

ALMA Newsletter

April 2010



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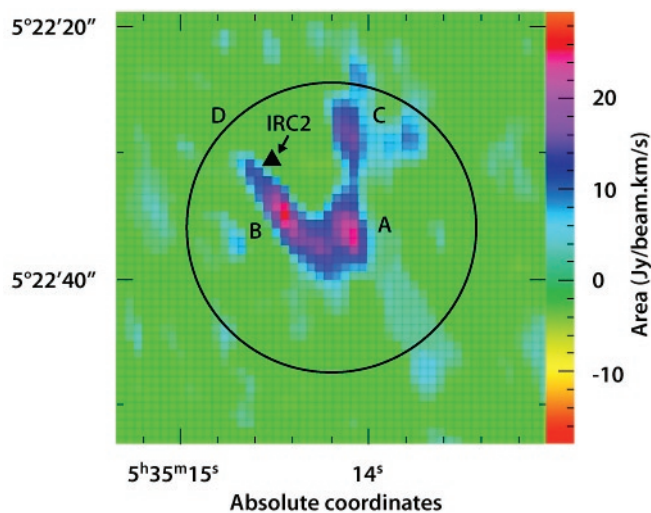
ALMA In-depth

How Will ALMA Make Images?

The invention of the optical telescope by Galileo 400 years ago marked the beginning of modern astronomy. Galileo used glass lenses mounted in a tube to construct his telescope. This allowed him to collect more light and to distinguish details that could not be seen with the unaided eye. The same principle applies to any single aperture optical telescopes such as the ten meter

diameter Keck telescope, the 8 meter Subaru telescope on Mauna Kea, or the four 8-m units of the Very Large Telescope on Paranal: they allow us to investigate very faint optical phenomena whose details cannot be studied with the unaided eye. The evolution of optical instruments also includes detector systems: first the unaided eye, then photographic plates, and today Charge Coupled Devices (CCDs) or detectors that are sensitive to “invisible light”, such as X-rays, UV and Infrared Radiation, and radio waves. Fluctuations in the earth’s atmosphere smear images, but astronomers have learned to improve image quality by techniques such as adaptive optics or speckle interferometry.

However, even if one could control all the effects of the atmosphere, the ultimate limit of all optical (this includes the “invisible light” mentioned above) instruments is determined by the ratio of wavelength to diameter of the instrument. For example, the highest angular resolution in the visible light with a single aperture is achieved with the Hubble Space Telescope (HST), which operates above the atmosphere: it is 0.04 arcseconds, which corresponds to two objects separated by 80m at the distance of the Moon. The ability to distinguish between two sources is referred to as the “angular resolution”.



The circle marks the angular resolution of the IRAM 30-m radio telescope at this frequency (101.5 GHz). The detail seen is because the interferometer has a much higher angular resolution since the maximum distance between antennas is of order 1 km, giving a beamsize of 3.3” by 1.7” as compared to the 23” beam of the IRAM 30-m single dish. The letters mark the locations of maxima found in ammonia emission.

ALMA Newsletter

April 2010

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ALMA In-depth

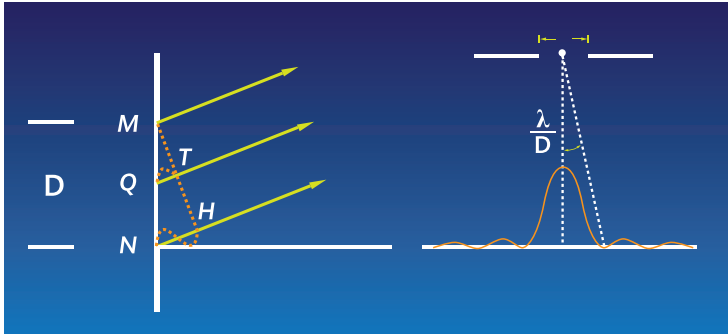


Fig. 1. A sketch designed to illustrate the concept of angular resolution. The size of the aperture in mm is D , and the wavelength of the wave, also in mm, is λ . There are two distant sources. The first is on axis, and is not shown for clarity. Waves from this source reinforce to produce the maximum as shown on the right. Waves from a second source pass through the aperture at an angle θ so have the same phase on the line MTH . At this angle θ , the waves at HN and QT have opposite phase, since QT is going negative whereas NH is going positive. This argument can be applied to pairs of waves. If we choose these at equal distances above the positions of HN and QT , the sum of the pairs is zero. The result is that the response is zero at an angle (measured in arcseconds) $\theta = 206000\lambda/D$ where λ and D have the same units. This so-called diffraction pattern is shown on the right. Such a pattern will smear the fine details of any image; the amount of smearing depends on the ratio of wavelength, λ , to aperture, D . In addition to this response, there are smaller secondary maxima, the sidelobes, as shown in the diagram on the right.

