Requirements for an Artificial Source on the ALMA Site

It is proposed that we place a small low-powered millimeter-wave source on one of the peaks overlooking the ALMA operations site. This will serve several purposes:

1) to provide a signal for interferometric holography measurements of the antenna surfaces
2) to provide a source of known and preferably changeable polarization so we can measure the polarization properties of the system and of the antennas
3) to provide a source with high signal-to-noise ratio to help measure things like coherence, phase stability, switching times and perhaps stability and sideband ratio.

Fortunately these different purposes produce a generally compatible set of requirements. The intention of this note is to derive the main requirements and to outline possible designs.

One important point to note is that for all the tests above it is planned that the observations will be made interferometrically. This places a requirement on the software in that it must operate correctly with two non-standard conditions:

a) the source does not move, so the fringe rate is zero and the delay does not change

b) the pointing position is different for each antenna and so is the delay value. (We will be able to calculate these values from the known positions of the antennas and the source.)

I don't know whether these capabilities are already in place but if not I hope that it will be relatively easy to incorporate them.

Location

The obvious place to put the source is on Chajnantor peak. There will be a clear view from almost all of the pads in inner array and the elevation angle is reasonable (of order 5 degrees) from them. APEX is already operating a source up there for holography. Here is a typical view with the central cluster in the foreground.

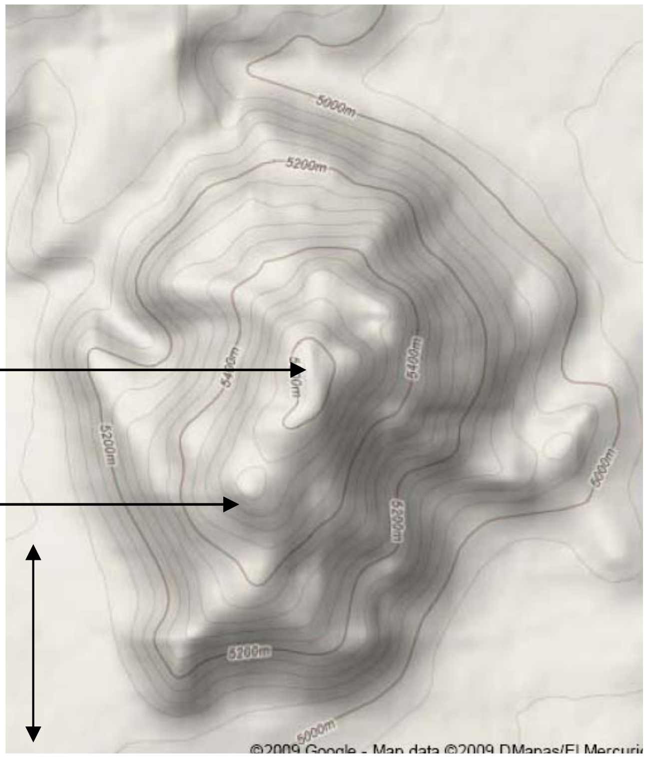
Recall that there is a Japanese IR telescope (mini-TAO) on the peak and that they hope to install a larger one there soon. This is also the chosen site for CCAT. There is a (steep) road up from the Pampa la Bola side – behind the ridge on the right in this picture. This picture also serves as a reminder that the conditions on such a site will be harsh.

The peak has an altitude of 5640m but we would put the source some way below this:

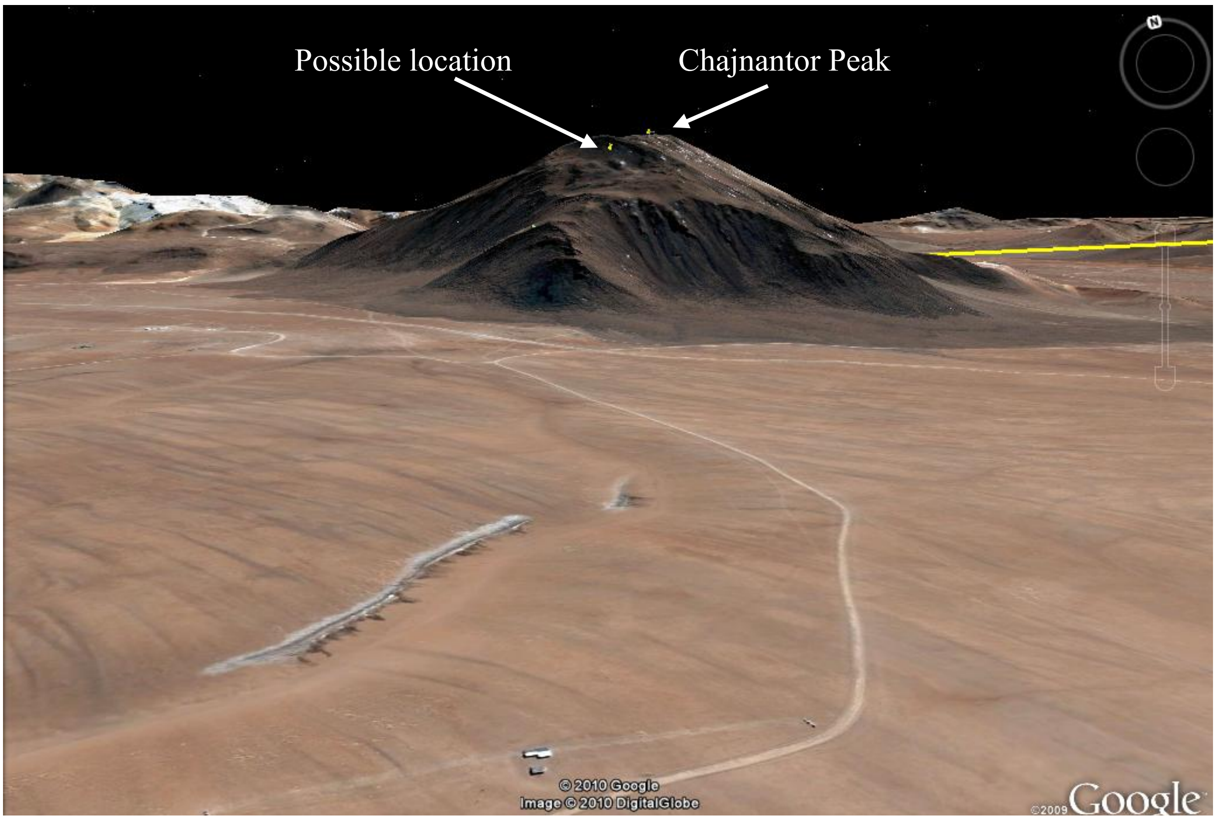
a) to ensure that there is a clear line of sight to antenna stations that are closer to the foot of the mountain, and

b) to make sure that the source is not on the sky-line. If you put it on the sky line you get a large change in the background signal as you scan the antenna around, which is highly undesirable for many of the these measurements. (This was pointed out to me by David Rabanus.)

In fact Chajnantor cone has a long north-south ridge with the peak at the northern end. It looks as if the place to go would be just below the southern end of this ridge. It should be reasonably easy to get access along the ridge at least as far as the point where the ground starts to drop away. Here is a map (North up).



Here is an (old) Google Earth view – the site test interferometer is in the foreground.



This location is at about 5500 m altitude and it is about 3.5 km north of the technical building or a little more than 4km from the central cluster. The elevation angle would be about 6 degrees from there. It is important to note that there will be significant atmospheric absorption in the higher frequency bands along this sloping path and that the path fluctuations will probably be a good deal larger than when we are observing astronomical sources, especially in the daytime. WVR corrections will not be possible because of the background.

