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SOME VLA GEDANKEN EXPERIMENTE
with emphasis on data processing

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In order to make clearer the type of capabilities needed to process the VLA data, it is worthwhile to dramatize a few experiments in attempt to get a feel for how the instrument will actually work. In the dramatizations below, a few liberties are taken. First, when a number of parameters are required for a data processing run, those discussed will not necessarily be the one available to the observer; he may set a smaller, more astronomically oriented group of parameters, which will be converted to the ones discussed. Therefore, these dramatizations give no information about the program control language.

Second, I wish to issue a strong caveat that computer run times are order-of-magnitude only. Not only are the estimates done without consideration of what computer the programs are run on, but no proper account has been taken of the effect of multiprogramming on run time.

CASE A

Observer A wishes to observe 3C 47 to a resolution of 2" at all four frequencies. He knows from Cambridge maps that the overall size of the map is about 90", and he knows that the flux is 3.8, 1.0, 0.4 and 0.3 Jansky at 1.4, 5, 15, and 23 GHz, respectively.

Day 1, Configuration B, 5 GHz

The observer appears at the telescope with his observing program on cards, calling for an observation of 3C 47 as soon as it rises, and a sufficient number of calibrator observations. These are read in and checked for errors, and, when the preceding observation finishes, A's program begins.

As soon as the telescopes arrive at 3C 47, the computer programs, after a few seconds of internal organization, and a ten second integration interval, inform the observer that there is a strong source in the field, that the SNR is 15 to 1 on a single correlator. After a pause of approximately two seconds, it adds the information that the source is probably partially resolved at the shortest spacings of ~2500λ (if the source had been less than about 30" in overall size the computer would have estimated the approximate overall extent by the behavior of the visibilities near the center of the u,v plane). Processing on a snapshot mode picture of the source is started at this time. The default value is for a map with a numerical field of view of 256. That is, there are map grid points at intervals of 0.7" (the beam size is 2") on a 3' x 3' field of view. This initial snapshot appears approximately two minutes after the last printout, and is printed on the observer's CRT in either a line printer contour-type display (with a resolution about 160 x 50) or a stipple-type contour display based on the same principle.

As soon as this display is written, a new computation is begun, and, after four minutes of observing a new map appears with ten times the observing (three times the SNR). New maps appear, each with 1.4 times the sensitivity of the last, after 6, 10, 18, 34 and 66 minutes of observing. At this point, the array is driven to a calibrator. Observations of the calibrator establish that all phases and amplitudes are within bounds. On return to 3C 47, the computer recognizes the source and does not produce a map, realizing that little would be added by a few seconds observation. The slightly nervous observer, however, requests a map utilizing data only from the current scan. Satisfying himself that it looks much like what he had seen before, he goes away to coffee. New maps, utilizing all of that day's data continue to be produced, after 2 hours, 4 hours, and 8 hours total integration time. After finishing observing, A requests a final map, and a final beam. After inspecting both, A decides the map is sufficient for his purposes without cleaning or reprocessing with interpolated (rather than extrapolated) element phases. Knowing his source is quite a lot smaller than the delay beam (about 6', full width at half maximum), he requests only a rough correction for delay effects, based on point source peak suppression, which is also statistically correct for zero mean random point distributions. This correction increases the brightness of the outer parts of the source by about 3%. A then makes a final display of this map, and takes it home with him.

Day 2, Configuration C, 15 and 23 GHz

Observer A feels that the beam and sensitivity are sufficiently good that he can combine observations at the two high frequencies into one day's observing. Therefore he prepares a card deck calling for five minute scans, alternating between the two frequencies. Actually, the final step of preparing this deck is done by a computer program in the asynchronous computer, and the deck is passed as card images on disk rather than an actual punched card deck.

It is A's intent to taper the observations at 23 GHz so hard that the beam size will be identical with that of the 15 GHz observation. This will cost about 15% in sensitivity, but even so, the map noise will still be about 0.15 mJy. Since A knows, from the lower frequency map that the 300 mJy from the source lies principally in about 100 map cells, he anticipates a 20:1 signal-to-noise ratio.

