MILLIMETER ARRAY
MEMO NO. 34

The Summer 1985 Concept of the Proposed NRAO Millimeter Arrray

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The purpose of this memo is to summarize the current state of thinking on the paradigm Millimeter Array system being discussed just before the Millimeter Array Science Workshop in Sept.-Oct. 1985. The memo will consist of updated versions of the summary material provided for the public discussons in Tucson/Charlottesville in May/June 1985, with some explanatory text.

Two arrays are proposed in order to cover the range of desired resolutions and fields of view. The current paradigm consists of a large array of ~21 movable antennas of ~10m diameter and a small array of ~21 antennas of ~4m diameter which are mounted on a structure ~29m in size in a multi-telescope (M-T) configuration with ~50% filling factor and 25m resolution. Figure 1 schematically illustrates the major options being discussed for configurations for the two arrays. The antennas in both arrays will operate in both aperture synthesis mode and single antenna mode, and Figure 2 summarizes the observing modes that are used to cover all resolutions from the $56''\lambda_{mm}$ beams size of the 4m antennas down to the resolution of the largest arrays of the 10m antennas. Single dish observing in total power/beam switching mode covers the largest two size scales, the M-T in aperture synthesis mode covers the next step of a factor of 2.5 in resolution, and the large array configurations $\geq$ 90m which cover all higher resolutions. Figure 3 illustrates the fundemental mosaicing problem involving the combination of 4m and 10m data to observe the field of view of the 4m antennas with the resolution of the 10m antennas or array of 10m antennas. It can be shown that to have the mosaiced beams in Figure 2 give the same sensitivity in the overlap regions of two (or four) beams, the ratio of antenna sizes should be 2.414 (or 3). A ratio of 2.5 is used for the current paradigm. The text and schematic equations in Figure 3 summarize the basic data processing problem in combining the data to provide images of the desired resolution. The main reason for two arrays with antennas of two different sizes is to allow imaging of a wide range of spatial scales. Figure 4 is a one page summary of array/mosaic parameters.