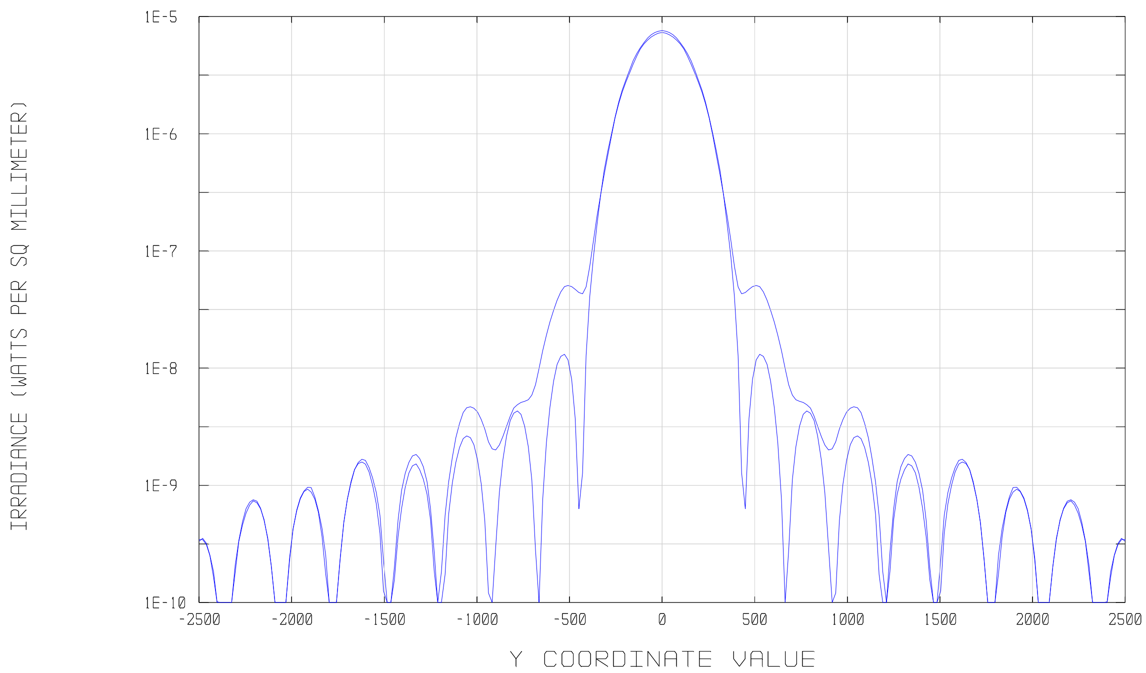
Obviously the final location will need to be decided after more detailed investigations of access and lines of site. The issues of if and how to provide power and communications will of course be key ones as well.

Distance to Source

One important point to check is that source would be sufficiently distant for our purposes. Since we are going to use the astronomical receivers we cannot do what is done for the tower holography where the feed is deliberately displaced outwards (by about 90mm, I believe) to be closer to the actual focus. Instead we have only the nominal 10mm of axial motion of the subreflector. With luck we should get a little more because we will be operating at one end of the range of gravitational corrections.

The paraxial focus position is f ', where 1/f ' = 1/f – 1/D, so the defocus f ' – f = +5.8mm for a focal length f = 4.8 m and a source distance D = 4km. Because of main reflector has such a fast f-ratio (f/0.4) there are however higher-order terms and the optimum focus is actually at about +7.8mm. The rms half-path residuals are then about 50 microns, which means that we will still get a pretty good beam pattern at one millimeter wavelength.

In fact for the holography measurements we have no problem correcting for these near-field effects. This is already included in the reduction software. When we are doing the measurements of the polarization primary beam, however, it will be much more convenient if we are actually measuring a good replica of the far-field pattern. Here is a simulation for 345 GHz of the case of D = 4km and refocus of +7mm, which seems to give the best result.



The lower curve is the far field pattern (obviously this assumes a perfect dish) and the upper curve is the result for a distance of 4km but with refocusing. This is power on a log scale. Obviously the inner sidelobes have come up a bit, but this still looks acceptable to me.

It would be worth doing some further checks, including polarization effects, in particular to find out whether it will be possible to do these measurements when the antennas are closer to the base of the mountain. My impression is that 3km will still be OK but below that we may have problems and in any case we are likely to reach the limit of axial focus adjustment on the subreflector. Since we will be measuring polarized phase and amplitude rather than just power we can in theory reconstruct the aperture fields and thence the far-field patterns. This would however be a complication in the data analysis.

A final point to note is that the physical width of the antenna beam will be roughly $\lambda D/d$ where d is the 12m (or 7m) dish diameter. For D = 4km this is about 300mm at 345GHz (as seen in the plot above). This means that from the point of view of the single dish beams, any reasonable size of source – e.g. a millimeter-wave horn – will be a point source. For the interferometer fringe, however, this is not so. In extreme case we might be using antennas say two kilometers or more apart, in which case an object 2λ across would be completely resolved by the fringes. This is of course just another way of saying that we will need to use a small horn to illuminate the entire plateau. More on that later, but the point to note here is that we could easily get significant phase effects, e.g. phase changes as a function of frequency, if we try to make measurements using pairs of antennas that are far apart. Fortunately this will hardly ever be necessary for any of the tests described above.

