID camera). They will produce large area shallow surveys/catalogs (at about 350 micron) which need to be exploited by ALMA in the next decades. Multi-beam heterodyne receivers are being deployed at many of these (IRAM-30m, APEX).

- NOEMA: major upgrade of the IRAM interferometer. The upgrades will consist of a doubling of the number of antennas (from 6 to 12 antennas), an increase of the bandwidth (from 8GHz to 32GHz), a doubling of the correlator for simultaneous dual-band imaging and a doubling of the East-West baseline (max=1.6km). So sensitivity multiplied by 4 and a resolution than can reach 0.2”. The correlators will provide full spectral coverage over the receiver bandpass with variable resolution (from 20 KHz to 2 MHz). The lower number of antenna and the smaller number of baseline: due to the smaller number of antennas, it may be easier to update with new instruments or new technology compared to ALMA. The receivers that are being deployed on NOEMA are indeed already next-generation as compared to the ones ALMA is operating at the moment. NOEMA will eventually cover the 70-375 GHz frequency bands, the final spectral line sensitivity will be within ~40% of the ALMA sensitivity, the continuum sensitivity ~60% of the ALMA one (in the common frequency bands, obviously). The development of a prototype 3-element heterodyne focal plane array that will serve to prepare for future multibeam FPA receivers for NOEMA is currently under investigation. NOEMA is designed to allow VLBI observations.

- IRAM 30m: the most sensitivity single-dish antenna in the 3mm, 2mm, 1mm, and 0.8mm bands. IRAM has a continuous upgrade strategy for heterodyne receivers and bolometers e.g. the integration of a dual-band KIDs array camera for the 1mm and 2mm atmospheric windows (NIKA2) is scheduled for 2015/2016. The telescope is part of the 3mm-GMVA and is also used for VLBI at 2mm and 1.3mm (BHC). It is key to complement NOEMA data with short spacing information.

- SMA: Future upgrade to increase the total bandwidth to 32 GHz. This will imply a significant increase in the sensitivity for the continuum. High efficiency for spectral surveys toward bright sources. Ability to efficiently cover large areas in the sky. It will operate at 230 GHz and 345 GHz only (690 GHz decommissioned). .Current plans foresee that the SMA will be operational until, at least, 2020.

- CARMA: Major funding issues, mid-scale facility proposal submitted, but future is uncertain.
- mmVLBI, the Global mm VLBI Array (GMVA), BlackHoleCam and the Event Horizon Telescope. Global array of mm/sub-mm telescopes capable of VLBI. Includes ALMA, LLAMA, SPT, Greenland Telescope, ARO, IRAM NOEMA/30m, as well as other

mm-capable single dish and interferometers. mmVLBI and GMVA are organized as common user access facilities, while the ETH and BlackHoleCam are dedicated experiments/collaborations to observe the event horizon of SgrA* and the M87 supermassive Black Holes. Extension of mmVLBI to include extremely long baselines with space missions (simialr to the cm-wave Radioastron) have been discussed and could dramatically improve resolution (Millimetron is proposed to do this, see below http://millimetron.asc.rssi.ru/index.php/en/).

- BICEP3 - BICEP3 will deploy to the Dark Sector Laboratory at Amundsen-Scott South Pole Station in the 2014-2015 Austral summer season. It will field 2560 detectors operating at 100 GHz. http://www.cfa.harvard.edu/CMB/bicep3/

Under construction

- CCAT: The Cornell Caltech Atacama Telescope is a planned 25m diameter single-dish facility which will operate at 5,600 m of altitude in Cerro Chajnantor, with construction recommended by the Astro2010 decadal survey in the US. Its instrumentation will span the 0.2-3.3 mm range. CCAT is optimized for fast wide-field continuum imaging, providing also wide field and multi-object spectroscopic capabilities. The median transmission of the CCAT site enables routine observations at a wavelength of 350um and as short as 200um for more than 10% of the time. It is thought that CCAT will operate primarily in the “large program” mode, rather than servicing smaller individual proposals. Its main goals encompass galaxy formation and evolution (surveying the population of submm sources), SZ effect, nearby galaxies, molecular cloud and star formation, and solar system (e.g., TNO, comets) studies (see http://www.ccatobservatory.org/docs/pdfs/CCAT_Science_Requirements_R1.pdf) The current thoughts on the planned first-light instrumentation include: 1) SWCam, a 63,000 pixel camera providing simultaneous imaging at 200, 350, and 450 um with FOV diameters of approximately 3’, 5’ (×3), and 7’ (×3) respectively, designed to measure SFRs and dust mass in galaxies through cosmic time. 2) LWcam, a 37,000 pixel camera with simultaneous diffraction limited imaging at 750, 860, 1100, 1300, 2000, and 3300 um and an equivalent FOV of 20’ diameter. Key science includes Sunyaev-Zel’dovich effect observations. 3) X-spec, a direct detection multi-object R~700 spectrometer in the 200-900 GHz range capable of obtaining simultaneous spectra for dozens of sources located over a 1 deg field. 4) CHAI, a dual-band (460-490 and 800-870 GHz) multi-object heterodyne spectrometer for 64 objects.