At these frequencies, the source is not reliably detected in ten seconds, so the observer must wait for the map with two minutes integration before the source is visible, and he at last knows he has not punched the wrong source coordinates in his cards.

About halfway through the second hour, the monitor system indicates a loss of 15 GHz LO power in antenna 23. Since observations at this frequency are occupying only half the time and since antenna 13 is already down with a refrigerator under repair, the operator becomes worried. He requests a beam computation with these conditions (about 4 minutes computation) and shows it to A, asking if it is going to be acceptable, or whether they had best switch to observing only at 23 GHz. After due consideration, A elects to continue, as the mean sidelobe level has gone only from -28 dB to -26 dB, and is still below the receiver noise level almost everywhere. Meanwhile, a repair crew has been dispatched, who, when they arrive at antenna 23, take it out of service, replace the 15 GHz LO multiplier module, test the fix, and return the antenna to service by the fifth hour of observation.

At the end of the day's observations the computed array beams are adequate at both frequencies. Because of the smaller, C, configuration, no delay correction has to be made. However, at these frequencies, the antenna beam is

$3\overset{\prime}{.}4$ and $2\overset{\prime}{.}2$ respectively, and must be divided out. At 15 GHz, the correction at the edge of the source is only 4%, but at 23 GHz, it is about 10%.

The calibrator observations revealed that the rms atmospheric and instrumental phase fluctuations were 18° and 30° at the two frequencies, respectively. A decided not to attempt a phase correction procedure because of the low signal-to-noise ratio at the higher frequency, where the correction is important, but to merely make the statistical correction in the conversion coefficients between map contours and fluxes or brightness temperatures. The net effect was to reduce the array gain, and broaden the array beam by about 5% and 15% at 15 and 23 GHz, respectively.

Day 3, Configuration A, 1.4 GHz

Observer A knows that radiation from the edges of his source would be surpressed by a factor of order 5 in the long interferometer with 50 MHz bandwidth. Since he knows that he will have adequate signal-to-noise ratio, he elects to avoid the problem by using 12 MHz bandwidth. Because of the spectrum of the source and the lower noise receiver, the signal-to-noise ratio will still be about 20 times higher than at 23 GHz.

With this adjustment, observation at 1.4 GHz goes much the same as at 5, except that when a receiver breaks at an antenna it takes three times as long to drive out and fix it.

CASE B

Observer B wishes to measure the log N-log S relationship at all four frequencies. Because he is rather discouraged by what the relation has done for science so far, he decides it is worth only a half day at each frequency.

His philosophy is to pick a reasonable expected N-S relationship, and configure the VLA in its optimum configuration to measure it. The <u>a priori</u> relation he chooses is

$$n = \min \begin{cases} 300\ (S\ \nu^{0.7})^{-2.5}\ \nu^{0.7} \\ 30000\ (S\ \nu^{0.7})^{-1}\ \nu^{0.7} \end{cases}$$

where n is the differential count, in number per steradian per Jansky, S is in Jy and ν in GHz. This model has the curious property that there are, at sufficiently low fluxes, 20,000 sources per steradian for any flux range of a factor of two.

Day 1, 23 GHz

The antenna beam is about 4×10^{-7} steradian. In order to detect two sources in a factor of two flux range, B must survey 250 antenna beams. His half-day observing gives three minutes observation on each beam. In this time the noise is about 1 mJy rms, so the survey extends only to the knee in the number flux density relationship, which at this frequency is at 5 mJy. In order to avoid missing extended sources, configuration D is used.

Day 2, 15 GHz

The antenna beam is about 10^{-6} steradian, so B wants to spend his half-day surveying about 100 antenna beams, at seven minutes each. In this time the rms map fluctuation is about 0.4 mJy, and the minimum detectable source is about 2 mJy. B expects to find about six sources in his survey--two between 2 and 4 mJy, 2 between 4 and 8, and 2 stronger than 8 mJy. Again configuration D is chosen.