To understand this fundamental limit, we assume that the first source is located exactly along the axis of the telescope tube, while the second is slightly offset from this axis. The angular resolution is determined by summing the light (visible or invisible) waves from these two sources as these reach the detector (see Fig. 1).

Any telescope, and our eye as well, works according to the same principle: A light wave that reaches the telescope along the axis of its tube is shaped by a lens, or a mirror, so that it reaches a certain point in the telescope, so called focus, in such a way that regardless of the way the light takes within the telescope, the waves add up. The best example is a burning glass. Radiation also arrives at other points near the focus (the focal plane), but here the light travelling through different parts of the telescope does not completely add up, and in the worst case, wave minima and maxima cancel each other out to produce a zero signal. The larger the telescope mirror or lens (the "aperture") is, the smaller is the image of a very compact light source on a CCD or photographic plate.

A second point like source in the sky that is displaced from the axis of the telescope tube by a small angle will be focused at a slightly different location on the CCD or photographic plate. We can distinguish it only from the on-axis source if this difference in locations is larger than the size of the diffraction pattern of the two sources. In the opposite case, the two diffraction patterns will smear out in single blob. The minimum separation angle that two sources must have in order to be separated by a telescope only depends on one quantity: the ratio between the wavelength of the observed radiation λ and the diameter of the telescope's lens or mirror D . The so called angular resolution in arcseconds is given by approximately $\theta = 206000\lambda/D$, where both λ and D are in mm.

Thus, a 12 meter diameter radio telescope, such as an ALMA antenna, receiving radiation at $\lambda = 3\text{mm}$ has about the same ability to distinguish two sources in the visible with the human eye, namely about 50 arc seconds (this angle would allow us to recognize features on the face of a human at 100 meters). The angular resolution is the same because the wavelength of light is about sixteen thousand times smaller than the 3 mm wavelength, but the aperture of the radio telescope is sixteen thousand times larger. This comparison highlights a problem of radio astronomy: since radio waves are much longer than visible light, the telescope diameter must be correspondingly larger to obtain the same angular resolution. Nevertheless, measurements



ALMA Newsletter

April 2010

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ALMA In-depth

in the mm/sub-mm wavelength region are essential for investigating the coolest components of outer space such as cold and dusty molecular clouds, where star formation is occurring. Only longer waves can escape from such regions, since visible light is absorbed and scattered by dust.

ALMA can operate at a wavelength as short as 0.3 mm. However, to resolve features in a planet-forming disk around a star like the Sun, one finds that ALMA must have a total extent, D , of 16 km. The angular resolution of ALMA is then 0.004 arc seconds (this is the apparent size of a truck at the distance of the Moon). This even exceeds the resolution of the Hubble Space Telescope. Over the 16 km distance, the intensities must be combined with an error

of less than two hundredths of a millimeter (1/16 of a wavelength) to produce accurate images. To reach this accuracy with a single mechanical structure on earth is beyond the limits of technology. There is another approach, illustrated in Fig. 2. Now parts of a single aperture are covered with non-reflecting material, except for two regions.

The waves reflected by the two apertures have a small time delay due to the speed of light. When these are combined, the angular resolution is given by the ratio of wavelength to the *separation* of the two reflecting regions. The result is that: (1) the width of the maxima depends on the separation, and (2) since the two uncovered regions are small compared to the total size of the antenna, the sidelobes (Fig. 1) are as large as the main lobe. In this example, the maxima and minima are referred to as “fringes”. In other words, constructive or destructive interference depends on small changes in source positions with respect to the axis of the antenna.

As shown in Fig. 2(c) and (d), when the distance between the two uncovered regions is larger, the fringe spacing is finer in angle. Deviations from the calculated response can be used to determine source positions to a small fraction of a fringe. The waves reflected from the uncovered regions must be aligned to produce these fringes.

