Atacama Large Millimeter/ submillimeter Array - ALMA

Science Requirements and Compliance Status

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Plan for Work on Scientific Specifications Document

- Present version was approved in mid 2006 see **http://edm.alma.cl/tiny/5gmox.html**
- With considerable reluctance we have decided that we do need to update this.
- We need to do this before we can have the final(?) Systems Requirements Review which should be done a.s.a.p.
- This is a Board-level controlled document so, ASAC will need discuss any revisions carefully and approve the new version.
- I think we can only do that at our next face to face meeting but we will need to have a reasonably firm new version well before then so we can do the review.
- Perhaps a dedicated telecon on this?

Issues

- Present version of specification does not include ACA
- Trying to use the spec to hold managers to their individual requirements has shown that there are some weaknesses – e.g. polarization only comes up indirectly in the science discussion.
- Also have very few operational requirements like how long does it take to do things – e.g. software overheads – or what fraction of the time the system should be available.
- Calibration details are in a separate document (not actually approved).
- Following presentation was given to the ALMA Annual Review in November 2008

The Big Picture

- **NOT seriously at risk:**
  - Sensitivity, depends on: receiver noise temperature, number of antennas and their surface accuracy and observing efficiency
  - Angular Resolution, depends on: lengths of baselines and achieving reasonable phase stability.
  - Spectral Resolution and Frequency Coverage: “just” requires receivers, LO system and correlators all to work correctly.
- **Still some question marks:**
  - Imaging quality, depends on: layout of antenna configurations, stability of antenna pointing, stability of LO system and receivers, phase correction.
  - User friendliness – ALMA plans to be the first(?) synthesis telescope that is seen by non-specialists an easy instrument to use. Mainly a software and organizational question.

The Big Picture (2)

- **Not likely to be achieved with present approach:**
  - Calibration accuracy: requirements - absolute flux accuracy of 5% and relative accuracy of 1% up to 370 GHz and 3% at higher frequencies - are tough. We don’t yet have a design for the calibration loads that meets our requirements.
  - Polarization measurements: spec of 0.1% of total power is also very challenging. Individual systems, e.g. receivers, are not at present meeting the requirements and the plan for injecting polarized calibration signals has been dropped.
  - Overall operational efficiency: this is not well specified or estimated but there are lots of indication that it could be low.
- **Real Show-stoppers:**
  - No technical issues that are apparent to me.
  - Clearly the continuing slippages in deliveries and acceptance are damaging in terms of morale and planning and in a worst case scenario these could snowball into an unmanageable situation.

Review of Requirements: 1. "Purpose"

1. Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z=10;
2. Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the Universe;
3. Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales smaller than 300 light years.
4. Image gas rich, heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
5. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
6. Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects in the solar system along with images of the planets and their satellites;
7. Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

These are mostly generic but there are some specifics: item 3 implies 0.02 arc sec resolution for a QSO at 1 Gpc, item 7 requires pointing at the Sun.

2. “General Requirements”

1. ALMA shall cover all available millimeter and submillimeter atmospheric windows.
2. ALMA shall be able to observe in both narrow (``spectral line'') and wide (``continuum'') bandwidth modes.
3. ALMA shall maximize sensitivity over its frequency bands.
4. ALMA shall maximize the flexibility of spectral line capability.
5. ALMA shall maximize imaging capability, both as an interferometer and as a collection of single antennas, at both large and small angular resolutions.
6. ALMA shall be able to measure all polarization cross-products simultaneously.

Compliance

1. Not on day 1: Bands 1 and 2 left out. Only 6 band 5 receivers.
2. Yes
3. Close to or better than specs.
4. Certainly very flexible: tunable filter bank on 12m array and the ACA FX system
5. “Very Good” – with ACA better than original plan
6. Yes.