The conclusion here is that the location on Chajnantor appears to be a good compromise between being too close, which places the source too much into the near field, and too far, which puts more atmosphere in the path.

Frequency Coverage

The holography measurements will be made with the astronomical receivers – the technique resembles “astro-holography” more closely than “tower holography”. In principle we can do this in any of the ALMA bands, but it would probably be good to make sure that we include the standard 86 GHz. This probably sets the lower limit of frequency coverage required.

For the polarization, Band 7 is regarded as the most critical but clearly we would like to be able to make measurements in all bands. Bands 8 to 10 will be getting difficult because of atmospheric absorption, but might be possible under very good conditions.

Most of the other tests mentioned would probably be satisfied by being able to measure at one or two frequencies per band. Measurements at an arbitrary frequency or being able to scan a band more or less continuously would be nice but not essential.

So the minimum requirement is to cover roughly 85GHz to 350GHz with a spacing of say 30GHz, but if it is easy to provide more frequency coverage then we should do so and it would certainly be good to extend the polarization measurements to the higher bands.

It is important to note that there is no tight requirement on frequency stability or accuracy. The reason for this is that we will be making all the measurements (at least everything that I can think of) with the full ALMA system, which is of course designed to work with incoherent sources – e.g. the delay is set so that there is no first-order phase change due to any frequency drift in the source. In general one would like to be able to place the line nicely in the middle of one of the frequency channels of the correlator, but about it. If we use TDM mode this means that an accuracy / stability of about 1MHz would be fine. If we are using the ACA correlator or if we want to use higher spectral resolution to get better signal-to-noise then better frequency control would be needed, but it is hard to think of a reason to try for better than 1kHz. So the lets set the requirement at 1MHz, with 1kHz as “nice to have”.

Power Required

The most demanding requirement is probably the holography, since we will be measuring the far out sidelobe patterns and we would like to do so relatively quickly. Even so we know that we are talking about very weak signals since we can already do this with astronomical sources with really rather good sensitivity and resolution. We have for example been using Saturn which has a flux of about 200 Jy at 86GHz. This means that the power density we are using in a 2GHz bandwidth and one polarization is 2×10^{-15} W/m^2. To get the same power from a source at distance D requires $4\pi D^2/G$ times this, where G is the gain of the horn that we use to transmit, or about 40nW for G = 10dB. This is about the lowest feasible gain – e.g. an open-ended waveguide. Since we will actually have a narrow-band source and we can use the resolution of the correlator, we could actually manage with even less than this. The signal-to-noise improves as the square root of bandwidth in this case, so we will gain a factor of 16 here if we are using the 256-channel TDM mode. One point that goes against us however is the fact that we will be looking at the mountain, so the system temperature will be perhaps 350K at band 3 and rather more at the highest frequencies.

From the above it is clear that we do not need a lot of power. In fact anything above a few microwatts would become a problem in starting to cause saturation and the like. Doing the calculation rather more explicitly, let's take a total power radiated of P = 100nW or -40dBm. Then the power received is $P\,G\,A_e / 4\,\pi\,D^2$ where A_e is the effective aperture, $A_e = \eta_A\,\pi\,d^2 / 4$. With d = 12m, $\eta_A = 0.7$, $A_e = 79\text{m}^2$ and taking G = 10 and D = 4km as before, we have a total link gain of 4×10^{-6} or -54dB. So the power received when we are fully pointed at the source and refocused is 4×10^{-13} W or -94dBm. This is a factor of 10 above the noise in a 7MHz wide spectral channel. This may not seem much, but we are of course using coherent integrations rather than just doing an instantaneous measurement. One has to be a little careful here because we have a c.w. signal and random noise rather than the usual coherent and incoherent noise, but I think that in the cases of interest – e.g. one antenna pointed at the source and other being scanned so that it is measuring the weak signals out in the sidelobes – we still gain the usual factor of sqrt(bandwidth×integration time), which is a further factor of ~500 for an integration time of 48msec. *(Need to check this statement.)* This already gives plenty of signal-to-noise for all the applications suggested above. For many of them we could in fact use much longer integration times than the 48 msec assumed here.