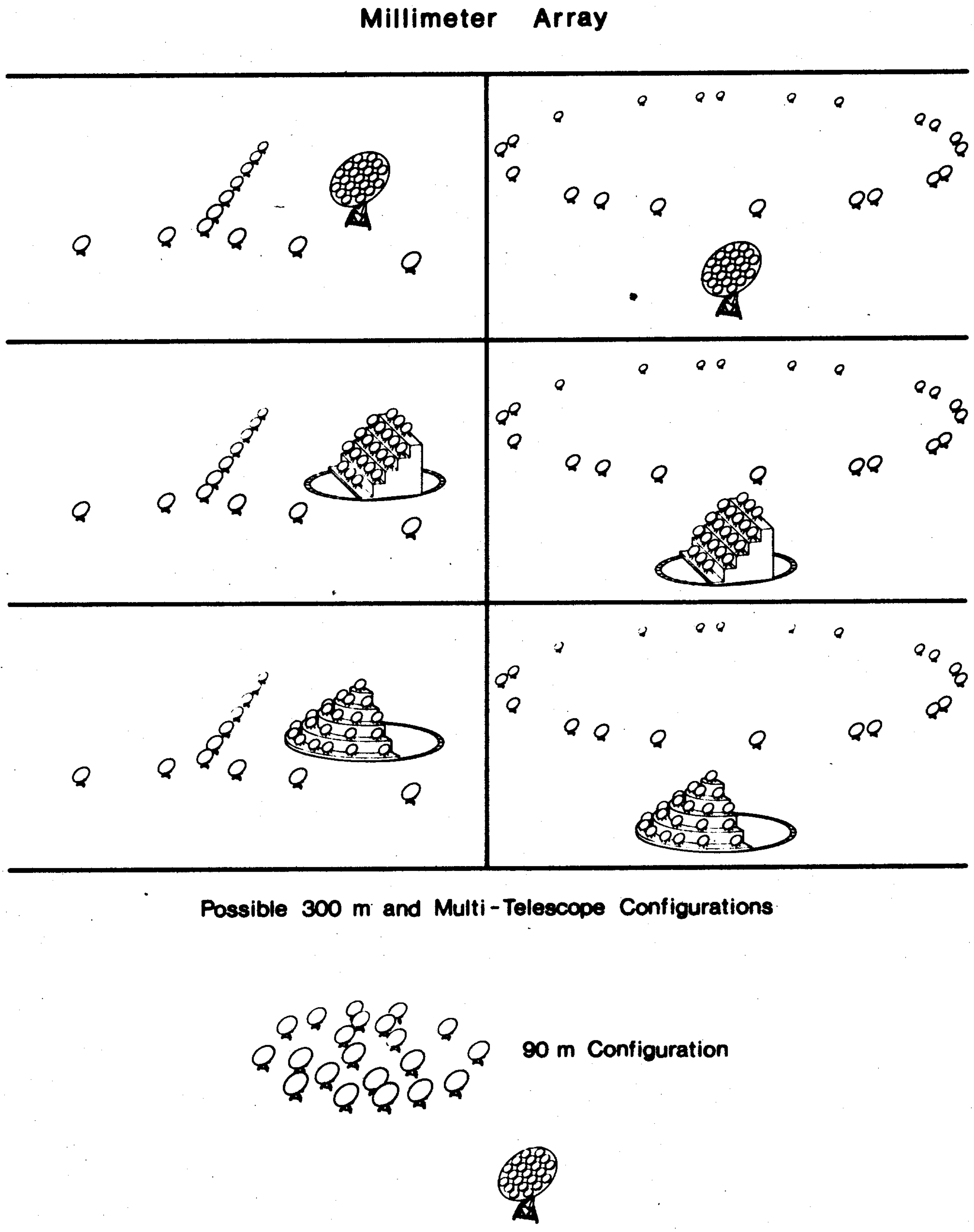
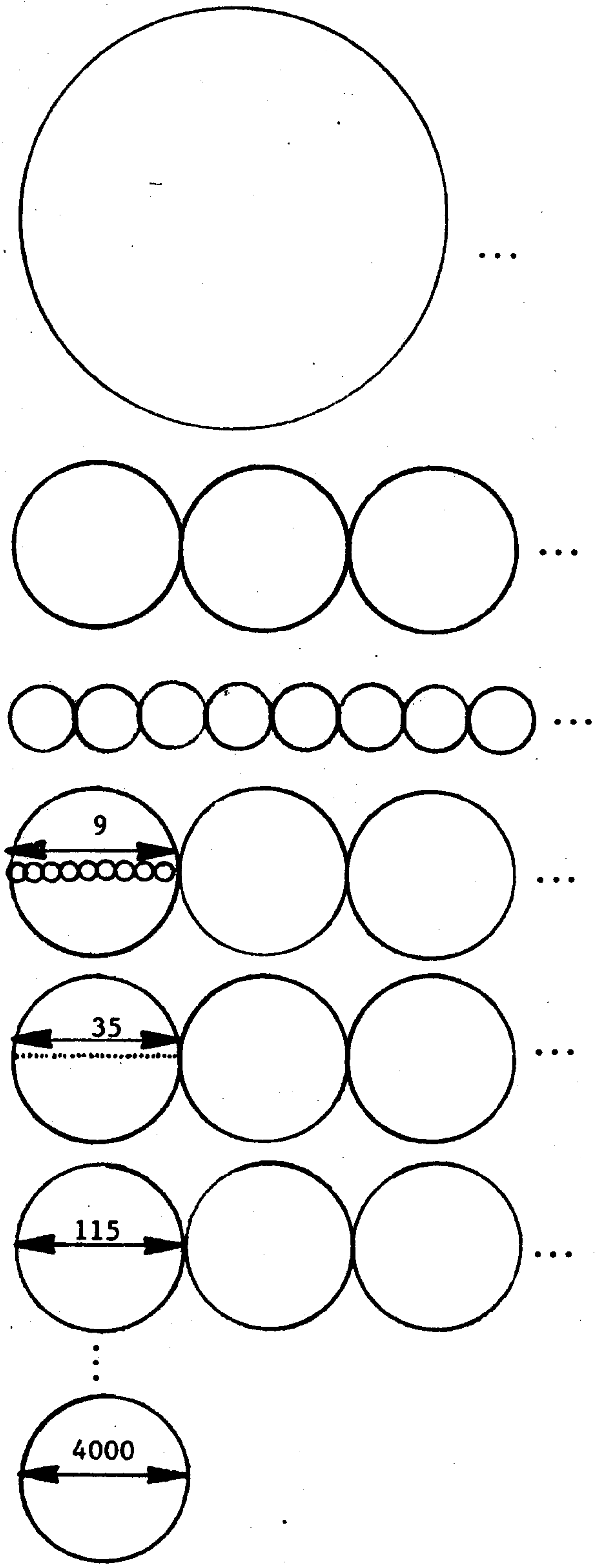

Millimeter Array
Possible 300 m and Multi-Telescope Configurations
90 m Configuration