3. Level 1 Requirements

1. The ability to detect spectral line emission from CO or C II in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours of observation.
2. The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0.”1. Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

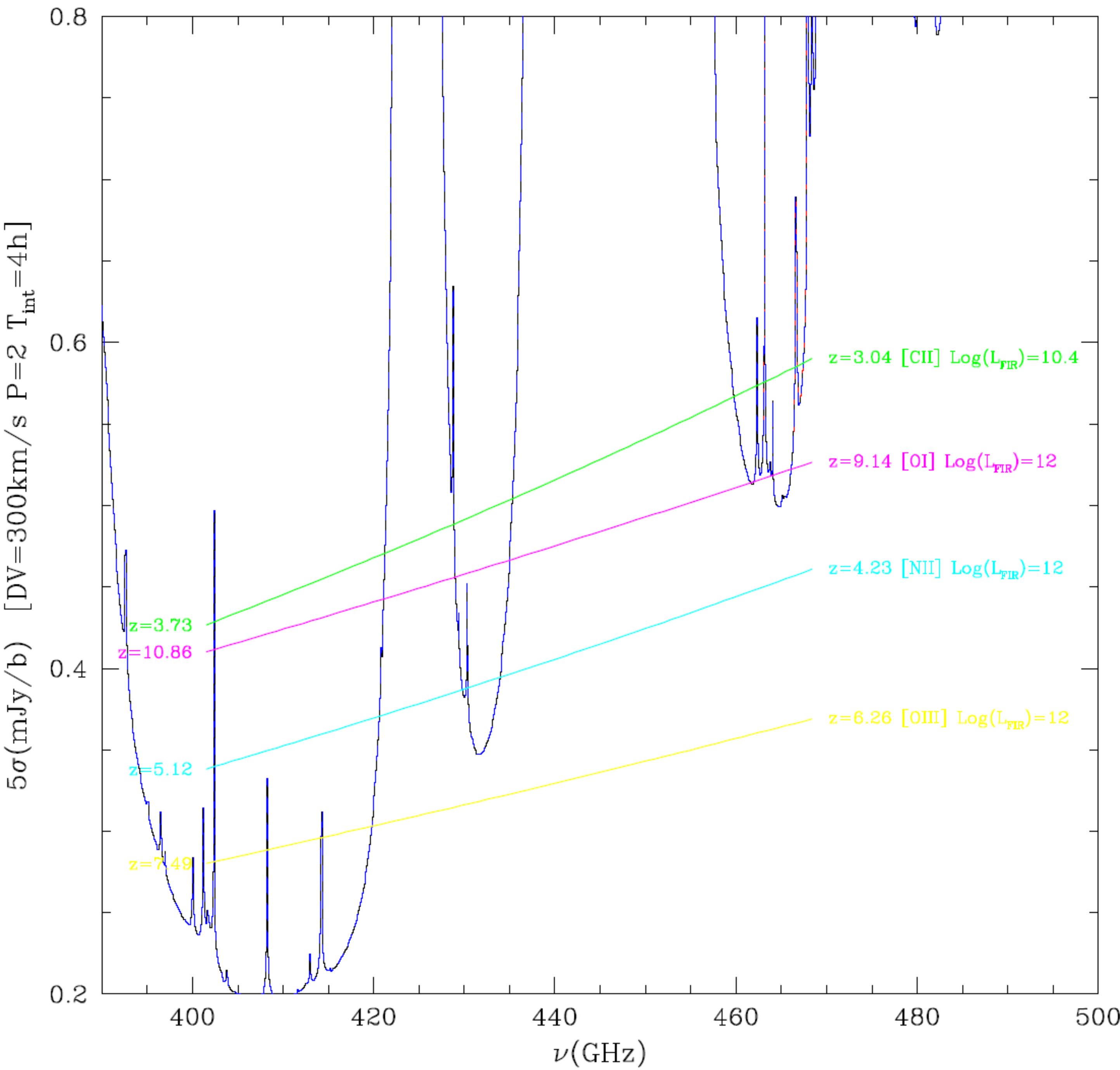
Level 1 Requirement 1

1. The ability to detect spectral line emission from CO or C II in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours of observation.