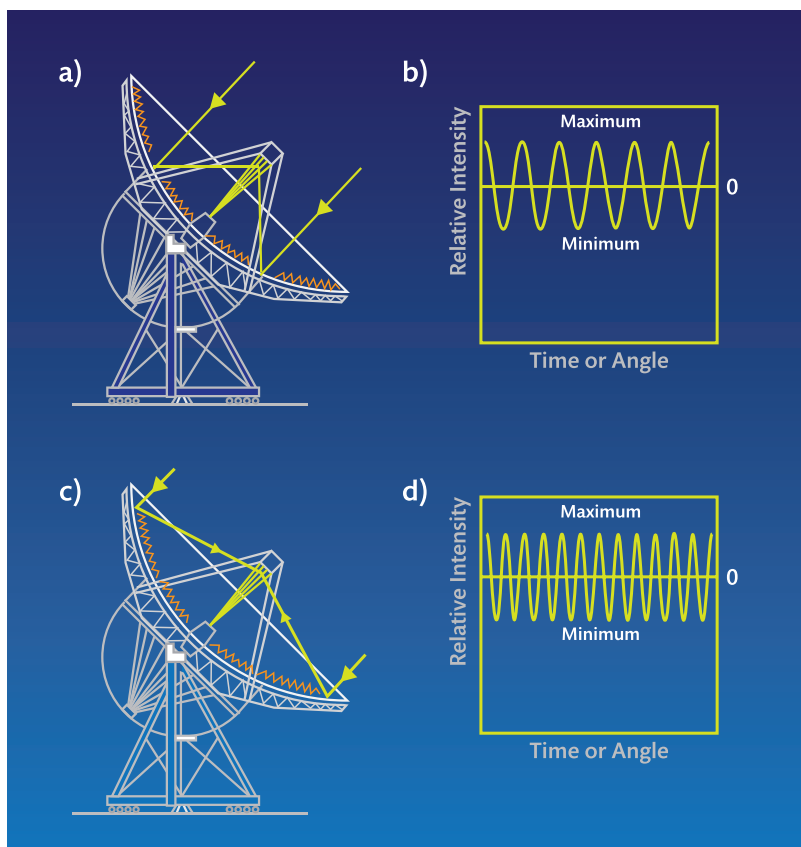


Fig. 2(a). The diagram on the upper left shows the filled aperture instrument with most of the main reflector surface, $M1$, covered with absorbing material. In this illustration, two regions are not covered. Then the power from a radio source is reflected only from these two regions, and then combined at the receiver. As shown in (b) in the upper right, the response is a series of maxima and minima with the same intensity, referred to as “fringes”. The outputs of the two elements are arranged so that the maxima and minima are symmetric about the zero level. This is the usual measurement method with interferometers. In part (c) the two uncovered regions are more widely spaced. The result is a set of more finely spaced fringes, as shown in (d), which gives a finer angular spacing between maxima or minima.