Day 3, 5 GHz

The antenna beam is now about 10^{-5} steradian. B wants to spend his half day surveying 10 antenna beams at slightly over an hour each. The rms noise on the maps is about 30 μJy with this integration time, so he can reliably detect sources with fluxes of about 0.15 mJy. There will be an average of less than two sources per antenna beam, so configuration in unimportant. However, sidelobes are important, as there is about a 10% probability that in one case the two sources in the beam have a 100:1 flux ratio. In order to get a somewhat wider separation between sources, B makes these observations with configuration C, giving an array beam of 7", and, to facilitate use of CLEAN, processes his data with five points per beam, using a 1ʺ.5 grid spacing in a 25 minute field of view, using a 1024 numerical field of view. This field of view is rather larger than the antenna beam, but is processed to be sure there is sufficient dynamic range available. The final maps, and the relatively few applications of the CLEAN algorithm require about 15 minutes computer time for each of the ten maps, two and a half hours total. B expects to see 16 sources, the strongest around 20 mJy, the weakest around 0.2 mJy.

Day 4, 1.4 GHz

At this frequency the antenna beam is no longer the overriding consideration; it is supplanted by the delay beam. A calculation shows that, with the D configuration the array is close to the confusion limit in the array beam. On the other hand, with the C configuration and 50 MHz bandwidth the delay beam is only about 20 minutes whereas the antenna beam is about 35. Therefore B chooses to observe at configuration C with 25 MHz bandwidth. His array beam is 20" and the rms map fluctuations due to receiver noise are about 15 μJy, far less than the sidelobes of sources in the antenna beam. There will be about 20 sources in the antenna-delay beam, the strongest about 50 mJy, some 28 dB above the weakest source one would like to detect.

In order to get this dynamic range, B processes a 70 minute field of view with a 512 numerical field of view, points spaced 10". He then locates the strongest sources, those stronger than 2 mJy. There are about ten. He cannot, with sufficient precision, apply CLEAN to these sources, because of the sky curvature effects. Therefore, for each of these sources, he moves the data to a new phase tracking center. That is, the phase of each point is changed by

$$\Delta\phi = (u,v,w) \cdot \underset{\sim}{\Delta S} \cdot \nu$$

where ΔS is the change in the source unit vector, and u,v,w are the baseline vector in time limits. The amplitude is increased by the factor

$$D = (B((u,v,w) \cdot \underset{\sim}{\Delta S}))^{-1}$$

where B is the autocorrelation function of the bandpass, normalized to B(0) = 1. Then, a map is made for each source, with small numerical field of view (appropriate for the size of the source--most are 64 x 64) and the CLEAN algorithm is run. This process requires about 15 minutes per source--2-1/2 hours total. Then the components from CLEAN are fed into an observation simulator, and the output subtracted from the data in hand. This is about an hour computer run. The resulting data set is fed into a three-dimensional transform, 1024 x 1024 x 8, which is about an hour's run. The cleaned components are now restored to the map, and the source count is made. The sidelobe contributions are now of the same order as the 15 μJy receiver noise fluctuations and remain of this order because of incomplete cleaning due to fact that the 2° rms atmospheric and receiver phase fluctuations cause the true array beam to differ from the computed one.

Thus, counting the standard intermediate maps produced while observing, B has used about five hours computer time, on top of the usual overhead of receiving and cataloging data for his 12 hour run. In practice, he will have made an error somewhere along the line, and will have rerun some programs, and we would expect his total computing requirements to be approximately 12 hours.

CASE C

Observer C wishes to make a map of the inner region of M17 with resolution 2" at all four frequencies. Because of the low declination of the source, a "day" for this program is eight hours, observing down to an elevation of 12°. Observer C is, of course, primarily interested in the small structure of the source.

Days, 1 and 2, Configuration C, 15 GHz and 23 GHz

Because C is interested in relatively faint features, he elects to observe a full day at each frequency, rather than sharing a day between them. The "natural" beam widths are 2"1 and 1"35 at the two frequencies, but the K band observation will be hard tapered to 2" to match the KU band resolution. The point source rms will be about 60 and 80 μJy at the two frequencies, corresponding to brightness temperature rms variations of about .06 K and .08 K. A brightness variation of 1/2 K will be just significant.

Because the source is large and complicated, and because a large dynamic range is needed, C wishes to map the entire antenna beam and then use CLEAN. With a point spacing of 4 points per beam, (0".5 spacing), numerical fields of view of 410 and 270 are required. Both are rounded up to 512. Because of the complexity of the field, CLEAN requires about two hours at each frequency. The preparation of the 512 x 512 maps input to clean require about 20 minutes each.