Figure 1

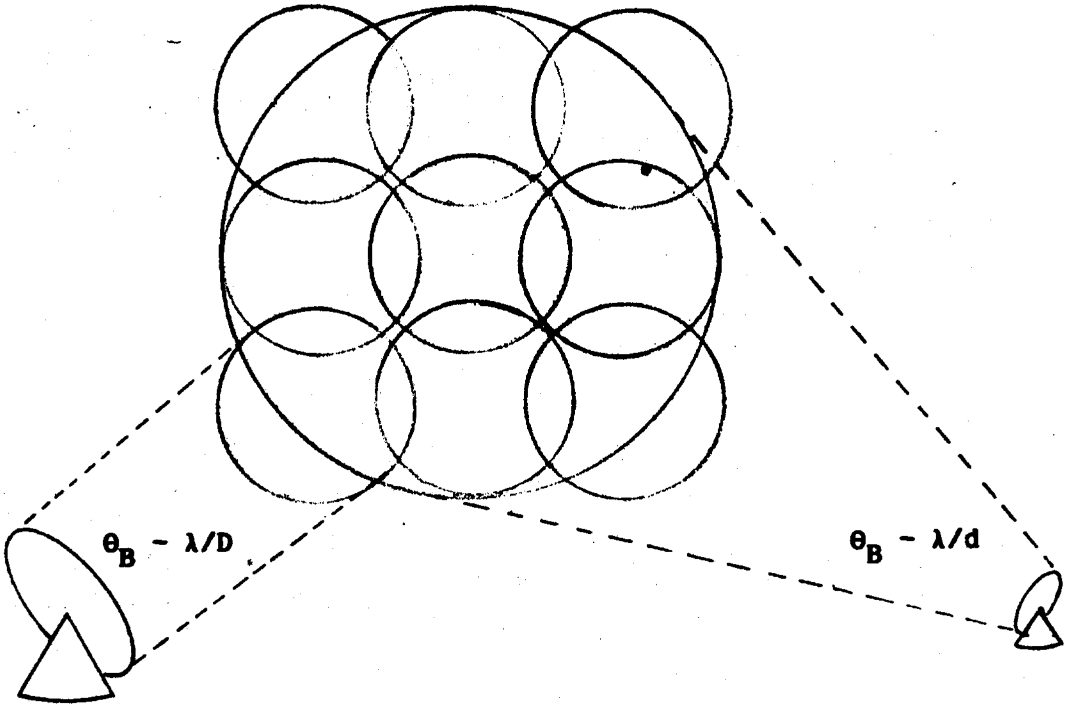
Millimeter Array Imaging/Mosiacing Problem



Resolution	Instrument/Observing Mode
56"λ_{mm}	4 m. Antennas / In Total Power/Beam Switching Mode
22"λ_{mm}	10 m. Antennas / In Total Power/Beam Switching Mode
7.6"λ_{mm}	25 m. Multi-Telescope Array of 21 4 m. Antennas In Aperture Synthesis Mode
2.2"λ_{mm}	90 m. Configuration of of 21 10 m. Antennas In Aperture Synthesis Mode
0.65"λ_{mm}	300 m. Configuration of of 21 10 m. Antennas In Aperture Synthesis Mode
0.19"λ_{mm}	1000 m. Configuration of of 21 10 m. Antennas In Aperture Synthesis Mode
0.006"λ_{mm}	35 km. Configuration of of 21 10 m. Antennas In Phase Closure Calibration Mode

Figure 2

The Mosaic Problem



D = 10 m. Antennas
Imaging λ/d field in
Total Power/Beam
Switching Mode

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$\{I_{\substack{T.P.\\Image}}(\alpha,\delta)\}$

Array of D = 10 m. Antennas
Observing 9 λ/D Fields (=λ/d)
In Aperture Synthesis Mode

||
\/

$9\ \{V_{JK}(u,v)\}_{\substack{B/2D\\Grid}}$

Multi-Telescope Array
of d = 4 m. Antennas
Observing λ/d Field in
Aperture Synthesis Mode

|| or ||
\/ \/

$\{V_{jk}(u,v)\}_{\substack{B/2d\\Grid}}$ or $\{V_{jk}(u,v)\}_{\substack{b/2d\\Grid}}$

$$I_{\substack{Complete\\Image}}(\alpha,\delta) = FT^{*}\left[\ FT^{*}\{I_{\substack{T.P.\\Image}}(\alpha,\delta)\} + \{V_{jk}(u,v)\}_{\substack{B/2d\\Grid}} + 9\{V_{JK}(u,v)\}_{\substack{B/2D\\Grid}}\right]$$

* FT = Fourier Transform

Figure 3

MILLIMETER ARRAY

Purpose:

Spectral Line and Continuum Imaging in the 9, 3, 2, and 1 mm. bands with a wide range of spatial sampling

Electronics Parameters:

Receiver temperatures: $100\ (\nu_{obs,GHz}/100)$ K

Bandwidths: 1 GHz (Cont.) to 100 kHz (Sp. Line)
Hybrid Correlator (512 Channels)

Antennas: 21 Antennas with diameter of 10 m. (1600 m² Collecting area), movable on transporters to 90, 300, 1000, ... m. configurations

21 Antennas with diameter of 4 m., mounted upon a Multi-Telescope (M-T) structure ~25 m. in size with M-T structure controlling azimuth and (perhaps) elevation pointing

Summary of Imaging Parameters[1] of Millimeter Array:

<table>
<tr><th>Instrument</th><th>Instrument Size</th><th>Antenna Size</th><th>Antenna Beam Size</th><th>Synthesis Beam Size</th><th>Map Size</th><th colspan="5">Mosaicing Map Size</th></tr>
<tr><td>4m Antenna[2]</td><td>4m</td><td>4m</td><td>**56"λ_{mm}**</td><td></td><td>n</td><td></td><td></td><td rowspan="4">50n</td><td rowspan="5">172n</td><td rowspan="6">590n</td></tr>
<tr><td>10m Antenna[2]</td><td>10m</td><td>10m</td><td>**22"λ_{mm}**</td><td></td><td>3</td><td rowspan="2">15n</td><td></td></tr>
<tr><td>25m M-T[3]</td><td>25m</td><td>4m</td><td>56"λ_{mm}</td><td>**7.6" λ_{mm}**</td><td>15</td><td></td></tr>
<tr><td>90m Config.[3]</td><td>90m</td><td>10m</td><td>22"λ_{mm}</td><td>**2.2" λ_{mm}**</td><td>20</td><td rowspan="2">70</td><td rowspan="3">230</td></tr>
<tr><td>300m Config.[3]</td><td>300m</td><td>10m</td><td>22"λ_{mm}</td><td>**0.65"λ_{mm}**</td><td>70</td><td></td></tr>
<tr><td>1km Config.[3]</td><td>1km</td><td>10m</td><td>22"λ_{mm}</td><td>**0.19"λ_{mm}**</td><td>230</td><td></td><td></td><td></td></tr>
<tr><td>Nkm Config.[4]</td><td>Nkm</td><td>10m</td><td>22"λ_{mm}</td><td>**(0.19"/N)λ_{mm}**</td><td>230N</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

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[1] Boldface entries identify the resolution of the instrumental configuration

[2] Total Power/Beam Switching Observing Mode

[3] Aperture Synthesis Observing Mode

[4] Phase Closure Calibration Mode

Figure 4

The previous material deals basically with the resolutions and fields of view that can be obtained with the paradigm Millimeter Array. The next major category of array parameters deals with sensitivity to detection of point sources or extended sources.

The principal sensitivity parameters for an aperture synthesis array are: system temperature (T_{sys}, in units of °K); antenna diameter (D_m, in units of meters); bandwidth ($\Delta\nu_{GHz}$, in units of GHz); integration time (Δt_{min}, in units of minutes); and the number of antenna pairs ($N_B = N(N-1)/2$, where N is the number of antennas in the array). Assuming a three-level correlator, the rms noise for each image pixel (or point source detection sensitivity) is given by (cf. MMA Memo 33):

$$\sigma = 1.71\ (T_{sys}/100)/\{(D_m/10)^2[\Delta\nu_{GHz}\ \Delta t_{min}(N_B/210)(n_a/n_M)]^{1/2}\}\ \text{mJy} \qquad (1)$$

adopting scaling parameters appropriate to snapshot observations with 21 antennas of 10 m diameter, a 1 GHz bandwidth (appropriate for continnum problems), and a system temperature (100 K) appropriate to the 3 mm region. In Equation (1) n_a is the average number of data points per occupied cell in the gridded u-v plane, a quantity which is dependent upon the adopted weighting and tapering. With no tapering and "natural" weighting, $n_a = n_M$, the mean number of data points in each occupied cell, whereas for no tapering and "uniform" weighting, $n_a = n_{HM}$, the harmonic mean number of data points per occupied cell. These two types of means are indicators of the distribution of data points in the u-v plane, and hence are important array parameters.

Surface brightness sensitivity is derived from equation (1), the scaling constant between Jy/beam and brightness temperature, and the synthesized beam solid angle. Although the synthesized beam solid angle ($\Omega_b = 1.1331\theta_b^2$) is dependent upon array geometry, one predictable case is that of the beam for a uniformly filled (or weighted) array (with maximum diameter or baseline, B_{km}, in units of km). The rms surface brightness sensitivity is then given by

$$\Delta T_b = 0.64(T_{sys}/100)[B_{km}/(D_m/10)]^2/\{f_{geom}[\Delta\nu_{GHz}\ \Delta t_{min}(N_B/210)(n_a/n_M)]^{1/2}\}\ \text{K} \qquad (2)$$

where we have defined f_{geom} to be the ratio of the true beam solid angle angle (Ω_b) to that for a uniformly filled aperture ($\Omega_{b,un}$). T_{sys} is determined by

$$T_{sys} = T_{rcvr} + T_{atmo}[1 - \exp(-\tau_1 \sec \zeta)] \qquad (3)$$

where τ_1 is the optical depth for unit air mass (at the zenith), ζ is the zenith angle, and for simplicity we approximate the air mass by sec ζ. While $T_{atmo} = 280$ K is a reasonable estimate, the value of T_{rcvr} varies as a function of frequency and τ_1 varies with both frequency and atmospheric conditions. Based on discussions of probable receiver sensitivities in the future, we will adopt $T_{rcvr} = 100(\nu_{GHz}/100)$ K (single side band).