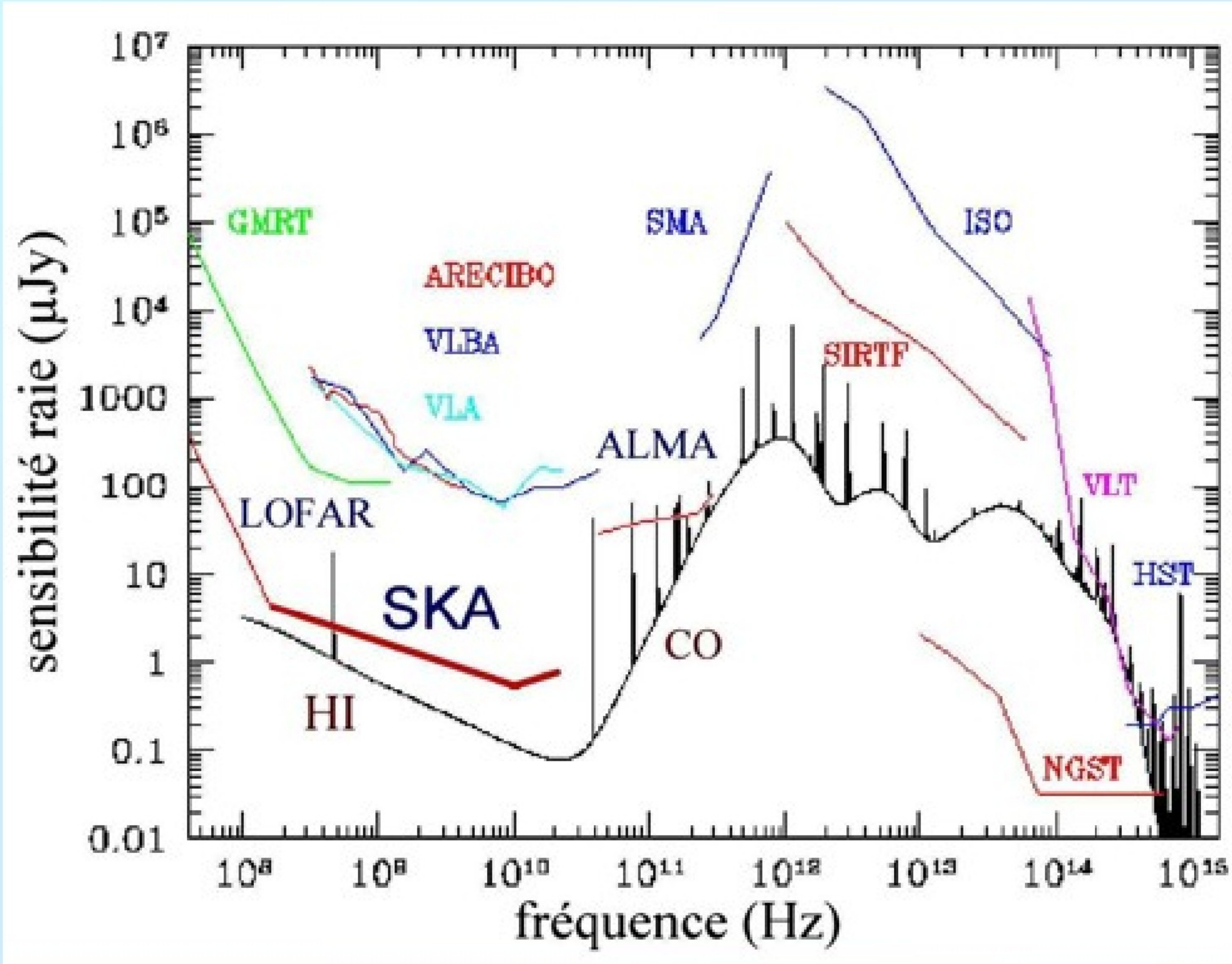
   If interpreted literally – i.e. we only have to detect either the CO or the C II – we are OK here because we should be able to do C II with some margin. Next plot shows five-sigma estimates for 4 hours integration for 300km/s resolution (or 16 hours for 75km/s resolution).

   I suspect however that the intention was to be able to detect both CO and C II and it looks as if we would miss the CO from the Milky Way by a factor of several. This is due to an accumulation of things: number of antennas, receiver performance, losses in warm optics and membrane and lower values now estimated for CO luminosity. Even the cosmology has gone against us since early estimates were made! I think the only strategy here is to keep doing as well as we can and not to let the “it’s only a couple of percent loss, so it doesn’t matter” idea creep in here and there and really add up to a lot.