The conclusion is that 0.1 microwatts will be plenty of power. In general one could probably make do with less at the lower frequencies, but ideally one would have at least this level at the higher frequencies, where the noise is higher and the antenna efficiency is lower. Obviously this is good because it means that either harmonic mixers or photo-mixers should be able to provide sufficient power.

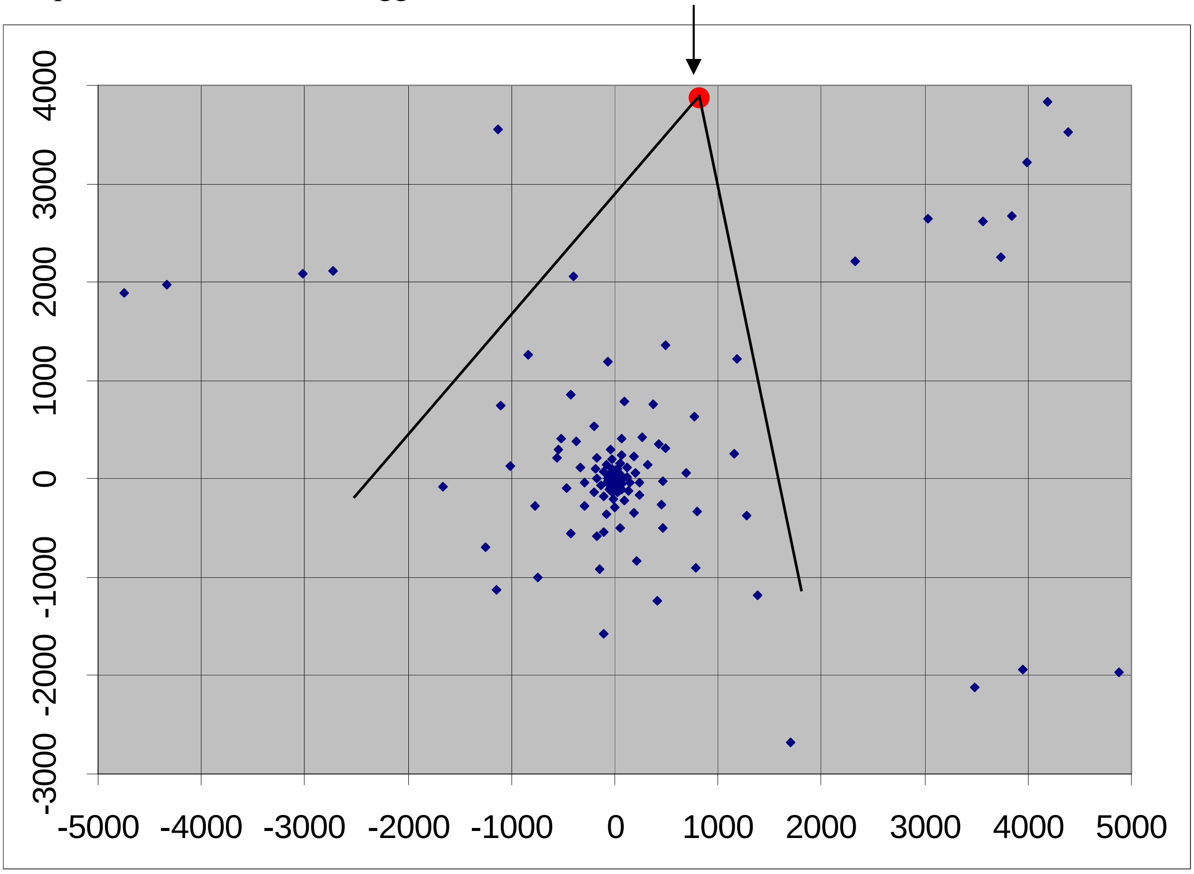
An important consequence of the fact that we are using signals at levels comparable to those from astronomical sources is that questions about interference with other facilities on the mountain can hardly apply. There are certainly no formal or legal restrictions on producing such low level signals. (We all radiate this sort of power across the ALMA bands ourselves, just by being warm!) The fact that we are making polarized signals means that we should do a check with the QUIET and ACT people that they cannot see it, and the fact that our signals would mimic a spectral line means that we should see whether it can be picked up by APEX as a sidelobe – e.g. scattering off the feed legs – but in both cases I would be very surprised if there were problems.