Day 3, Configuration B, 5 GHz

Observer C is very concerned about dynamic range, and feels that the use of CLEAN will give him a larger dynamic range than the use of the delay beam for far sidelobe suppression (he obstinately maintains this position even after arguing about the subject with B. Clark). Therefore, he will, once more, synthesize the full antenna beam and apply CLEAN. To get out to the edge of the antenna beam he will decrease the bandwidth to 25 MHz. The resulting 17 μJy rms (point source) corresponds to an rms brightness temperature fluctuation of 0.15 K, so that the minimum observable brightness contrast is about 1 K.

In order to get at least 4 points per beam, desired for CLEAN, C must make a 2048 x 2048 map, a process requiring some forty minutes at the end of his observing day. The CLEAN process, on such a large and complicated map, is a very long one. It utilizes approximately one day of computer time. The ratio of computer time to observing time therefore exceeds one, and this time must come out of the lesser requirements of other observers, over a period of some days.

Day 4, Configuration A, 1.4 GHz

Observer C is at last persuaded to abandon his policy of mapping the whole field of view at this configuration, because of signal-to-noise problems. To map the entire antenna beam requires reducing the bandwidth to 1.5 MHz. The 70 μJy rms point source noise implied by the narrow bandwidth would translate into a 80 K rms brightness noise. It is clearly more effective to limit the beam, because the far sidelobe effect will, almost certainly, be below 80 K rms even without cleaning.

Furthermore, cleaning a large and complex field is a major computing load growing about as the fourth power of the numerical field of view. To get four points per any beam for the full element beam requires a 4096 x 4096 x 8 three dimensional transform. The transform itself is a relatively minor operation requiring only about eight hours. However, the CLEAN process on such a large field becomes prohibitive--to CLEAN the field to a reasonable level would require on the order of a thousand hours computation, and could be expected to be a one year project.

Because of both scientific and data processing reasons, then, C elects to observe at the full 50 MHz bandwidth. The required numerical field of view is then set by the bandwidth: $(4\% \text{ bandwidth})^{-1}$ x 2 (plus and minus extents) x 2 (to null rather than half power) x 4 (points per beam) ≈ 512. Within this reduced field of view, no curvature corrections need to be made, so that a 512 x 512 numerical field of view is sufficient.

The full bandwidth point source equivalent noise level of 12 μJy corresponds to a rms brightness temperature fluctuation of 14 K, and a minimum believable contrast of about 70 K.

The cleaning process for C's 512 x 512 maps requires about two hours CPU. However, he elects to do some further processing on his data, making new maps with wider beams in order to get to the unmapped portion of the field of view. He therefore remaps the area with a 4" beam, 8" beam, and 16" beam. All are done with a 512 x 512 numerical field of view, four points per beam. The increasing beam size more than makes up for the loss of sensitivity due to the taper, yielding rms brightness fluctuations of 5 K, 2 K, and 1 K respectively. With the 16" beam, curvature problems are appreciable and a 512 x 512 x 4 transform is required. The 16" beam causes a taper with a width of 2-1/2 km to be applied. There are sufficiently few tracks within any smaller radius that it is not profitable to continue tapering toward larger beams, because of the increasing sidelobes.

CASE D

Observer D wants to measure the variation in rotation measure over the face of the source 3C20. His strategy is to make, in one day, simultaneous maps at frequencies such that the expected rotation measures differ by about 1/4 turn, and then, on a second day to repeat the process at a significantly different frequency. The rotation measure (averaged) of 3C20 is about 170 radians/m^2, so 90° rotation occurs, at 21 cm, in about 150 MHz. D will probably have to compromise this slightly to fit within the instantaneous bandwidth of the upconverter.

With a 50 MHz bandwidth, the map noise will be about 15 μJy per beam. It is necessary to have this be less than .001 of the source brightness. We therefore want a source brightness contribution of about 15 mJy per beam. Since the source flux is 12 Jy, this implies an upper limit of about 800 picture elements on the source. Since the source is, overall, about 30" by 80", the A configuration (~600 picture elements on the source) is nicely tailored for the observation.