The following Table 1 is an updated version of the sensitivity parameters listed in the table in MMA Memo 29, but with 21 antenna configurations for the arrays of 10 m antennas (Y21, a VLA-like configuraion; R5CIR21, a circular array with randomized antenna locations; and FCIR90M, a filled circle array which is 90 m in diameter) and one possible 21 antenna configuration of 4 m antennas in a Multi-Telescope array (TRACKM21).

Figure 5 is a plot of ΔT_b as a function of array size (B_{km}), for the smaller MMA configurations and observing situations with eight hour of integration time, 21 antennas with diameters of 10m or 4m, and an average system temperature of 100 K. The left abscissa of Figure 5 is for the 1 GHz banddwidth appropriate to continuum problems and the right abscissa is for spectral line problems with 100 kHz channel width. The line with alternating long and short dashes is Equation (2) with $f_{geom} = 1$ and $n_a = n_M$. The other lines and symbols are obtained from correct computations (cf. Table 1) of f_{geom} and n_a, for both uniform and natural weighting, for the Y21, R5Cir21, FCir90m, and TrackM21 configurations.

In addition to quantities already defined, Table 1 contains entries for σ_{sid}, a fractional estimate of the beam sidelobe level (for natural and uniform weighting) as defined by Cornwell in MMA memo 18. The numbers in Table 1, the plots in Figure 5, and the coefficients in the above equations reflect system temperatures of 100 K. For other system temperatures one multiplies σ and ΔT_b by (T_{sys}/100). When both polarizations are combined these quantities are divided by 1.414 because the coefficents in Equations (1) and (2) are then 1.21 and 0.45, respectively.

Table 1

Summary of Parameters for $\delta = 60°$ Obs. with Various Arrays and $T_{sys} = 100°$

Config.	Y21		R5CIR21		FCIR90M		TRACKM21		
Config. Diam.	300 m.		300 m.		90 m.		25 m.		
Antenna Diam.	10 m.		10 m.		10 m.		4 m.		
Gr. u-v Plane	71 X 71		71 X 71		17 X 17		15 X 15		
Obs. Time	8^h	2^m	8^h	2^m	8^h	2^m	8^h	2^m	
n_{HM}/n_M	0.26	0.93	0.67	0.99	0.18	0.77	0.13	0.60	
f_{geom}	5.8	2.1	1.1	1.0	1.9	1.3	2.0	1.6	
$\sigma_{sid,nat}/\lambda_{mm}$	.0325	.0565	.0200	.0499	.0717	.0798	.1006	.1064	
$\sigma_{sid,un}/\lambda_{mm}$	.0189	.0526	.0171	.0494	.0570	.0700	.0754	.0857	
$\theta_{b,nat}/\lambda_{mm}$	1.30"	1.20"	0.51"	0.49"	2.09"	1.99"	6.95"	6.90"	
$\theta_{b,un}/\lambda_{mm}$	0.54"	0.82"	0.48"	0.49"	1.53"	1.75"	4.88"	5.44"	
σ_{nat}(mJy)	0.079	1.22	0.079	1.22	0.079	1.22	0.49	7.6	Divide by 1.414 when both polarizations are combined
σ_{un}(mJy)	0.154	1.28	0.096	1.23	0.187	1.40	1.38	9.9	
$\Delta T_{b,nat}$(mK)	0.64	11.5	4.07	68.8	0.25	4.2	0.14	2.2	
$\Delta T_{b,un}$(mk)	7.08	25.8	5.62	69.1	1.12	6.2	0.79	4.5	

The sensitivity numbers in Table 1 are reasonable estimates for 100 GHz observations under good atmospheric conditions, however they are always too small at least a factor of 3 for observations above 200 GHz because of atmospheric absorption and emission. In Equation (3) we expressed the system temperature as a composite of receiver noise and the effects of observing emission from a relatively "hot" atmosphere. However, absorption of the source signal, so that observation of a source with brightness temperature T_b through an atmosphere with temperature T_{atmo}, zenith optical depth of τ_1, and zenith angle ζ will give an observed brightness temperature which is