ALMA Newsletter

April 2010

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ALMA In-depth

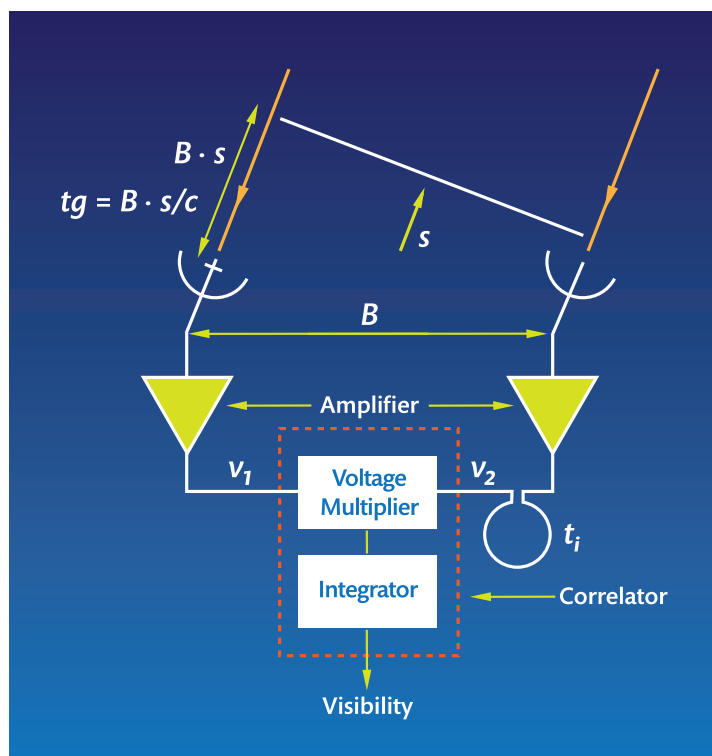


Fig. 3. Shown is the schematic of a two element interferometer. This consists of individual antennas whose size is small compared to their separation or “baseline”, B , projected in the direction of the source (this is analogous to the distance D in Fig. 2 but B changes as the source moves across the sky). In this illustration, the inputs are amplified at each element then combined in the Voltage Multiplier. The result is the visibility, that is, the response of the instrument, as a function of the baseline. The output is summed over a short time in the Integrator. It is usual to adjust the time delay, τ_i , electronically so that the waves reaching the voltage multiplier are aligned, that is, in phase; thus the mechanical alignment of a reflector is replaced by an electronic alignment. As the source rises and sets the projected baseline changes. Thus the measurement of a source at different times is made with different projected baseline spacings, so additional measurements of source structure and position are possible.

Slightly changing this scheme, we can replace the single large aperture of diameter D by two small antennas (each with its own receiver) of size $d \ll D$, separated by a distance D . Such an arrangement is simpler to achieve than one large mechanical structure. Then one obtains the angular resolution of a single aperture with a diameter D . By varying the separation, one can obtain an estimate of the source size and position that is more accurate than a filled aperture of diameter D , since the positional accuracy depends on timing which can be very accurate, rather than mechanical stability which is subject to external conditions such as wind and temperature. In the following, we change notation, replacing the separation of the regions “ D ” by the baseline “ B ”.

The outputs of the small antennas are aligned by electronic means, which is easier to control than the mechanical alignment of a single large antenna that would have the size of the separation B . The usual practice is for these small antennas (each of diameter $d \ll B$) to track a source as it moves across the sky. By varying the antenna separation B , one finds that for some sources the response changes. That is, the difference of maximum and minimum divided by the sum of these (*the source visibility*) will change with antenna spacing.

So far in this presentation we have shown how one can determine the position and size of a radio source with a two element interferometer. One could imagine moving the antennas, so the source is measured with different baselines, and in addition, one could measure the source from rising to setting, thus allowing for a number of different projected

baselines. In the early days of radio astronomy, this approach only allowed one to distinguish between some very simple possibilities such as a single source, a double source, or extended doubles but it was *not* possible to obtain images. With multi-antenna arrays, the approach can be different, and the models more complete. In the following we indicate how mathematics can be used produce images, like those produced by optical telescopes, as shown in Fig. 4. This requires a more elaborate framework. To prepare this, we first present a number of details that are needed.



ALMA Newsletter

April 2010

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ALMA In-depth

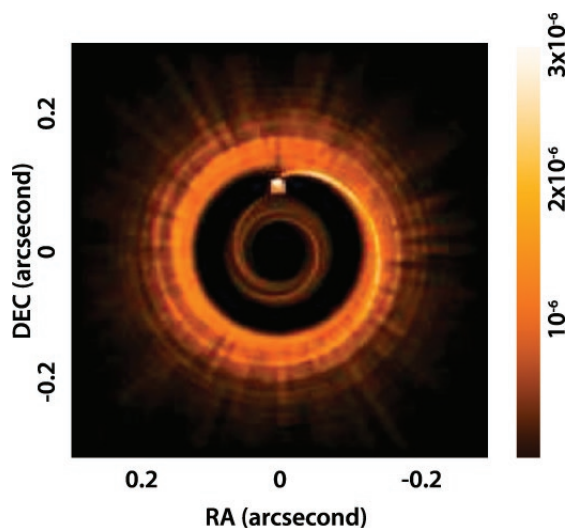
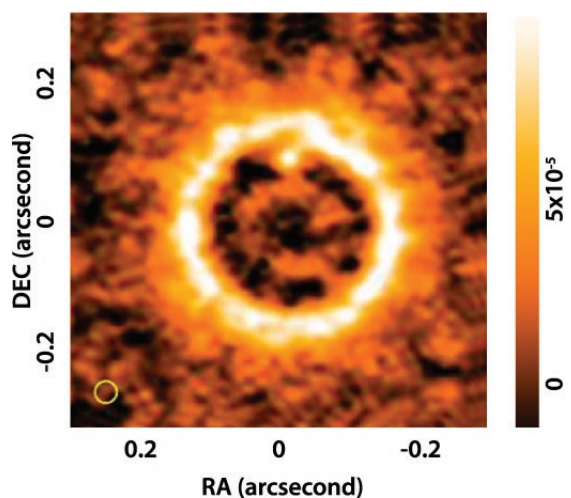


Fig. 4. Here we show a simulation to illustrate the imaging quality of ALMA. On the left is a model image of a proto-Jupiter embedded in a proto-planetary disk. On the right, we show the result of imaging this region with ALMA in an extended configuration after 8 hours. The measurement is carried out at a wavelength of 0.8 mm, so the angular resolution is 0.02 arc seconds (the beamsize is the small circle in the lower left). At this resolution, the disk is clearly imaged, but the details of the ring structure are smeared. Measurements made in a shorter time or with fewer antennas will be worse.