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- LLAMA: The Long Latin-American Millimeter Array is one ALMA-design 12m Vertex antenna operating at the Alto Chorrillos site in the Argentine province of Salta, close to the city of San Antonio de los Cobres, built and operated by Brasil (FAPESP) and

Argentina (CONICET). (presentation in Spanish) The baseline subtended to the ALMA site is approximately 183 km. The antenna is expected to operate in VLBI mode, and the resulting resolution would be 1 milli-arcsecond at 1 mm, thus filling the intermediate baselines gap between ALMA and the global VLBI network. In principle, other similar projects like LLAMA can be developed in the next decade, (let's say within South America) since the cost is relatively cheap, antennas are just a copy of ALMA antennas (so therefore well characterized) and could help filling the intermediate baselines of the global mm-VLBI array.

- Dome A Observatory: a 15-meter THz telescope to build in Antarctica after 2015. A prototype called DATE5 (The Dome A 5-m terahertz telescope) is currently being built.
    - see page 6 of this PPT
    - science news

- ASTE-2 - Japanese initiative in the ~25m single-dish class, possibly intended for high site, near CCAT. Seems to be progressing slowly, but there would be widespread interest from Europe and elsewhere if it were to gain momentum.

- LST: The Large Submillimeter Telescope is a Japanese plan to construct a 50m mm/sub-mm singe-dish antenna optimized for wide-area imaging and spectroscopic surveys in the 70-420 GHz range. The current plan is to build the telescope near the CCAT site. The telescope should also allow VLBI observations. The LST is designed to perform cosmological surveys on very large areas (100-1000 deg^2) and to work in synergy with ALMA, SPICA, etc.

Space

Under study

- **SPICA**: the Space Infrared Telescope for Cosmology and Astrophysic is a JAXA-ESA collaboration to launch the next large far infrared astrophysics mission around 2025. It will be equipped with 3 meter class cryogenic telescope (<6 K) operating in the L2 orbit. The instrumentation will cover the 5-210um wavelength range. The payload will consist of three instruments: SAFARI (SpicA FAR-infrared Instrument), a FIR imaging spectrometer (30 - 210 μm, spectral resolution of 10 to 10000), and two mid-infrared instruments, namely the MIR coronograph (3.5/5 - 27 μm) and the MIR camera/spectrometer (5 - 38 μm). SPICA will study the evolution of galaxies, stars and planetary systems.
http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index_English.html

- **Millimetron:** Millimetron ("Spektr-M" project) is a project of the Russian Federal

Space Agency. It is a space observatory with a 10-m cooled deployable telescope (<10K) To be equipped with state-of-the-art receivers, enabling observations in the mm/submm to far-infrared wavelength range between 200 microns and 17 mm. It will operate in single-dish mode or as a station in a space-ground VLBI network. In the VLBI mode the Millimetron, will provide extremely high angular resolution allowing for example imaging studies of the direct environment of black holes. As a single dish observatory, Millimetron will provide unique capabilities to conduct detailed and deep imaging and high resolution spectroscopy with unrivalled sensitivity, probing and characterizing the earliest epochs of the Universe as well as the complete evolutionary track of star formation and exo-planetary systems. http://millimetron.asc.rssi.ru/index.php/en/

Proposals

- **FIRI:** Far-infrared Interferometer. Extremely ambitious (complex, costly, risky, potentially high-impact) concept developed in EU and NA, typically with 2-3 free-flying or tethered SPICA-class (~3.5-m, cold) telescopes in its most ambitious form, or a couple of smaller ~1-2-m telescopes mounted on a boom.
- **Other concepts:** Large single dish concepts are also being considered (e.g. SAFIR, GISMO. Also some partially-filled-aperture ideas are proposed in the White Paper written for the 2013 ESA L-class call, which include the three concepts outlined. http://www.firi.eu/

IR/Optical/UV

Ground based

In operations

- **Wide field imaging telescopes** using very small apertures (professional cameras and lenses). “A la Dragonfly” to probe the Optical light (very deep, maybe down to 31 mag/arcsec^2?)

- **2-4 meter class telescopes:** WHT**,** LAMOST, AAT (SAMI), APO (BOSS, APOGEE, MaNGA, and SDSS 5?)
    a. **WEAVE**: is designed to exploit Gaia’s scientific legacy and is a prime focus spectrometer for the William Herschel Telescope (WHT). It will have a field-of-view of 2 degrees and about 1000 fibres. It will provide a low resolution survey for radial velocity measurements of stars that are too faint to be observed by the Gaia spectrometer, along with a high resolution survey to make accurate

determinations of the metallicities and temperatures of the bright stars observed by Gaia. The instrument PDR took place in early 2013, and the start of the surveys should be in 2017, provided adequate funding is secured by all partners (UK, Netherlands, Sweden, France, Spain).

b. **DESI**: Other projects are under study or in a development phase elsewhere; such as the Dark Energy Spectroscopic Instrument, (DESI-formally Big BOSS) on the 4m Mayall telescope at Kitt Peak. This has a field-of-view of 3 degrees and 5000 fibres. These other projects present opportunities for bi-lateral collaboration from European countries.