Beam Pattern

As already indicated, I am assuming that we may want to do these sorts of measurements at times when the antennas are not in the central cluster. If we cannot then this will make a pretty strong restriction because on the current plans some of the antennas will only visit the central pads one a year or perhaps even less frequently. We therefore want quite a wide pattern to make sure that we get signals at antennas in at least all of the inner part of the array. It could in principle be much narrower in elevation, which would of course increase the gain of the horn and therefore reduce the power requirement further. For some of the designs discussed below, however, we need to turn the feed, in which case we would want to make the pattern as circular as possible.

Here is a plan to show the sort of angle required.

The position for the source suggested above is about here.



It is seen that all of the inner array is well covered if by a beam represented by the dark lines. The full angle is about 50 degrees so this is consistent with our assumption above of a roughly one steradian solid angle, which corresponds to a gain of 4π.

Polarization Properties

This is where thought is needed. The options are:

1) Single linear polarization (probably vertical since that scatters less off rocks and the like).

2) Two fixed linear polarizations (probably vertical and horizontal so the effective angle is not a function of where you are viewing it from). Note that we can presumably arrange that the signals are at the same frequency but in general we would not be able to control their relative amplitudes and phases. Therefore the normal use would be to switch between the two – either one on or the other, but not both.

3) Single linear polarization but variable. The concept is to do this either by rotating the whole unit or keeping the source fixed and rotating at least one and probably two grids in front of it. This means that the power could be kept constant when the angle is changed or at least that the change in power could be calculated. Note that the actual angle seen by the antenna would depend to some extent on the location relative to the plane of the final grid.

The questions are:

a) what do we need to be able to measure all the instrumental terms in an interferometric set-up? Coupled to this is the question of how many antennas we would be using as I presume that we need to use the closure relationships to solve for the full set of leakage terms. I see *no reason why we could not use say 4 antennas, and therefore have 6 full-Stokes baselines, if that is the magic number.*

b) a presumably slightly simpler case is where we are just measuring the polarized primary beam of one antenna and are only interested in the changes in the instrumental terms with respect to their values on boresight (presuming that we have already measured the boresight).

Note that one of the parameters we want to establish is the absolute orientation of the polarization vector which is, I believe, the one thing that you definitely cannot do astronomically unless you have a source of known orientation.

The ALMA receivers receive two linear polarizations with different orientation, as follows:

Band	Orientation
1	135
2	-135
3	-80
4	80
5	-45
6	45
7	0
8	-90
9	90
10	180

These are the original values. Band 7 was altered so that in the new cartridges the angle is 37.5 degrees. For quite some time to come we will be working with a combination of the old and new cartridges.

With respect to the options above I think this means that option 1 is already ruled out – if we stick to vertical or horizontal polarization, bands 8, 9, and 10 and the old-style would get effectively no signal in one of the channels. Band 3 would be problematical with only a 10 degree offset. Perhaps we can choose an intermediate angle that gives a reasonably good coupling to both channels on all the bands? I suspect that there is not enough information in option 1 anyway, but I have not thought this through.

I believe it must be true that Option 3 gives us everything that we need. The reason for avoiding this if at all possible is that, as far as I can see, it requires a moving mechanism.

The polarization produced should be a pure as possible. In practice it should be possible to obtain 30 dB cross-pol with grids but one has to analyze carefully what happens off-axis. Since ALMA has a 0.1% polarization requirement we certainly need to know what is being produced to this sort of level. Note however that the flow-down is not direct – I think one needs to go through the analysis of what accuracy one would get in the leakage terms and how that relates to the errors in the final Stokes parameters.

More discussion of this issue of the polarization purity required to come!