Atomic lines in band 8



Plot by
F Combes



Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

5σ in 1hour

Level 1 Requirement 2

2. The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.

This requires good angular resolution – 0.01 arcsec gives 1.5 AU at this distance and this should be reached with the longest baselines at 300 GHz and with shorter baselines at higher frequencies. OK

Good imaging quality, dynamic range and brightness sensitivity are also required. We expect to meet all of these requirements.

This requirement also sets limits on spectral resolution and purity (e.g. line shape to derive kinematics). Again these should be OK.

More significantly this is the only top-level mention of polarization requirement ("magnetic field structures"). We are confident we will be able to provide good polarized images but the 0.1% given in the detailed specs is at risk – it has not been "flowed down" adequately.

Level 1 Requirement 3

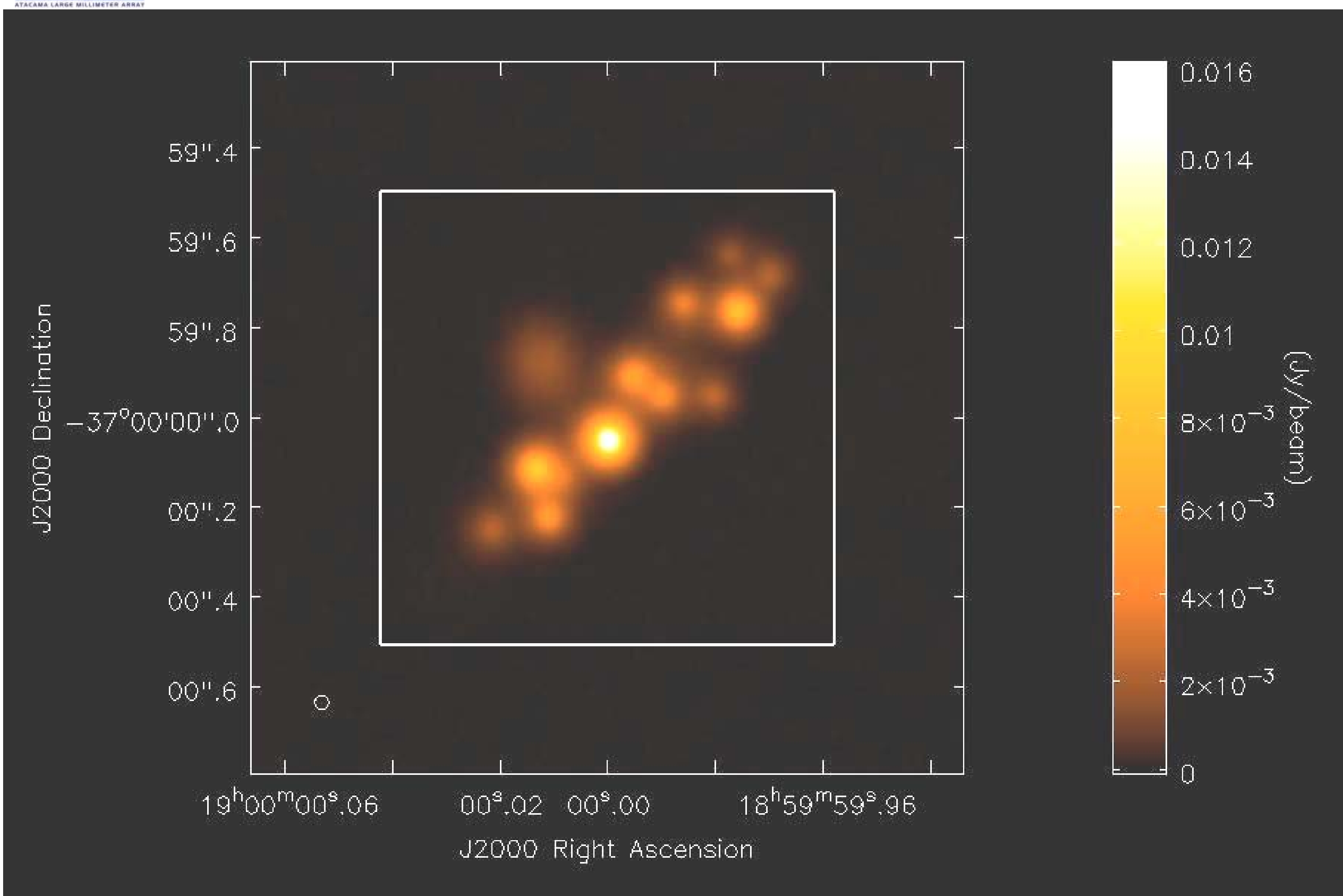
3. The ability to provide precise images at an angular resolution of 0.”1. Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