- **10m-class telescopes**
    - **Subaru** telescope, 8.2 m optical and infrared telescope located at the top of Mauna Kea will continue its operation at least until 2033. It will most likely focus on prime focus instruments to conduct wide field surveys.
    - ***VLT - Paranal*** - Equipped with multi-object near-IR integral field unit (IFU) spectrometer, KMOS, and wide-field optical IFU, MUSE, covering a square arcmin (or rather less at much higher spatial resolution with AO enabled). ESO roadmap currently foresees VLT instrument development continuing into the 2020s at a rate of one new instrument or upgrade per year. New instruments will likely include MOONS and 4MOST, both wide-field spectrometers, the former optimised for redshift surveys in the “optical redshift desert”, the latter optimised for Gaia-related spectroscopic observations. Also, ERIS (**E**nhanced **R**esolution **I**mager and **S**pectrograph) on UT4, exploiting powerful new 4-laser Adaptive optics facility. Gravity, (etc.)
    - ***Keck (add info)***
    - ***Gemini*** provides two 8.1m telescopes located on Mauna Kea and Cerro Pachon equipped with instruments operating from 360-5000nm to provide imaging and spectroscopy. Niche is high spatial resolution in near-infrared over relatively small field of view. GPI (Gemini Planet Imager - an extreme AO imaging polarimeter/integral field 0.9-2.4-micron spectrometer) has been a recent success.

    - **GTC** (Gran Telescopio de Canarias). Diameter of 10.4 m, equipped with instrumentation covering optical, up to MIR wavelengths (OSIRIS and Canaricam are operational) and many more instrumentation like EMIR in development.

- **VLTi:** ESO's Very Large Telescope Interferometer consists of an array of four 8m telescopes (UTs) and four 1.8m telescopes (ATs). Two second generation instruments will be installed during 2015 and 2016, which can both combine four UTs or ATs simultaneously, thereby yielding measurements of visibility amplitude and closure phases on six baselines.

  - The `Gravity' instrument will enable spectro-interferometric observations (with a resolving power of ~5000), in K-band, of objects much fainter than previously possible (down to K=11 for spectroscopy). It includes the capability of observing two sources separated by up to 2 arcsec, so that a fainter source can be observed while tracking fringes on a brighter neighboring star. Off-axis fringe tracking will allow sources as faint as K=15 to be observed, and narrow-angle astrometry with 10 microarcsecond accuracy. The main science goal for Gravity is precision astrometry, in particular in the neighbourhood of Sgr A*, but also for exoplanet searches.
  - The `Matisse' instrument will provide dispersed visibility data in the thermal IR (L, M and N bands, with resolving power of 30-1000), and will achieve its full potential once paired with an external, four-telescope fringe tracking instrument (under consideration at ESO). Its main goals are 1) image synthesis (of circumstellar environments, but also possibly AGNs), 2) detection of hot jupiters or protoplanets, and 3) observations of minor bodies of the solar system.
  - The development of third generation instruments will soon be considered. The serious contenders at the moment are 1) a visible instrument with high spectral resolution capabilities (~30000) and 2) a high dynamic range imager in the near-infrared. A possible expansion of the VLTI imaging capability is also part of the prospective exercise at the same timescale as ALMA2030.

- LBTI provides a baseline of 22 m and most probably an increased sensitivity with respect to VLTI, this corresponds to a 100 mas resolution. It possesses a possibility for nulling interferometry in the 8-14 micron regime tailored for exozodis detection (~1sigma = 10 zodis).

Under construction

- **GMT:** The Giant Magellan Telescope is a 24.5 m telescope being developed by an international consortium that will be located at Las Campanas Observatory in Chile. Construction is scheduled to begin in 2014, and first light is expected in 2020. GMT will have nearly five times the light-gathering power of today's largest telescopes, and angular resolution an order of magnitude better than that of the Hubble Space Telescope. The three instruments selected to be built for first light are the GMT-Consortium Large Earth Finder (G-CLEF), the optical multi-object spectrograph GMACS, and the GMT Integral Field Spectrograph (GMTIFS). G-CLEF is a high-resolution optical spectrograph that will enable both unprecedentedly sensitive radial-velocity searches for extrasolar planets and pioneering studies of the intergalactic medium and the first stars. GMACS is a workhorse low and medium resolution optical spectrograph with applications from nearby stars to the most distant galaxies, and GMTIFS is a near-infrared AO-fed integral field spectrograph and imager that will be used to study the black hole at the center of the Milky Way and the dynamics of high-redshift galaxies. Other future capabilities include the MANIFEST fiber feed and positioning system that will enable all of the GMT spectrographs to access the telescope's full ~20’ field of view and achieve higher spectral resolution, a multi-object near-IR spectrograph, and near-IR high-resolution echelle spectrograph.

E-ELT The European Extremely Large Telescope (E-ELT) is a 39.3-m telescope being designed by ESO and its partner institutes for Cerro Armazones in Chile, the top of which (at a height of 3060m) is being levelled in June 2014. E-ELT will have 798 mirror segments, each 1.4m, with a 4.2-m secondary mirror. The adaptive 1.6-m M4 mirror has over 6000 actuators and will compensate for atmospheric turbulence using six laser guide stars. The first-light instruments are a wide-band integral field spectrograph (HARMONI) and a diffraction-limited near-IR camera (MICADO), the latter fed by the MAORY adaptive optics facilty, and these will be followed by a MOS, a high-resolution spectrometer (HIRES) and a mid-IR instrument.