Other Requirements

Because of its location, the device obviously needs to be extremely reliable. It would also be a great help if it had very low power requirements so that it could be run from a (very robust) solar cell and a battery. In conflict with this is the fact that if it contains electronics it might be necessary to keep it warm. This implies good thermal insulation as a minimum. On the other hand it is probably not a huge problem to run a power line along the ridge from the mini-TAO. For their holography transmitter APEX use a generator at the foot of the mountain and run a line up. (I think they used solar originally but it got wiped out by an ice storm. I am not keen to be reliant on a generator but running a line all the way up is presumably also a possibility. It seems possible that a photonic solution could be devised which requires no electrical power at all – i.e. sending the very small amount of power needed to bias the photo-mixers up in the form of light in another fiber (see more below).

Obviously an ideal solution would be one that has no control requirements. This again seems a possibility with the all-photonic system. If not, and we do put in a power line, then running a simple line along-side the power (or even putting it on the wire as a modulation) is presumably not too difficult. APEX use radio control which is I suppose not difficult to do but in theory I guess it violates our radio-quite zone code.

Straw-man Designs

1) Conventional.

I suggest that all we need is a YIG (or multiplied DRO) source in the 20 to 30 GHz band and a harmonic generator. To meet the minimum requirement the source would be fix-tuned and perhaps locked to a crystal to be sure that we have adequate frequency stability. (A YIG by itself would probably be good enough if the temperature is controlled and a DRO certainly should be fine.) It would be tempting to use a version with a simple synthesizer but obviously this immediately requires more complicated remote control. I believe that there are plenty of either of these on the market, but we would probably need a mil-spec version to make sure it survives in low temperatures. One thing to watch is that the oscillators themselves are usually running at a lower frequency so sub-harmonics are present which come up in the multiplication. A filter to remove these might be worthwhile. Some amplitude control would useful so a variable gain amplifier could be included, but again control is then required.

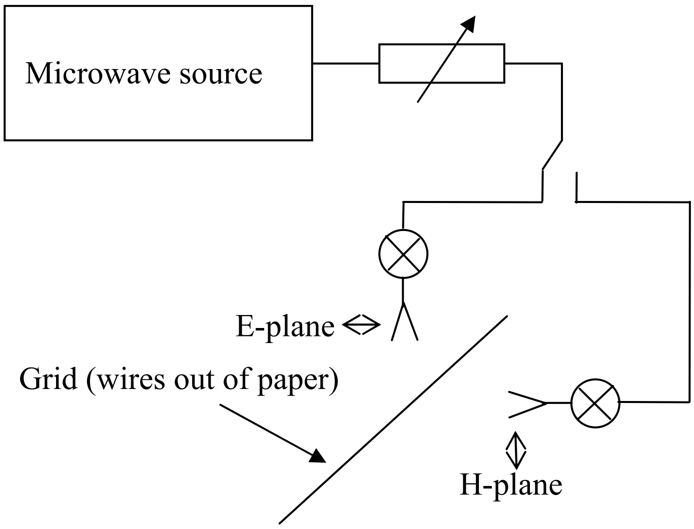
For the harmonic generator I have had good success up to about 375 GHz just using the harmonic mixer from a spectrum analyzer and driving it at ~15GHz and at quite a high level (~ +16dBm?). I don't have any real measure of what power was being generated. The power requirement above implies that the conversion loss can be over 50 dB but of course the energy gets spread over the harmonics. To be sure of getting a known amount of power at 300 GHz and above we would probably need to talk to people like RPG, Virginia Diodes and perhaps Spacek.

The tricky bit is how to cover such a wide range a frequencies with a reasonably well-controlled beam pattern. This is of course not at all difficult for a single waveguide band (an open-ended wave-guide or a very small horn would do) but the trick is to find a way of doing it for a frequency range of 85GHz to at least 350GHz and preferably beyond. It is tempting to think about some of the quasi-optical tricks that people have tried – some sort of planar antenna (Maltese Cross?) plus a lens for example. There may be suitable things that one can buy, but obviously we need to talk to people who have done this sort of thing.

Another option that would probably work would be a rather gently tapered horn, which should still work when over-moded and would give a relatively narrow beam, followed by a convex lens to spread the beam. In this case the lens could perhaps be cylindrical to give the preferred wider spread in azimuth than in elevation.

Naturally these components all go in a box and are surrounded by absorber. A very weather-tight window would be needed with good polarization properties. This would also require some investigation – foam might be an option.