There seem to be some problems with the definition given here. a) Suppose we observe a source with a peak flux 0.1 Jy/beam and integrate for ~1hour at 230 GHz. The thermal noise should then be ~10 μJy/beam, so this spec requires a fidelity of ~10^4 on the peak and 10^3 at the 10% contour. Simulations show that even with a 50-element array it is hard to do better that a fidelity of a few hundred with “perfect” data – i.e. no instrumental or atmospheric errors. b) “Representing the sky” is ill-defined – at the very best one can only make a map which represents the sky observed with some ideal beam shape – e.g. a Gaussian described by some set of parameters – but no such definition is given. c) The elevation limit of 20 degrees is tough it means Declination -90 to +40.

Having said all this, I actually expect ALMA’s imaging performance to be very good by any standards – certainly far better than current mm arrays.

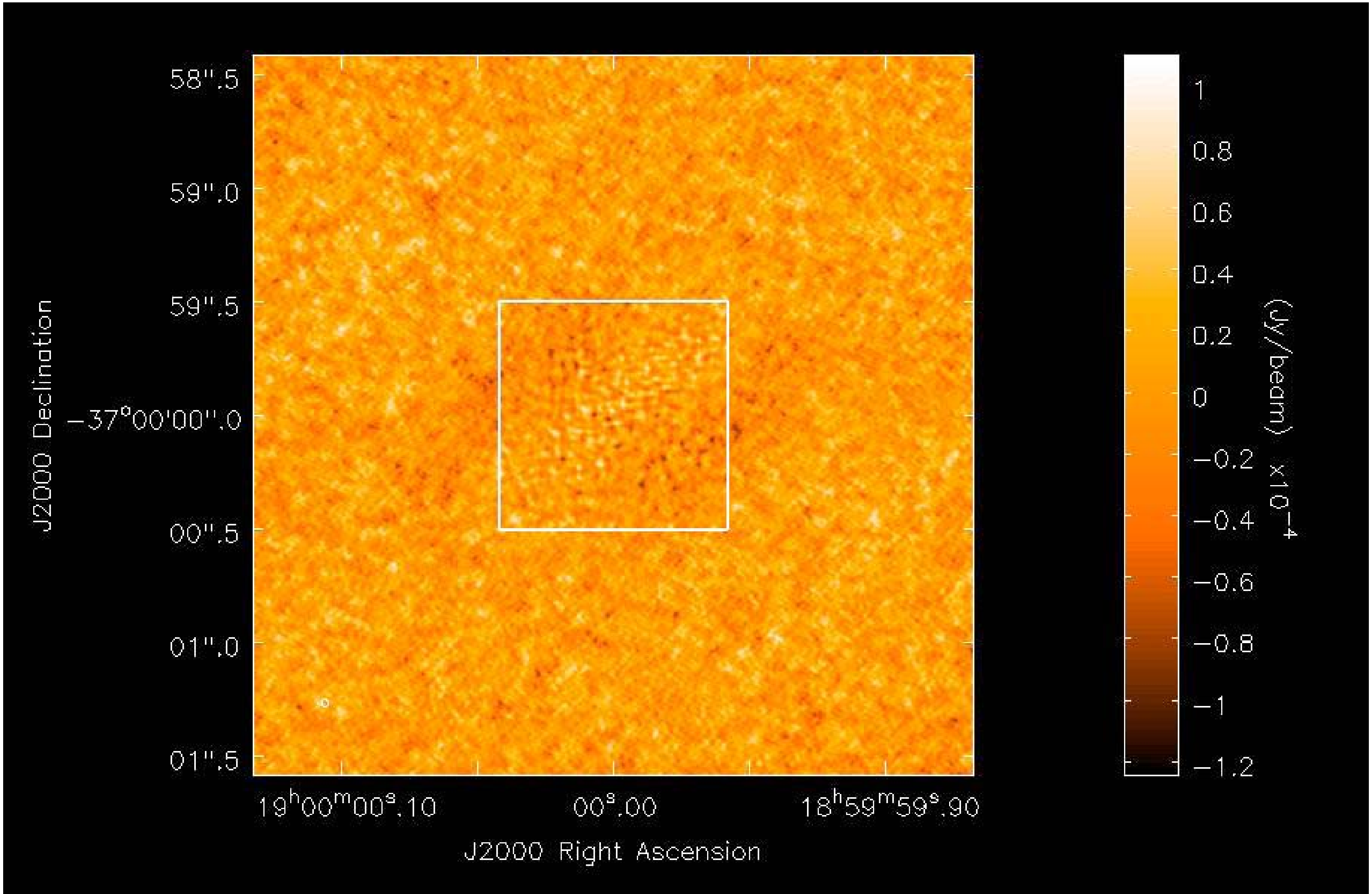
Again the issue is to keep paying attention to all the details.