- E-ELT/HARMONI: 0.4-2.4microns IFU spectrograph with four different plate scale settings to cover diffraction limited to natural seeing observations (4masx4mas; 10masx10mas;20masx20mas;60masx30mas); max field of view 9x6.5arcsecs with the widest scale down to 0.6x0.9 arcsecs; spectral resolution R~500; 4k; 10k; 20k. Simultaneous opt-NIR planned.
- E-ELT/MICADO: 50arcsec diameter field of view with 4mas pixels and slit spectroscopy with TBC resolving power. <40mas astrometric performance.
- E-ELT/MIDIR instrument based on METIS; 30arcsec imaging field; R~100,000 IFU spectroscopy 3-5um (perhaps also N band - 14um); Q-band (to 28um) as a goal. E-ELT/HIRES R>50 0000 spectral resolving power; could be broad wavelength coverage (0.4-2.4um). MOS - wide range of facilities foreseen from multi-IFU AO assisted (multiplex of 10s) to seeing limited, fibre fed (multiplex of 100s). On longer timescales,
- ELT-PCS planetary camera and spectrograph (a SPHERE-type instrument for the E-ELT) - potential to image exo-Earths.

- **TMT:** TMT is the Thirty Meter Telescope, a wide-field telescope with 30 meter diameter. The optical beam of this telescope will feed at least eight different adaptive optics AO/instrument combinations covering a broad range of spatial and spectral resolution. TMT will couple unprecedented light collection area (almost 10 times

more than one of the Keck telescopes) with diffraction-limited spatial resolution. The first light instruments are the **Wide Field Optical Spectrometer (WFOS), the Infrared Imaging Spectrometer (IRIS) and the Infrared Multi-object Spectrometer (IRMS).**
  - The Wide Field Optical Spectrometer (WFOS) will provide near-ultraviolet and optical (0.3 – 1.0 μm wavelength) imaging and spectroscopy over a more than 40 square arcminute field-of-view. Using precision cut focal plane masks, WFOS will enable long-slit observations of single objects as well as short-slit observations of hundreds of objects simultaneously. WFOS will use natural (uncorrected) seeing images.
  - The Infrared Imaging Spectrometer (IRIS) will be mounted on the observatory MCAO system and be capable of diffraction-limited imaging and integral-field spectroscopy at near-infrared wavelengths (0.8 – 2.5 μm).
  - The Infrared Multi-object Spectrometer (IRMS) will allow close to diffraction-limited imaging and slit spectroscopy over a 2 arcminute diameter field-of-view at near-infrared wavelengths (0.8 – 2.5 μm).

- **LSST** : LSST is the Large Synaptic Survey Telescope - an 8m-class optical survey telescope with a very large field of view of 10 square degrees. It will survey the full Southern Sky every couple of days down to a approximately r ~ 24.5 mag per visit. Each field is visited a few thousand times in ~10 years of operation. It will operate in the 300-11000 nm range in six photometric bands (ugrizy, similar to Pan-STARRs). Two of the main science drivers are time-domain astrophysics and dark energy. In particular, LSST will open a completely unexplored window into transient phenomena, and is planning on making all their transient alerts public in real time. First light is expected around 2020, with regular operations starting 2023ish.

- **TAO**
  The University of Tokyo Atacama Observatory project is going to have a 6.5m infrared-optimized telescope at the summit of Co. Chajnantor (5640m alt.) in northern Chile. The construction is now underway, and the first light is expected in 2017-2018. Thanks to the low water vapor (PWV~0.5mm) and the high altitude, a new atmospheric window at 25-38 micron, as well as a continuous band at 1-2 micron including Paschen-alpha at 1.875 micron, become available. Two first generation instruments are currently under development: SWIMS, a NIR wide-field multi-object camera/spectrograph capable of simultaneous 0.9-2.5 micron MOS spectroscopy with R~1000 in a FoV of 9.6 arcmin. SWIMS is expected to be a workhorse instrument to cover from Galactic objects to distant galaxies/AGNs. The other is an MIR camera/spectrograph MIMIZUKU covering 2-40 micron with high spatial resolution of <1 arcsec and capable of high -precision relative photometry. MIMIZUKU is expected to carry out studies of stellar disks and extrasolar planet formation.

Under study

- ***MSE***: Mauna Kea Spectroscopic Explorer ⇒ maybe include the potential multi-spectro dedicated 10m replacing CFHT. Not clear if this will happen and when. http://www.cfht.hawaii.edu/en/news/MSE

Space missions

In operations

- **HST** - The Hubble Space Telescope is a 2.4m UV/optical/IR space telescope, launched in 1990. Through five servicing missions it has received numerous upgrades to its instrument complement. Many of the capabilities of HST are not replicated elsewhere. At present there are four operating instruments on HST:

  - The Space Telescope Imaging Spectrograph (STIS) offers a variety of imaging and spectroscopy in the ultraviolet and optical wavelength ranges (1140 - 11000 A) at low and medium resolution, as well as a high spectral resolution echelle capability.
  - The Cosmic Origins Spectrograph (COS) offers high throughput UV spectroscopy in the 900 - 3000 A wavelength range at low and medium resolution, through a 2.5" aperture. It is optimized for point sources.
  - The Wide Field Camera 3 (WFC3) provides a range of UV, optical and near infrared imaging capabilities as well as grism observations. The field of view of the UV and visible detector (UVIS) is 2x162"x162" at 0.04"/pixel, and the IR detector has 136"x123" spatial coverage, at 0.13"/pixel.
  - The Advanced Camera for Surveys (ACS) has two sets of detectors, the Wide Field Camera (WFC) with 2x2048x2096 pixels, 0.05"/pixel, and an area coverage of 202"x202". The Solar Blind Channel (SBC) has a 1024x1024 pixel detector with 0.032"/pixel, spanning 34"x31".