Geometry plays a large role in interferometry. The baseline, that is, the distance projected in the direction of the source in Fig. 3, changes as the source moves a function of time. For two antennas arranged on an East-West line, when the source rises or sets, the baseline projected in the direction of the source is small. When the source is higher in the sky, this baseline length is larger. A sketch of the projected baselines, as a function of time, for a two element interferometer is shown in Fig. 5.



For radio interferometers, it is possible to divide the amplified output of each antenna without seriously degrading performance, so the output of a given antenna can be combined with the outputs of many other antennas. This pair-wise combination allows simultaneous measurements of a source. This is much faster than changing the separation of two antennas. In the ALMA 12-m array, such a pair-wise combination is done by a specially designed computer, the correlator (which is used for a complex comparison of outputs), which can combine the outputs of 1225 antenna pairs.

The data arranged on a rectangular grid in the (u,v) plane are shown in Fig. 5. These results were taken with a three element interferometer. The baseline for A-C is larger than for the baseline A-B, so the visibilities are at a larger distance from the origin of the (u,v) plane. With 3 antennas, one can measure three independent sets of positions in the (u,v) plane: A-B, A-C, B-C. In Fig. 6, we show filled squares to represent the three sets of data.

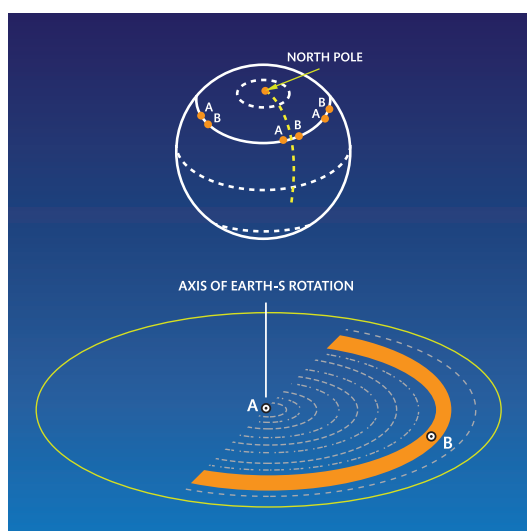


Fig. 5. In this example, the two elements of the interferometer are arranged on an East-West baseline on earth. We assume that the separation of the interferometer elements is small compared to the size of the earth, so the geometry can be two dimensional, that is, flat. For clarity, the radio source is assumed to be in the direction of the north celestial pole. The baseline length (divided by wavelength, and projected in the direction of the source) can be separated into two orthogonal directions, referred to as "u" and "v". Placing measurements in the (u,v) plane is the standard method used to arrange the response of the interferometer.

ALMA Newsletter

April 2010

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ALMA In-depth

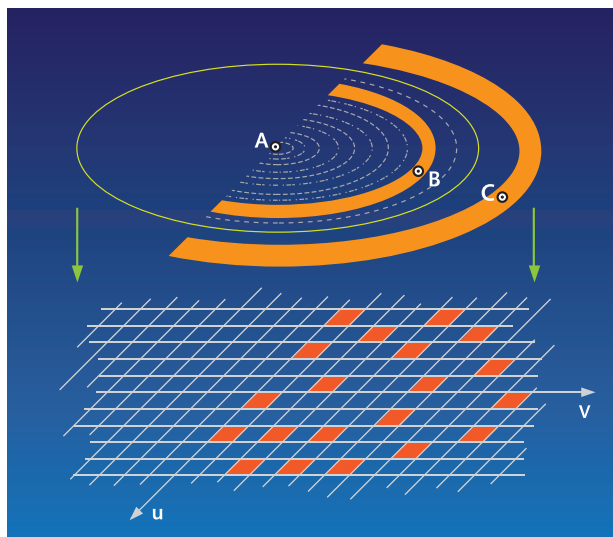
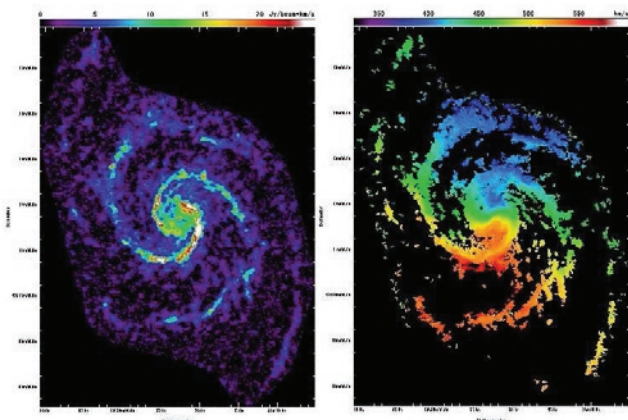