Simulation of Imaging by Lewis Knee



Error Map

Rms in square is 27 microJy, c.f peak flux of 16 milliJy
So limit is ~2 parts in 10^3 with a perfect system – no errors



4. Detailed Requirements (first 5)

Compliance

Requirement Category	Specification	Number [SCI-90.00.00.00-nnn-00]	Compliance
1. Frequency	ALMA should be able to observe in all atmospheric windows between 31.3 and 950 GHz.		Yes
1.1 Bands	In order to achieve this technically, the receiving system shall be separated into 10 bands, of which four shall be built during ALMA construction: band 1 = 31.3-45 GHz; band 2 = 67-90 GHz; band 3 = 84-116 GHz; band 4 = 125-163 GHz; band 5 = 163-211 GHz; band 6 = 211-275 GHz; band 7 = 275-373 GHz; band 8 = 385-500 GHz; band 9 = 602-720 GHz; band 10 = 787950 GHz. Ref [RD2] Table 1.1, CRE81.	10	Yes (Bands 1 and 2 left out. Only 6 band 5 receivers)
1.2 Tunability	It shall be possible to tune ALMA completely across the observable windows, i.e., reach a spectral line transition at any arbitrary observable frequency.	20	Yes (by design)
1.3 Spectral resolution	It shall be possible to configure the correlator to achieve sufficient resolution (0.01 km/s) at 100 GHz to *resolve* thermal line widths.	30	Yes
1.4 Intraband tuning	It shall be possible to retune ALMA to a second frequency within a band from a first in the same band in a time not greater than 1.5 seconds. Switching frequencies (e.g. to cancel primary-secondary standing waves of this frequency) shall take no more than 10 ms. Note that this applies to Total Power Modes when switching within (rather than between) bands.	40	Yes (by design) Software ?
1.5 Interband tuning, second band ready	It shall be possible to retune ALMA to a new frequency in a different band that is currently on standby (``warm'') in a time not greater than 1.5 seconds; there shall be two standby bands in addition to the band currently employed for array observations.	50	Yes 2 standby bands?

Detailed Requirements (next 6)

		Compliance
1.6 Interband tuning, second band unready	It shall be possible to retune ALMA to a new frequency in a different band in a time not greater than 15 minutes.	60 Yes
1.7 Spectral dynamic range	The required spectral dynamic range is 10000:1 for measurement of weak spectral lines in the presence of stronger ones, and 1000:1 for weak lines in the presence of strong continuum emission.	70 some problems
1.8 Image dynamic range	The required image dynamic range, for small sources in a single larger field, is 50000:1, peak to rms with self-calibration in interferometric mode.	75 ??
2. Sensitivity	ALMA shall maximize sensitivity over its frequency bands	
2.1 Flux sensitivity	ALMA shall routinely obtain sub-millijansky point source sensitivity at all observing frequencies, within ten minutes of integration time, under median atmospheric conditions (τ=0.082, [RD33]) in Interferometric Mode. (in 600s, expected zenith sensitivities are B3: 0.01mJy; B6: 0.02 mJy; B9: 1.0 mJy)	80 Yes (very loose spec)
2.2 Site	ALMA shall be sited at the Llano de Chajnantor, to take advantage of the extremely dry and phase-stable conditions there, which derive from the transparent and stable atmosphere over the site.	90 Yes !
2.3 Antenna complement	ALMA shall be comprised of 64 12-m antennas (see Appendices).	100 No !!