  HST's ability to provide deep, precise, and stable pan-chromatic imaging, as well as slitted and slitless spectroscopy, coronography, and astrometry make it a versatile observatory, capable of tackling science problems ranging from the architecture of the universe, mysteries of dark matter and dark energy, births and deaths of stars, and the recipes for building planets. The current and projected status for HST is good. At present, operations into the early 2020 timeframe appear feasible, and based on orbital analyses and instrument performance, continuing further into the 2020 decade is realistic. http://www.stsci.edu/hst

Under construction

- **JWST:** JWST is NASA's flagship mission, a 6.5 m diameter segmented telescope operating at near- and mid-infrared wavelengths (0.6-28 micron). Scheduled to launch in 2018, JWST will probe the early universe, address questions of galaxy formation and evolution, the birth of planetary systems, and search for the ingredients of life. Its instrument complement contains a diverse array of observing modes, from imaging to grism, slit less, multi-object and integral field unit spectroscopy, coronography, and aperture masking interferometry.
  - The Near Infrared Camera (NIRCam) covers a 2.2x4.4 arc minute field of view from 0.6-5 micron, with 0.032" pixels from 0.6-2.3 micron, and 0.065" pixels from 2.4-5.0 microns. A variety of filters provide imaging capability along with grism spectroscopy at a resolution of 2000, and NIRCAM has a coronographic capability from 0.6-2.3 micron. T
  - he Near Infrared Imager and Slitless Spectrograph (NIRISS) provides imaging over a 2.2x2.2 arc minute field of view, covering the 0.9-5 micron range at 0.065" per pixel. It also provides slit-less spectroscopic capability from 0.6-2.5 micron at resolutions from 150-700, as well as aperture masking interferometry from 3.8-4.8 microns.
  - The Near Infrared Spectrograph (NIRSpec) has a variety of spectroscopic modes, from single slit and multi-object spectroscopy to IFU spectroscopy, at wavelength ranges of 0.6-5.0 microns, and resolving powers from 100 to 2700. The sizes of the slits range from a few arcseconds to 3.4x3.4 arc minutes (for the multi-object spectrograph, with 0.5" shutters).
  - The Mid-Infrared Instrument MIRI covers the 5-28 micron wavelength range, with imaging (0.11" pixels, field of view 1.23'x1.88'), single slit and IFU spectroscopy (resolution up to 3500, slit widths of a few arc seconds), and coronography at several wavelengths.

  A more complete description of the science questions driving the instrumentation can be found in Gardner et al. (2006 Space Science Reviews, vol. 123, p 485), with updated white papers available at http://www.stsci.edu/jwst/doc-archive/white-papers. A summary of JWST's contribution to particular science questions, as discussed in recent peer-review literature can also be found at http://www.stsci.edu/jwst/jwst-science-corner/.

- **Euclid:** Euclid is a mission led by the European Space Agency designed to study dark matter and dark energy through high precision studies of weak gravitational lensing and baryonic acoustic oscillations. Its planned launch is 2020, to the L2 point. The mission lifetime is 6 years and it is designed to map 15,000-20,000 sq. deg., with very deep mapping of 40 sq. deg. Euclid is a 1.2m diameter wide-field

telescope that will produce a legacy dataset with images and photometry for over a billion galaxies and several million spectra, out to a redshifts z>2. At low redshift it will resolve the stellar populations of all galaxies within 5 Mpc. The instrumentation consists of an optical camera (VIS, 550-900 nm, 0.18” PSF), and a NIR camera/spectrograph (NISP, equipped with Y, J, H filters for imaging at 920-2000 nm and capable of R=250 spectroscopy for wavelengths 1100-2000 nm). Euclid is also expected to detect hundreds of galaxies 6.3<z<8.5, brighter than J~26 (see EUclid Definition Study Report at http://sci.esa.int/euclid/48983-euclid-definition-study-report-esa-sre-2011-12/#).
Euclid is also gonna be used for exoplanets science using microlensing and transients.

- **Gaia:** The satellite (**Gaia**) was launched on 19 December 2013 (nominal mission end is 2018 after 5yr). This space satellite is designed to deliver a three-dimensional map of the Milky Way. Gaia will provide unprecedented positional measurements for about one billion stars in our Galaxy - about 1 per cent of the Galactic stellar population - and Local Group, together with radial velocity measurements for the brightest 150 million objects. While the mission itself will likely not be active in 2020-2030 time-frame its products (catalogs) will have important impact. Astrometric precision is ~25 microarcseconds (GRAVITY 10 microarcseconds). Astrometric characterization of known and discovery of new exoplanets (measurement of real mass).