Fig. 6. In this two part plot, the upper part is the spatial location of three elements of an interferometer with antennas labeled A, B and C. As in Fig. 6, as the source moves across the sky, the response of the interferometer traces a path in the (u,v) plane. Shown below is a rectangular grid where the visibility data, shown as black squares. This is the (u, v) plane. The units of (u,v) are antenna spacings in wavelengths. Closer to the origin, $(u, v)=(0, 0)$, are from B-C, while those further are from A-B and are furthest from the origin are those from A-C. There are gaps in the center of the (u, v) plane since the spacing of the antennas is larger than the size of each antenna.

In the mm/sub-mm wavelength region, atmospheric effects, especially changes in the water vapor content, can smear images. This is similar to the apparent motion of stars in the visible (so-called “seeing”). In addition, there may be changes in the instrument during a measurement. Corrections for such effects are possible. With three antennas, it is possible to find improvements in the phases of astronomical signals since the relative phase of antennas A and B minus the relative phase of antennas A and C must equal the relative phase of antennas B and C. This is referred to as “phase closure.” With four antennas, similar corrections can be found for amplitudes; this is referred to as “amplitude closure”. With ALMA, there are many more than 4 antennas, so these procedures are even more effective.

In the case of ALMA, corrections for the time delays relative to an assumed position for a source are continuously applied. These are referred to as “phase tracking.” Thus, although one speaks of “fringes”, this is only a historical term leftover from the early days of interferometry. At ALMA, measurements using the two element interferometer system at the Operations Support Facility (OSF) results in a pair of plots of source amplitude and phase. For these tests, unresolved sources are used. If the time delays are correct, the amplitude response and phase response should be constant. These measurements are meant to test the performance of the system, including stability, sensitivity and behavior of time delays. At the ALMA Array Operations Site (AOS) at 5 km elevation, the outputs of more than 50 antennas will be combined pair wise, to give more than 1225 products simultaneously. Then the analysis becomes less simple, but still understandable on the basis of the previous examples.

If all of the (u,v) plane can be filled with data, one can, after some mathematics, obtain almost the same detail as that measured with a filled aperture of the same size.



This is a false color plot of the integrated emission of the carbon monoxide rotational transition between the first level and the ground state of the molecule from Messier 51 (=NGC5194).

The carbon monoxide is thought to represent the distribution of the molecular hydrogen, which cannot emit at low temperatures. These results show the positions of Giant Molecular Cloud Associations where stars will be formed. These data are a combination of the single dish data from the Nobeyama 45 meter telescope combined with the interferometer data from the Combined Array for Research in Millimeter Astronomy (CARMA). The CARMA data consist of data from 151 individual positional measurements covering a 6 by 8.4 arc minute region. The angular resolution of the image is 2.2 arc seconds.

Credit: J. Koda et al. (2009 ApJ 700, L132)