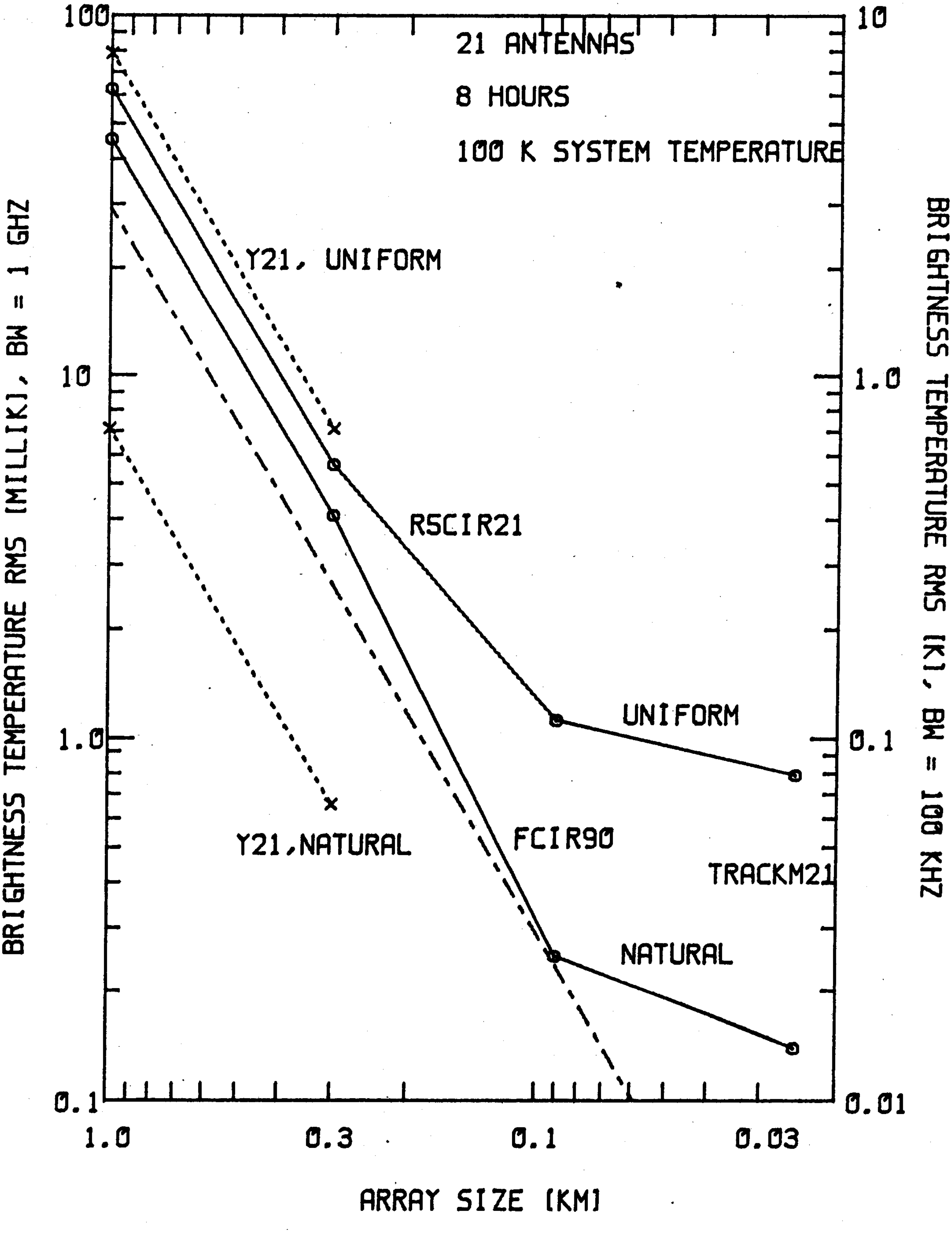
21 ANTENNAS
8 HOURS
100 K SYSTEM TEMPERATURE
Y21, UNIFORM
R5CIR21
UNIFORM
Y21,NATURAL
FCIR90
TRACKM21
NATURAL
BRIGHTNESS TEMPERATURE RMS (MILLIK), BW = 1 GHZ
BRIGHTNESS TEMPERATURE RMS (K), BW = 100 KHZ
100
10
1.0
0.1
10
1.0
0.1
0.01
1.0
0.3
0.1
0.03
ARRAY SIZE (KM)

Figure 5

$$T_{b,obs} = T_b \exp(-\tau_1 \sec \zeta) \quad . \tag{5}$$

The purpose of sensitivity Equations is to evaluate the signal to noise for observations of sources of flux density S_ν and brightness temperature T_b. For this purpose the dependence on reciever temperature and atmosphere is

$$S_\nu/\sigma = T_b/\Delta T_b \propto \exp(-\tau_1 \sec \zeta)/\{T_{rcvr} + T_{atmo}[1 - \exp(-\tau_1 \sec \zeta)]\} \tag{6}$$

so one can define an effective system temperature,

$$T_{sys,eff} = \{T_{rcvr} \exp[\tau_1 \sec \zeta] + T_{atmo} [\exp(\tau_1 \sec \zeta) - 1] \tag{7}$$

that includes the atmospheric effects of both emission and absorption. Equation (7) should be used with Equations (1) and (2) to determine the effective signal/noise, and for $\nu \geq 200$ GHz, the atmosphere can dominate $T_{sys,eff}$.