For the second day's observation, D could choose to observe at 6 cm, measuring a polarization rotated only a few degrees from the intrinsic. However, in order to maximize his chances of catching two components in the line of sight with different rotation measure (by noting the beat effects on the percentage polarization), D prefers to observe at 1.7 GHz. In addition, since the six cm flux is only 5 flux units, if D observed at this frequency he would have to sacrifice either signal-to-noise ratio or resolution (probably by observing at configuration B and tapering the beam to 3" instead of the natural 2").

After making his two day observations, D makes maps of the total power and linear stokes parameters at the four frequencies. He makes maps with 4 points per beam in a 4' field (limited by delay beam), a numerical field of view of 512. He then uses the map manipulation routines for further processing. On a map of this size each simple map operation will take about two minutes, and functional operations (square root and arctan) about three times that.

First, to get a mean brightness, D simply adds the eight circular polarization maps. Then, to eliminate confusion from low intensity regions, he performs a logical operation on the map, making a mask with all of the map areas above the 10% of peak brightness contour. Then he divides the Stokes parameter maps by the intensity map, to get percentage polarizations. Then, he applies the rectangular to polar conversion functions (square root sum of squares and arctan2) to the four pairs of Stokes maps, converting to percentage linear polarization and position angle. The four percentage polarization maps are averaged, and the rms deviation at each map point is computed and displayed, to search for multiple line-of-sight components with different rotation measures.

Subtracting the adjacent frequency observations gives a first estimate of a rotation measure map. A logic operation to reduce the subtracted map modulo the 180° ambiguity in position angle will be necessary. The final map of rotation measure is made by subtracting the 1.4 GHz and 1.7 GHz position angles, and using logic operations between this map and the adjacent wavelength map (a total of about half a dozen simple operations) to resolve the 180° ambiguities. To reduce his errors a little farther, D will also do the same set of operations on the other maps, and appropriately weight and average, producing, in the end, a map of rotation measure and a map of intrinsic polarization angle.

About two hours of computer time will have been used for the map manipulations, which, granting D the patience, are most conveniently done interactively.

CASE E

Observer E wishes to observe the field of M31 at all four frequencies, using full resolution in each case. Since bright galactic sources in our galaxy are a few parsecs in size, E expects typical structures of order 1". In order to map some of these structures he prefers to observe with full resolution at the high frequencies, rather than matching the low frequency resolution.

One problem he knows he will encounter is confusion due to the many, presumably weak, sources expected in M31. In order to approximate the effect of this confusion he makes a wild guess about what the log N-log S plot will be in this very special area of sky. He adopts

$$n = 500 \left(S \nu^{0.5}\right)^{-2.0} \nu^{0.5} .$$

Day 1, 23 GHz

With the above N-S relation, the median strongest source in the beam is 23 mJy. The rms point source noise fluctuations is 70 μJy, so the weakest detectable source will be about 0.35 mJy, a range in flux of about 18 dB. E expects to see about 70 sources.

With full bandwidth, the delay beam and antenna beam are essentially equal in size. Because he is rather short on sensitivity, E observes with this bandwidth, and, in the end discards his map at about 1' from center to eliminate data too much contaminated by the delay effect. The beam width is 0".12. Since the 18 dB dynamic range required is not too great, E is satisfied with a 2' field of view with only two points per beam, a 2048 numerical field of view.

After making the map (forty minutes of computer time), E notes that there are four of the seventy sources on it which are sufficiently complicated to be worth further study. These are corrected to the center of the field of view and a new (64 x 64) map made of them with four points per beam, at 15 minutes computer time per source.

E then makes maps with reduced resolution, hard tapering the array to beams of 0".25, 0".5, and 1", with numerical fields of view of 2048, 1024, and 512. This uses an additional hour of computer time. These smeared maps, the four detailed maps, and the large map showing the general location of all of the sources are E's final output for this configuration.

Day 2, 15 GHz

At this frequency the full bandwidth delay beam is rather smaller than the antenna beam. In order to survey a larger area, E reduces the bandwith to 25 MHz. Therefore his rms map fluctuation will be about 100 μJy. The median strongest source in the beam is 30 mJy, resulting again in a desired dynamic range of 18 dB.