ALMA Newsletter

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ALMA In-depth

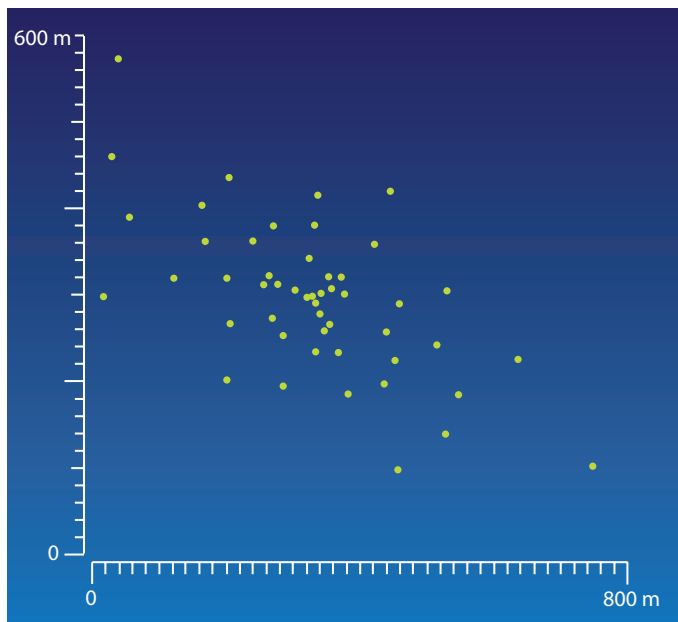


Fig. 7. The locations of the antennas in the ALMA 12 meter array at the AOS are shown as small circles, for so-called "configuration 10". The extent of the vertical and horizontal coordinates is shown in the plot. For the formation of images, the data are taken by correlating (a complex comparison) signals between pairs of these antennas. When the interferometer is used to measure a source from rising to setting, a larger region in the (u,v) plane is filled (see the lower part of Fig. 6). Because more of the (u,v) plane is filled, the image quality will be better. However, not all of the locations in the (u,v) plane will be filled, so the uncorrected image, even for 50 antennas in the 12-m array, is affected by instrumental effects.

In Fig. 7 we show a plot of the antenna positions for ALMA in a typical configuration as dots. The (u,v) data from this are the products of the outputs of pairs of antennas. These are arranged on coordinates in the (u,v) plane that are the spacings (i.e. relative positions) of the antennas. Thus, the antennas at the center of Fig. 7 are closely spaced, so the (u,v) data are near the origin, while the products of all antennas with those at the top and to the extreme right of this plot are further from the origin.

In many cases, the astronomical source is measured from rising to setting. Then in the (u,v) plane, the positions of the individual ALMA elements will appear to rotate, so more of the (u,v) plane is filled. The ideal is to fill the entire (u,v) plane with data, so that this sampling reproduces that which one could obtain with a filled aperture. However, even tracking a source from rising to setting and measuring a source in many configurations, there will still be

gaps in the sampling. More typical are the beams produced by short integrations (in this case 5 minutes) as shown in Fig. 8. Compared to a single dish beam, this has much larger instrumental effects, but to some extent, images can be corrected further for the missing data.

It is expected that there will be some degradation of images caused by atmospheric effects or instabilities in the instrument. To reduce such degradations the ALMA antennas will rapidly measure an astronomical calibrator followed by a longer measurement of the target source. In addition, there will be sensors to measure the atmospheric water vapor content above the antennas. These will be used to correct for phase shifts caused by small pockets of water vapor, which affect incoming astronomical signal. Taken together all of these corrections will allow ALMA to produce the best possible images. For the shortest wavelengths to be used at ALMA, this is equivalent to a length of 20 micrometers. However the diffraction effects shown in the right side of Fig. 4 will be the ultimate limit on the detail that one can measure.

Even if all of the corrections for instrumental and atmospheric effects are made, the ALMA beam will be as shown in Fig. 8 upper panel. The somewhat large sidelobes, caused by an incomplete coverage of the (u,v) plane, will give rise to inferior images. Post-data-taking corrections can be applied to improve the images.

From the preceding, one can understand that an interferometer that consists of many identical elements can image details of a source down to angular scales determined by the largest spacing of the individual antennas. However, there is also a limit determined by the closest spacing between antennas. Since these may not touch, this spacing is 15 meters for the ALMA 12-m array. At a wavelength of 3 mm, this corresponds to an angular scale of 50