Unfortunately, it is necessary to adopt typical values for τ_1 in order to estimate properly signal/noise. Table 2 gives values of $T_{sys,eff}$ for the latitude of the VLA site, $T_{atmo} = 280$ K, frequencies of 100 and 230 GHz, declinations of 30°, 0°, and -30°, a range of values of τ_1, and the range of hour angles that can be accessed for each declination. Note that the observing time needed to obtain a particular level of signal to noise is proportional to $(T_{sys,eff})^2$.

Table 2 illustrates how strongly atmospheric absorption and emission affect the system temperature for the larger values of τ_1 and air mass. The top of Mauna Kea is known to frequently have τ_1 at 230 GHz in the range 0.1-0.15, while the NRAO 12m site has best days with $\tau_1 \sim 0.25$. It is restating the obvious to note that: (1) the lowest possible τ_1 at 230 GHz, for a reasonable amount of time, is an extremely important parameter of a site; (2) observing to large air masses is counter-productive in signal/noise-limited observations; and (3) since observations near meridian transit are most productive, one has another reason for requiring excellent synthesized beam characteristics for short observations.

Table 2

Values of $T_{sys,eff}$ for 100 and 230 GHz and a Range of Declinations, Zenith Optical Depths, and Hour Angles

```
Latitude, Declination: 34.0  30.0  freq(GHz):  100   Trcvr:  100 K
 HA =      0.0    1.0    2.0    3.0    4.0    5.0    6.0  hrs
  z =      4.0   13.3   25.7   38.1   50.3   62.3   73.8  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       100    100    100    100    100    100    100  degrees K
0.05       120    120    122    125    131    143    174  degrees K
0.10       140    141    145    151    164    191    263  degrees K
0.15       162    163    169    180    201    245    370  degrees K
0.20       184    187    194    210    240    304    497  degrees K
0.25       208    211    221    242    282    370    649  degrees K
0.30       233    237    250    276    328    444    831  degrees K
0.35       260    264    280    313    377    526   1049  degrees K
0.40       287    293    312    352    431    617   1309  degrees K
0.45       317    323    346    393    489    719   1620  degrees K
0.50       347    355    382    437    551    833   1992  degrees K
0.55       380    389    419    484    619    959   2437  degrees K
0.60       413    424    459    534    692   1099   2969  degrees K
0.65       449    461    502    588    772   1256   3605  degrees K
0.70       487    500    546    645    857   1430   4366  degrees K
0.75       526    541    593    705    950   1624   5276  degrees K
0.80       567    585    643    770   1050   1840   6364  degrees K
0.85       611    630    696    839   1158   2080   7665  degrees K
0.90       657    678    751    912   1275   2348   9220  degrees K
0.95       705    729    810    990   1402   2646         degrees K
1.00       755    782    872   1073   1539   2978         degrees K
```

```
Latitude, Declination: 34.0  30.0  freq(GHz):  230   Trcvr:  230 K
 HA =      0.0    1.0    2.0    3.0    4.0    5.0    6.0  hrs
  z =      4.0   13.3   25.7   38.1   50.3   62.3   73.8  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       230    230    230    230    230    230    230  degrees K
0.05       256    257    259    263    272    288    330  degrees K
0.10       284    285    290    299    316    352    449  degrees K
0.15       313    315    322    337    365    424    592  degrees K
0.20       343    346    357    378    418    504    763  degrees K
0.25       375    379    393    421    474    593    967  degrees K
0.30       409    414    431    467    536    692   1211  degrees K
0.35       444    451    472    516    602    802   1503  degrees K
0.40       482    489    515    568    674    925   1852  degrees K
0.45       521    530    560    623    752   1061   2270  degrees K
0.50       562    573    608    682    836   1213   2769  degrees K
0.55       605    618    659    746    927   1383   3367  degrees K
0.60       651    665    712    813   1025   1571   4081  degrees K
 .65       698    715    769    884   1131   1781   4934  degrees K
0.70       749    767    829    961   1246   2015   5956  degrees K
4.75       802    822    892   1042   1371   2275   7177  degrees K
0.80       857    880    959   1129   1505   2565   8637  degrees K
6.85       916    942   1030   1221   1650   2888         degrees K
0.90       977   1006   1104   1320   1808   3247         degrees K
0.95      1042   1074   1183   1425   1978   3647         degrees K
1.00      1110   1145   1267   1536   2162   4092         degrees K
```

```
Latitude, Declination: 34.0   0.0  freq(GHz):  100   Trcvr:  100 K
 HA =      0.0    1.0    2.0    3.0    4.0    5.0  hrs
  z =     34.0   36.8   44.1   54.1   65.5   77.6  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       100    100    100    100    100    100  degrees K
0.05       124    124    127    134    149    200  degrees K