- **PLATO :** Recently selected by ESA as the M3 mission, it is expected to be launched in 2024. PLATO will discover and characterize a large number of close-by exoplanetary systems, with a high precision in the determination of the planet mass, of planet radius, and of stellar age. It will provide the key information needed to determine the potential habitability of the new detected exoplanets. PLATO has also been designed to investigate seismic activity in stars, enabling the precise characterisation of the planet host star, including its age. PLATO will be equipped with 32 telescopes (pupil diameter of 120 mm) with a focal plane array of 4 CCDs each with 45102 pixels providing a very wide FoV of 1100 deg. The cameras are arranged in four groups of eight. Each group has the same FoV but is offset by a 9.2° angle, allowing to survey a total field of ~2250 deg2 per pointing. The proposed total mission lifetime is about 6 years.

- **Cheops :** The CHaracterizing ExOPlanet Satellite (CHEOPS) will be the first mission dedicated to search for transits by means of ultrahigh precision photometry on bright stars already known to host planets. By being able to point at nearly any location on the sky, it will provide the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. It will also provide precision radii for new planets discovered by the next generation ground-based transits surveys (Neptune-size and smaller).

- **TESS :** Transiting Exoplanet Survey Satellite (TESS) has been selected for development in Sep 2011 of Explorer-class mission proposals. The satellite is scheduled to launch in 2017. The satellite will work on much the same principle as the Kepler satellite: planetary transit photometry. The advantages with respect to Kepler:
    a. TESS will survey the entire sky through the use of four wide-field telescopes. This survey area is over 400 times larger than Kepler's field of view.
    b. TESS each of those four telescopes will have a CCD detector. Combined those cameras will have a total of 192 megapixels, compared to Kepler's 95 megapixel CCD.
    c. TESS will study approximately 2,000,000 stars, compared to Kepler's 150,000

Under study

- **WFIRST:** The Wide-Field Infrared Survey Telescope (WFIRST) is a NASA observatory designed to perform wide-field imaging and slitless spectroscopic surveys of the near infrared (NIR) sky for the community. The current Astrophysics Focused Telescope Assets (AFTA) design of the mission makes use of an existing 2.4m telescope to enhance sensitivity and imaging performance. **WFIRST-AFTA** will settle essential questions in both exoplanet and dark energy research and will advance topics ranging from galaxy evolution to the study of objects within the Galaxy and within the Solar System.

- **HDST** - High definition space telescope (12 m) telescope under discussion in USA; main science goals are (1) Exoplanets; (2) Universe in High-definition - resolving 1pc out to 25 Mpc, resolving 100pc star forming regions throughout the universe. UV (90 nm) to near-IR (2.5 mm, non-cryo): http://www.aura-astronomy.org/news/hdst.asp - note that HDST is an offshoot from the *ATLAST* 8-12 m UV-to-IR space telescope concept (http://www.stsci.edu/institute/atlast)

- **SPICA** - see submm/FIR facilitties section. http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/index_English.html

Proposals

- **PFI** (Planet Formation Imager) is a proposed space interferometry project probably beyond 2030-2030 time frame, http://planetformationimager.org. Optical interferometry is destined to play the crucial role in advancing our understanding of planet formation and that PFI will be required to explain the increasing wealth of exoplanet demographic information anticipated in the coming decades. PFI will be a powerful complement to and extension of ALMA, ELTs, and JWST in our quest to understand the origin of the planets and to fully explore notions of habitability. PFI will target planet-forming disks as well as warm, newly-born planets around stars in nearby star forming regions. PFI must operate at near- and mid-IR wavelengths with 0.1 to 1 AU resolution to resolve structures in dusty disks at solar system scales. The PFI facility will have the potential to unmask all the major stages of planet formation, from initial dust coagulation, gap formation, evolution of transition disks, mass accretion onto planetary embryos, and eventual disk dispersal. PFI images will directly detect the cooling, newly-formed planets themselves, opening up both spectral investigations and also providing a vibrant look into the early dynamical histories of planetary architectures. Only long-baseline interferometry can provide the needed angular resolution and wavelength coverage to reach these goals and from here we launch our planning efforts."

- ***ATLAST:*** The Advanced Technology Large Aperture Space Telescope (ATLAST) is a NASA concept study for the next generation of UV/optical space observatory. ATLAST will have a primary mirror diameter in the 8m to 16m range that will allow us to perform some of the most challenging observations to answer some of our most compelling astrophysical questions. ATLAST will have an angular resolution that is 5 - 10 times better than the James Webb Space Telescope (JWST) and a sensitivity limit that is up to 2000 times better than the Hubble Space Telescope (HST)

X-rays/Gamma rays

Ground based

In operations

- **MAGIC:** The MAGIC Collaboration has built in 2002 / 2003 a first large atmospheric imaging Cherenkov telescope. Placed in Canary Islands, it has two telescopes (MAGIC-I and II), with a surface of 236 m^2 each. With the accent of these instruments on large mirror surface and best light collection, cosmic gamma-rays at an energy threshold lower than any existing or planned terrestrial gamma-ray telescope have become accessible. So far achieved has been a threshold of 25 GeV. https://magic.mpp.mpg.de/

- **HESS:** High Energy Stereoscopic System study the very high energy gamma-ray astrophysics. Placed in Namibia, it is a system of imaging atmospheric Cherenkov telescopes. It covers the rnage of 10s of GeV to 10s of TeV. https://www.mpi-hd.mpg.de/hfm/HESS/

- **VERITAS:** the Very Energetic Radiation Imaging Telescope Array System is placed in Arizona. It is an array of four 12m optical reflectors for gamma-ray astronomy in the GeV - TeV energy range. Their highest sensitivity is reached in the range 50 GeV - 50 TeV, being maximum in 100 GeV-10 TeV. This is complementary to the NASA Fermi mission.