ALMA Newsletter

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ALMA In-depth

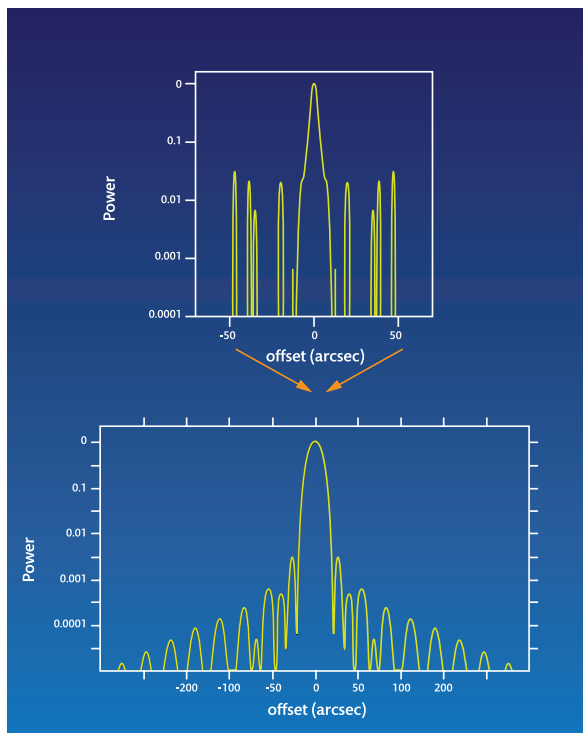


Fig. 8. Shown above is the cross section of a simulated ALMA beam produced after a 5 minute integration with the antenna positions shown in Fig. 10. The beam can be thought of as the image of a very compact source. This determines the detail that one can image. This plot was made for a wavelength of 1 mm. The vertical scale is in powers of ten to accommodate the large range in intensity. This causes some distortion in the width of the sidelobes. The full width of the main beam is 0.3 arc seconds. The peaks beside the main beam are sidelobes; these are caused by the incomplete sampling of the (u,v) plane. The peak power in the highest sidelobe is about 1/40 of the power in the main beam. This beam is produced by the fifty 12 meter antennas of ALMA. In addition, the Atacama Compact Array (ACA), consisting of four 12 meter and twelve 7 meter antennas will improve the shape of this beam by lowering the sidelobes and recording all of the source flux density. That is, use of the ACA will improve the shape of the ALMA beam but will not improve the angular resolution of ALMA. Shown below is the cross section of the beam of a single 12 meter filled aperture at a wavelength of 1 mm. The main beam has a full width to half power of 20 arc seconds, that is, 66 times larger than the beam produced by ALMA at 1 mm. However, the power received in highest sidelobe is 1/400th of that in the main lobe. Thus, the unfilled ALMA array produces a higher angular resolution, but with the drawback of larger instrumental effects. The lines connecting the upper and lower panels show the relation of the angular scales. That is, the single dish telescope has a much worse angular resolution than ALMA, but the instrumental effects present in an ALMA beam are larger than those in a single dish beam.



arc seconds. Source structures larger than this will not be recorded. Since one of the high level ALMA science goals is to produce excellent images, this is a severe restriction. To overcome this limitation, the ALMA project has been extended to include the "Atacama Compact Array" or ACA. The ACA consists of an interferometer consisting of 7 meter diameter antennas (the "ACA 7-m array") together with single 12 meter antennas for total power (ACA TP Array). Use of this combination of smaller antennas and interferometry provides the response to extended emission. Simulations of the response of the ACA allow an estimate of the performance. The result is the response of the combination of the ACA with the 12 meter interferometer array as shown in Fig. 9.

From Fig. 9, the response of the ACA four 12 meter Total Power antennas (in the TP Array) is about a factor of two below the response of other parts of the system. In part this is caused by the smaller number of antennas in the TP Array. To equalize the responses, the ACA must spend four times as much time on a specific source. Thus, the ACA must be scheduled independently of the 12m Array.

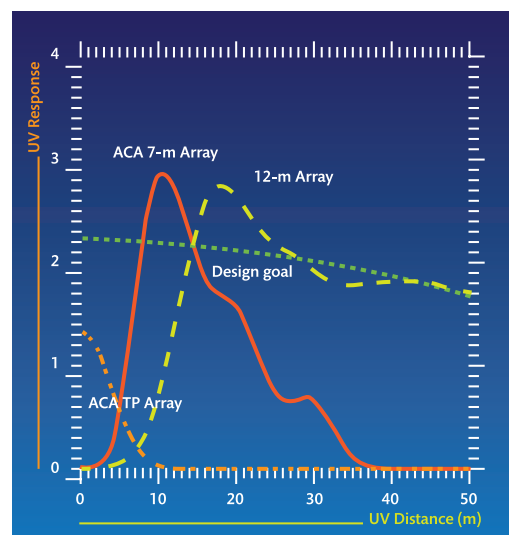


Fig. 9. This shows the response of the ALMA instrument to sources of extended source emission. There are three components: the ACA 12m Array which consists of the antennas in the interferometer array (response is shown as a dashed line), the four ACA 12 m antennas used for total power measurements (their response is shown as a dash-dotted line), and the twelve 7m antennas (their response is shown as a solid line).