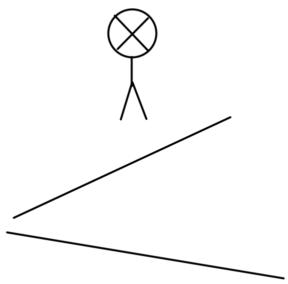
To make option 2, we would presumably use a coax switch and have two multipliers and a grid which reflects one polarization and transmits the other:



One is tempted to suggest having them both on so that, since they are driven by the same source, one can produce a signal of any polarization state by adjusting the relative phase and amplitude of the two contributions. The problem of course is that there is no realistic chance of producing signals of the necessary purity and accuracy in this way, especially as we have harmonic generators in the paths. I therefore think that this is a non-starter.

For option 3) one could just have a single multiplier and a grid at a small angle to clean up the polarization and mount both these on a turn-table which rotates them all about the axis of the peak of the beam pattern. Note however that, unless the beam is perfectly circular, then an antenna that is not right in line with the axis of rotation would see a varying power.

The alternative suggestion is to have two grids (somewhat tilted with respect to the beam to cut reflections) which can rotate in the plane of the grid.



By choosing the angles or rotation of the two grids one can control both the orientation and the power in the beam reasonably well. I suspect the details of this with the wide angles would be messy. It is not clear whether it is easier to motorize and control the rotation of two grids as compared to one complete source module.

2) Photonic

Essentially the concept is that one does all the complicated control, signal generation and such like in the relative comfort of the AOS technical building and only puts the absolute minimum of components up on the peak. All we then need to do then is find a way of getting a few fibers up there! What I have in mind is essentially a very stripped-down version of the ALMA photonic reference distribution system: i.e. make light at two frequencies differing by the RF frequency that we want and mix them in photo-mixer that takes the place of the harmonic generator in the conventional schemes above.

For the system in the control building, I defer to the experts. I understand that designs for a suitable optical comb generator exist. Recall that no control of the RF phase is required so we don't need any expensive master lasers. As has been emphasized the RF power requirement is pretty low, but I don't know what this converts to in terms of optical power or the question of what distance the light can be sent by fiber without getting into problems with Bragg scattering, etc. If necessary I suppose that an optical amplifier could be used before the photo-mixer but I guess that this requires a good deal of bias power and probably control. If an amplifier is not needed then it appears that the only power required is that for the bias of the photo-mixer and that should be very small. I suppose that it could be generated by laser light and a few photo-diodes, is that right? This is where the scheme shown for option 2 above comes into its own. There are no moving parts and the two photo-mixers can be driven by separate fibers, so that all the control is back in the AOS-TB.

The design of the antenna that couples the power out of the photo-mixer and produces a suitable beam raises pretty much the same questions as with the harmonic generator. Waveguides are certainly possible but will be over-moded in all but the lowest band. One option here would be to use a separate photo-mixer and feed horn for each band – they could be driven by separate fibers and simply sit side-by-side in the source.

Obviously one of the larger challenges in this case is getting the fiber up the mountain. Note however that it does not have to be buried. It might be possible to just run it down the front face of the mountain and then connect it to the ALMA system where it runs round the bottom of the hill. Spare fibers have been planned in the ALMA system. The alternative would presumably be to run along the ridge to the TAO and then hook into the system that they and CCAT will no doubt be installing. That is however likely to take quite some time and it would be of order 15km total run from the AOS TB. This suggest the alternative of asking the TAO people whether we could house the optical source there and just run the fiber along the ridge, which would be more like 1km.

Commentary

The main driver here is the requirement for calibrating the polarization so the top priority is to sort that out. Other questions one might ask are:

1) If we do need to be able to make a source giving a range of polarization angle this is clearly a major design driver. Is it foolish to do the polarization source right away? Should we perhaps get something set up for holography first? I would resist this. We are not working too hard on polarization right now but we really must start paying attention to it soon.

2) The wide beam is something of a driver. Is it really necessary to cover some much of the array or would it be enough to cover just the antennas needed to make baselines of a km or so? That would reduce the full width of the beam to 15 or 20 degrees which might be easier.

I have been looking for ways of doing this that are relatively cheap and simple but ended up making it sound rather complicated. I hope that others can suggest even simpler solutions.

Richard Hills 13th Sept 2010