Under construction

- **CTA:** Cherenkov Telescope Array (overlap with particle physics, but essentially astronomy). Large array(s) of telescopes for ground based detection of 100 GeV - 100 TeV gamma rays. 10x increase in sensitivity at least over current instruments. The aims of the CTA can be roughly grouped into three main themes, serving as key science drivers: a) Understanding the origin of cosmic rays and their role in the Universe, b) Understanding the nature and variety of particle acceleration around black holes and c) Searching for the ultimate nature of matter and physics beyond the Standard Model. https://portal.cta-observatory.org/Pages/Home.aspx

Space missions

In operations

- **INTEGRAL:** The INTErnational Gamma-Ray Astrophysics Laboratory was launched in October 2002, and it is a project of the European Space Agency, woth contributions of Russia and NASA. It is providing a new insight into the most violent and exotic objects of the Universe, such as neutron stars, active galactic nuclei and supernovae. INTEGRAL is also helping us to understand processes such as the formation of new chemical elements and the mysterious gamma-ray bursts, the most energetic phenomena in the Universe. Environments of extreme temperature and density, near the event-horizons of black holes, are a major topic of study with INTEGRAL. INTEGRAL is dedicated to the fine spectroscopy (E/E = 500) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3-35 keV) and optical (V-band, 550 nm) energy ranges. http://heasarc.gsfc.nasa.gov/docs/integral/inthp_about.html

- **Swift:** Swift is a first-of-its-kind multi-wavelength observatory dedicated to the study of gamma-ray burst (GRB) science, built by NASA with international participation. Its three instruments work together to observe GRBs and afterglows in the gamma-ray, X-ray, ultraviolet, and optical wavebands. The main mission objectives for Swift are to: Determine the origin of gamma-ray bursts; Classify gamma-ray bursts and search for new types; Determine how the burst evolves and interacts with the surroundings; Use gamma-ray bursts to study the early universe; Perform the first sensitive hard X-ray survey of the sky. The observatory covers gamma-ray, X-ray, UV and optical. Spectrosocpy from 180-600 nm and 0.3-150 keV. GRBs positions with precision 0.5"-5" http://swift.gsfc.nasa.gov/about_swift/

- **AGILE:** AGILE is a small Scientific Mission of the Italian Space Agency (ASI) with participation of INFN, IASF/INAF and CIFS. AGILE is devoted to gamma-ray astrophysics and it is a first and unique combination of a gamma-ray (AGILE-GRID) and a hard X-ray (SuperAGILE) instrument, for the simultaneous detection and imaging of photons in the 30 MeV - 50 GeV and in the 18 - 60 keV energy ranges. http://agile.asdc.asi.it/

- **Chandra:** The Chandra X-ray Observatory is the U.S. follow-on to the Einstein Observatory. The Chandra spacecraft carries a high resolution mirror, two imaging detectors, and two sets of transmission gratings. Important Chandra features are: an order of magnitude improvement in spatial resolution (up to 0.4"), good sensitivity from 0.1 to 10 keV, and the capability for high spectral resolution (up to 0.012 A) observations over most of this range. Chandra's capabilities provide unprecedented science and Chandra Users are making important contributions to all areas of astronomy, including the solar system, stars, interacting binaries, compact objects, supernovae, galaxies, and AGN. http://cxc.harvard.edu/

- **XMM-Newton:** XMM-Newton, the X-ray Multi-Mirror Mission, is the second cornerstone of the Horizon 2000 program of the European Space Agency (ESA). The observatory consists of three coaligned high throughput 7.5m focal length telescopes with 6" FWHM (15" HPD) angular resolution. XMM-Newton images over a 30' field of view with moderate spectral resolution using the European Photon Imaging Camera (EPIC), which consists of two MOS and one PN CCD arrays. High-resolution spectral information (E/dE~300) is provided by the Reflection Grating Spectrometer (RGS) that deflects half of the beam on two of the X-ray telescopes. The observatory also has a coaligned 30 cm optical/UV telescope, the Optical Monitor (OM). http://heasarc.gsfc.nasa.gov/docs/xmm/xmmgof.html

- **Suzaku:** is an X-ray mission developed by ISAS/JAXA and NASA and some japanese and U.S. institutions. Suzaku covers the energy range 0.2 - 600 keV with the two instruments. Suzaku also carries a third instrument, an X-ray microcalorimeter, that lost all its cryogen before scientific observations could begin. http://heasarc.gsfc.nasa.gov/docs/suzaku/index.html

- **NuSTAR:** The Nuclear Spectroscopic Telescope Array Mission (NuSTAR) is a Small Explorer mission led by Caltech and managed by JPL for NASA's Science Mission Directorate. NuSTAR is the first mission to use focusing telescopes to image the sky in the high-energy X-ray (3 - 79 keV) region of the electromagnetic spectrum. Our view of the universe in this spectral window has been limited because previous orbiting telescopes have not employed true focusing optics, but rather have used coded apertures that have intrinsically high backgrounds and limited sensitivity. The objectives of NuSTAR are related to AGNs, hard X-ray emitting compact objetcs in the Galaxy, non-thermal radiation in young supernova remnants (SNR), and observe supernovae on the Local Group.