Detailed Requirements – Polarization

			Compliance
4.0 Polarization	ALMA shall be able to measure all polarization cross-products simultaneously		Yes
4.1 Signal measurement	It shall be possible to measure all polarization cross-products simultaneously in interferometric and in autocorrelator total power modes.	310	Yes (by design)
4.2 Polarized flux error	The error in polarized flux for a source where the circularly and linearly polarized fluxes are zero shall be no more than 0.1% of the total intensity on axis after calibration.[5]	320	Unlikely
4.3 Polarization position angle	It shall be possible to determine the position angle of linearly polarized flux density to 6°.	330	Probably
4.4 Relative polarization channel stability	Sensitive polarimetric interferometric observations require system stability in the independent polarization channels. To measure polarization accurately in interferometric mode to 0.1% levels requires a differential gain stability between the two polarization channels of better than 1×10^{-3} in 5 minutes, the typical time between which calibration of instrumental polarization can be performed. This applies to all receiver systems.	345	Problem here is that this is only defined in time and not by elevation

- There are a number of issues here including the polarization performance of the front-end cartridges, most of which do not currently reach the goals set for polarization purity, the system stability as a function of elevation, which is critical for polarization calibration, and the lack of a device for injecting signals of known polarization.

Detailed Requirements (last 8 of 42)

			Compliance
5.0 Calibration	The final visibilities shall be on a calibrated flux density scale, accurate to within 5% at all frequencies in all modes.	350	Not likely
6.0 Other			
6.1 Solar	It shall be possible to observe the Sun at all frequencies.	360	Yes, but [1]
6.2 Phased Array	It shall be possible to phase up the array, with provision of an output sum port, either hardware or software.	370	No
6.3 VLBI	It will be possible to use ALMA for VLBI, both with a single element, or with phased array (or subarray) output, at frequencies TBD although the electronics for realization of VLBI performance are not included in the ALMA construction plan. The accuracy of phasing up shall be TBD.	380	No (removed at rebaselining)
6.4 Subarrays	It shall be possible to have at least four subarrays in which the observing frequency and antenna control in each is completely independent of the others.	390	Yes (by design)
7.0 Software			
7.1 Ease-of-use	ALMA shall be ``easy to use'' by both novice and expert astronomers. (Ref [AD1], p 15.)	400	Still goal
7.2 Software tools	ALMA shall provide tools for preparation of proposals, preparation of observations, and reduction of data.	410	Yes
7.3 Data Reduction	There shall be a standard data reduction performed for most projects successfully completed, resulting in a properly calibrated image cube (the ``pipeline''). This shall require minimal input from the astronomer in most cases.	420	Yes but not in early days.

[1] there are some issues about the requirements for the solar filter

Summary of Detailed Requirements

- In general we are in reasonably good shape on these – most of the areas that I see as real problems have already been mentioned.
- In general however these are a rather unhappy mix of generalities "ALMA shall maximize sensitivity over its frequency bands", numbers that are somewhat arbitrary "ALMA shall be comprised of 64 12m antennas" and very detailed, design-dependent points:

  "For on-the-fly observations (0.5 degree/s) at 950 GHz, the beam crossing time is 3.3ms. Oversampling the Nyquist rate to keep loss of signal-to-noise ratio below 1% requires analog total power continuum sampling of 0.5msec or faster."
- I am also aware of quite a few issues that are not properly covered by the present Science and Systems requirements combined. Examples are: the contribution of the front-ends to pointing errors, the effects of receiver beam alignment on imaging quality and, more generally, the need to limit the overheads on the observing time due to software, system response and calibration.
- We are currently discussing whether, at this late stage, a substantial restructuring of the requirements would do more harm than good.

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The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership among Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).