0.10       149    151    157    171    204    326  degrees K
0.15       175    178    188    211    266    485  degrees K
0.20       204    208    222    255    336    685  degrees K
0.25       234    239    258    302    415    938  degrees K
0.30       266    273    297    354    504   1258  degrees K
0.35       300    308    339    410    604   1662  degrees K
0.40       336    346    383    472    717   2171  degrees K
0.45       374    387    431    539    845   2815  degrees K
0.50       415    429    482    612    990   3627  degrees K
0.55       458    475    537    691   1152   4652  degrees K
0.60       504    524    596    778   1336   5946  degrees K
0.65       552    576    660    872   1543   7579  degrees K
0.70       604    631    727    974   1777   9642  degrees K
0.75       659    689    800   1086   2040         degrees K
0.80       717    752    878   1207   2338         degrees K
0.85       779    818    961   1340   2673         degrees K
0.90       845    889   1051   1484   3052         degrees K
0.95       915    965   1147   1641   3479         degrees K
1.00       990   1045   1250   1812   3961         degrees K
```

```
Latitude, Declination: 34.0   0.0  freq(GHz):  230   Trcvr:  230 K
 HA =      0.0    1.0    2.0    3.0    4.0    5.0  hrs
  z =     34.0   36.8   44.1   54.1   65.5   77.6  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       230    230    230    230    230    230  degrees K
0.05       262    263    267    275    295    364  degrees K
0.10       295    298    306    325    369    533  degrees K
0.15       331    335    348    379    452    746  degrees K
0.20       369    375    394    437    546   1015  degrees K
0.25       409    417    442    501    652   1355  degrees K
0.30       452    462    495    571    772   1784  degrees K
0.35       498    510    550    647    907   2326  degrees K
0.40       546    560    610    729   1059   3010  degrees K
0.45       598    615    674    819   1230   3873  degrees K
0.50       652    672    743    917   1424   4963  degrees K
0.55       710    734    817   1023   1642   6339  degrees K
0.60       772    799    896   1139   1889   8076  degrees K
0.65       837    868    981   1266   2167         degrees K
0.70       907    942   1072   1403   2480         degrees K
0.75       980   1021   1170   1553   2834         degrees K
0.80      1059   1105   1274   1716   3233         degrees K
0.85      1142   1194   1386   1894   3684         degrees K
0.90      1230   1289   1506   2088   4192         degrees K
0.95      1324   1390   1635   2299   4765         degrees K
1.00      1424   1498   1773   2528   5412         degrees K
```

```
Latitude, Declination: 34.0 -30.0  freq(GHz):  100   Trcvr:  100 K
 HA =      0.0    1.0    2.0    3.0  hrs
  z =     64.0   65.5   70.0   76.8  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       100    100    100    100  degrees K
0.05       146    149    160    193  degrees K
0.10       197    204    229    309  degrees K
0.15       255    266    309    453  degrees K
0.20       320    336    402    633  degrees K
0.25       392    415    509    857  degrees K
0.30       473    504    633   1136  degrees K
0.35       564    605    777   1483  degrees K
0.40       666    719    943   1915  degrees K
0.45       781    847   1136   2453  degrees K
0.50       909    992   1358   3123  degrees K
0.55      1053   1155   1616   3957  degrees K
0.60      1213   1339   1914   4995  degrees K
0.65      1394   1547   2260   6288  degrees K
0.70      1596   1782   2659   7898  degrees K
0.75      1823   2047   3122   9903  degrees K
 .80      2077   2345   3657         degrees K
0.85      2362   2682   4276         degrees K
0.90      2681   3063   4993         degrees K
0.95      3039   3492   5823         degrees K
 .00      3439   3976   6783         degrees K
```

```
Latitude, Declination: 34.0 -30.0  freq(GHz):  230   Trcvr:  230 K
 HA =      0.0    1.0    2.0    3.0  hrs
  z =     64.0   65.5   70.0   76.8  degrees
tau        Tsys = Trcvr*EXP(tau*sec z) + Tatmo*[EXP(tau*sec z) - 1]
0.00       230    230    230    230  degrees K
0.05       292    295    310    355  degrees K
0.10       361    369    403    511  degrees K
0.15       438    453    511    704  degrees K
0.20       525    547    635    946  degrees K
0.25       622    653    779   1246  degrees K
0.30       731    773    946   1620  degrees K
0.35       853    908   1138   2086  degrees K
0.40       990   1061   1362   2666  degrees K
0.45      1144   1233   1620   3388  degrees K
0.50      1316   1427   1919   4287  degrees K
0.55      1508   1646   2265   5406  degrees K
0.60      1724   1893   2665   6800  degrees K
0.65      1967   2172   3128   8535  degrees K
0.70      2238   2487   3665         degrees K
0.75      2542   2843   4285         degrees K
0.80      2883   3244   5004         degrees K
0.85      3265   3696   5835         degrees K
0.90      3694   4206   6797         degrees K
0.95      4174   4782   7910         degrees K
1.00      4712   5433   9199         degrees K
```