- **Fermi (FGST):** The Fermi Gamma-ray Space Telescope was built by NASA to unveil the mysteries of the high-energy universe. FGST's main instrument, the Large Area Telescope (LAT), operates more like a particle detector than a conventional telescope. Fermi studies the cosmos in the range 8 keV-300 GeV. http://www.nasa.gov/mission_pages/GLAST/spacecraft/index.html

- **MAXI:** the Monitor of All-sky X-ray image (MAXI) has as main purpose to monitor for events such as flares and bursts in X-rays watching all the sky all the time. MAXI, is developed to be mounted on the Japanese Experimental Module of the International Space Station. MAXI monitors the X-ray variability once every 96 minutes for more than 1,000 X-ray sources covering the entire sky on time scales from a day to a few months. Continuously monitors astronomical X-ray objects over a broad energy band (0.5 to 30 keV). http://maxi.riken.jp/top/

Under construction

- **Astro-H:** is a facility-class mission to be launched (2015) on a JAXA H-IIA into low Earth orbit. It carries out a Calorimeter Spectrometer (XCS), providing non-dispersive 7 eV resolution in the 0.3-10 keV bandpass. Other three instruments include the Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5-80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends Astro-H's energy band to 300 keV; and the Soft X-ray Imager (SXI) expands the field of view with a new generation CCD camera. http://astro-h.isas.jaxa.jp/en/

- **eROSITA:** the primary instrument on-board the Russian "Spectrum-Roentgen-Gamma" (SRG) satellite which will be launched in 2016. It will perform the first imaging all-sky survey in the medium energy X-ray range up to 10 keV with an unprecedented spectral and angular resolution. It will cover the range 0.3-10 keV, with a resolution of 138 eV at 6 keV. The effective area is higher than in XMM up to 3 keV, but with lower resolution. http://www.mpe.mpg.de/eROSITA

- **ATHENA:** The Advanced Telescope for High-Energy Astrophysics is an ESA observatory type mission expected to be launched in 2028. Athena will address key aspects of structure formation and evolution from the epoch of re-ionization to the present and the still poorly understood and complex feedback processes involved. In particular, the heating history of the Universe due to both gravitational and non-gravitational processes, as well as the role of feedback from massive black holes to their host galaxies and in chemical evolution of the intergalactic and intracluster mediums will be studied. Detecting the typical AGN beyond z=6 and observing absorption lines from gas during the epoch of re-ionisation by observing bright z>6 gamma-ray bursts are key observations to investigate the formation and growth of the first black holes and the first stars. This X-ray telescope will combine unprecedented collecting area (2m2 at 1 ke V) with an excellent angular resolution (5") and a wide field of view (40'x40') . It will be equipped with two instruments: a wide field (5') instrument performing spectrally-resolved (2.5 eV) imaging over a broad energy band (0.31-10? KeV) and a very wide field imager (40'x40') with an energy resolution of 150 eV at 6 keV.

- **NICER:** The Neutron star Interior Composition ExploreR Mission (NICER) is a NASA mission dedicated to the study of the extraordinary gravitational, electromagnetic, and nuclear-physics environments embodied by neutron stars. NICER will enable rotation-resolved spectroscopy of the thermal and non-thermal emissions of neutron stars in the soft (0.2-12 keV) X-ray band with unprecedented sensitivity, probing interior structure, the origins of dynamic phenomena, and the mechanisms that underlie the most powerful cosmic particle accelerators known. It is planed to be launched in late 2016, to be placed in the ISS. The instruments will perform x-ray timing and spectroscopy. The effective area is up to twice that of XMM-Newton pn at 1 keV. http://heasarc.gsfc.nasa.gov/docs/nicer/

Proposals

- **Smart X:** SMART-X is a single-telescope X-ray observatory with 0.5" angular resolution, working in the 0.2-10 keV. The effective area expected will be 100 times (at 0.3 keV9 and 30 times (at 1 keV) that of Chandra. It will include a calorimeter. The gratings will reach R~5000 at less than 1 keV (well above Chandra), with 10" resolution. http://smart-x.cfa.harvard.edu/

- **LOFT:** The Large Observatory for X-ray Timing (LOFT) was a candidate mission for the M3 ESA launch. Discarded from the selection it is now in a frozen state. Main target is "How does matter behave under extreme conditions?" The main advantage is its high-time-resolution. It would cover 2-50 keV range. http://sci.esa.int/loft/

- **AXSIO:** Advanced X-ray Spectroscopic Imaging Observatory, a NASA concept for a broad-bandpass, high-sensitivity, high-resolution X-ray imaging spectroscopy mission.

- **Concepts http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html** Basically NASA focus their concepts in a notional calorimeter mission (N-CAL), a notional X-ray grating spectrometer, AXSIO (see below), a notional wide-field imager (N-WFI), and various combinations of these capabilities on a single platform.

- **Other missions from European countries, China and multinational collaborations are:** A-STAR, DAMPE, EDGE, GRAVITAS, MIRAX, NHXM, PheniX, XIPE.

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