The data processing is essentially identical to that at 23 GHz, except that curvature effects have entered, and it is necessary to make his map with a three dimensional transform rather than two, using a 2048 x 2048 x 4 transform, making the production of the main map a computation project requiring an hour and a half of computer time.

The eventual output of the configuration is a set of maps at resolutions of 0".2, 0".4, 0".75 and 1".5.

Day 3, 5 GHz

To keep the delay beam comparable to the antenna beam at this frequency requires going all the way down to 4 MHz bandwidth. This is satisfactory as the resulting 35 μJy map fluctuation is still below what might be expected from dynamic range considerations. The median strongest source in the beam is 50 mJy, requiring a dynamic range of 25 dB.

Because E wishes to CLEAN distant sources from the map, he wants to eliminate the fringe rate integration effect. Therefore, he calls for 3 second sampling rather than the usual 10 seconds, and manages to convince the VLA management that his program is of sufficient importance to justify the computer time.

After observing, E makes a map at 3-1/2 points per beam (0".6) over the eleven minute beam, 4096 numerical field of view. Because of the curvature effects, it is necessary to make a 4096 x 4096 x 16 transform, requiring some 15 hours of computer time. When the map is completed, E wishes to make a CLEAN map. The case here is not as hopeless as it was for observer C, who had much structure at about the same level, filling the beam. Here, things are still recognizable as discrete sources, and an adequate CLEAN can be performed by subtracting only about 20,000 point components from the 16 million map points, a total time of about 100 hours competition. E would have to find this time spread out over some weeks.

In order to avoid having to reCLEAN at different resolutions, E transforms the CLEANed map back to (u,v), hard tapers it, and retransforms to make maps at resolutions of 1".1, 2".2, and 4".5. A two dimensional transform is sufficient for this job, since, to a reasonable order, the curvature effects in the transform are cancelled by those in the inverse transform. The whole process requires about four hours computation.

Day 4, 1.4 GHz

To keep the delay beam comparable to the antenna beam at this frequency requires going to a bandwidth of 1.5 MHz. This bandwidth results in a map noise fluctuation of 70 μJy. The strongest source in the beam will be about 90 mJy. The map dynamic range desired is thus 25 dB.

Observations and reductions proceed as at 5 GHz, except that the size of the main transform is 4096 x 4096 x 64, requiring about sixty hours of computation. The final output maps cover the 35' beam with resolutions of 2", 4", 8" and 16".

The roughly two weeks of computer time required to process four half days of observing time for this experiment clearly indicate that this sort of thing can't be done very often.

CASE F

Observer F believes that he can measure a deviation from Gaussian statistics in the electric fields generated by coherent processes on the sun. He wishes to observe at maximum resolution, to try to observe a single coherent plasma cloud, and at lowest frequency, where coherence effects are most important. He wants to use configuration A, 1.4 GHz frequency. He will connect a pulse height analyzer to the summed IF output, and attempt to detect a change in statistics when the array is aimed at a noise storm. F will use the minimum bandwidth, 0.5 MHz.

Because what he wants to do is unusual, F has an addition made to the on-line program--for him the console digit switches are made to be an offset from the observation card, rather than an absolute position.

The observation request cards are prepunched for the center of the sun in the planetary format. To get these cards F has arranged ahead of time to calculate the required quantities--the topocentric positions and derivatives. One card per hour is required.

Even with the modifications in the control software, it is a difficult job to put the instantaneous array beam down on a suitable burst. With the numerical field of view cut to 64 x 64, it still requires over a minute to get a display of a 10 second map, and repositioning the instantaneous beam by the console digitswitches to a storm outburst may, in the end, result in repositioning to where a storm was a minute ago.

When a given area quiets down, F devotes a few minutes to making a hard tapered map (to reduce computing time F tapers the beam to 15" and makes maps with two points per beam) of the whole sun to see if there is not a better place to look for storms.

The whole process is frustrating and exhausting, and, although unlike most observers, F does not have to spend months reducing further his observations, he is so exhausted after two days of observing that he is well willing to go home and rest for a while before making up another observing request.