25 METER - MILLIMETER WAVE TELESCOPE

REPORT # 2

A CONSIDERATION OF FUTURE POSSIBILITIES FOR RADIO TELESCOPE SYSTEMS IN THE 1-9 mm WAVELENGTH REGION

W. E. Howard
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HISTORICAL BACKGROUND: The present push for telescopes and instrumentation for the millimeter region of the spectrum had its roots almost two decades ago when Coates and his co-workers at NRL first used millimeter wave systems in radio astronomy. Little attention was devoted to that work because more exciting gains in instrumentation were taking place in the centimeter range of the spectrum where, during the 1950's and early 1960's, larger antenna systems were under design or construction that were to take full advantage of the new, lower noise temperature receivers that were being developed. At least twice in the history of radio astronomy there were critics who claimed that the new dishes being planned could not possibly pay off scientifically since it was "well-known" that there were only five or six sources in the sky that could be observed. Specifically the criticism was levelled at the 25 m antennas in the late 1950's that were to operate at 3 cm and at the 5-11 m antennas in the mid 1960's that were to operate at millimeter wavelengths. These critics failed to realize, of course, that improved receivers and other ancillary equipment would permit far more radio sources to be observed than had earlier been predicted and, perhaps more important, that these systems would open entirely new fields of radio astronomy for exploration. As these new observing systems came into operation, earlier uncertainty was allayed as the frontiers of radio astronomy were extended to shorter wavelengths.

It is both interesting and instructive to observe the efforts of radio telescope designers during the golden era of scientific funding, the 1960's. The Whitford Report in 1964 proposed the construction of what is now called the "VLA", a very large, high-resolution, pencil-beam array with low side-lobes to be constructed as a U.S. national facility. The design of this array is now well underway, the initial stages of funding have been achieved and the instrument will begin partial operation in the late 1970's and full operation in the early 1980's. The need for single dishes was not overlooked by the Whitford Committee. They recommended that two fully steerable 300 ft paraboloids be built, probably as university-based, or regional facilities, but despite some design activity, no proposals to build such a dish were successful in the United States. The Committee also recommended that an engineering study be undertaken to determine the largest possible steerable parabolic antenna that could be constructed. Such a study was carried out by J. W. Findlay and co-workers at NRAO in the mid-1960's who found that it was possible to construct a 200 m telescope that would operate satisfactorily at 10 cm wavelength for a cost of approximately $45 million (1966 dollars). Since that time radio astronomers have designed a number of large steerable telescopes that have included the NEROC 134 m, the British 114 m, the W. German 100 m and the NRAO "homology" 65 m telescopes. It is no coincidence that the sequence in which these designs were developed is, in general, a sequence of continually decreasing telescope diameter and, simultaneously, a sequence of continually decreasing operating wavelength. By the late 1960's the greatest advances in receiver development were being made at long millimeter wavelengths and as the desired operating wavelength for a telescope under design became shorter, cost and engineering constraints were forcing a corresponding reduction in antenna diameter.

Two of these major telescope designs have been successful to the point of funding expectation (the British 114 m telescope) or of operation (the W. German 100 m telescope). A third, a giant ground plane reflector of 576 m diameter and 7.4 m height, is under construction in the Caucasus, USSR and, when complete, will operate at wavelengths down to 8 mm. These instruments are, or will shortly be, preeminent in the centimeter wavelength region of the spectrum. All are located outside the U.S. and there is some concern that this country will not have a competitive, centimeter-wave single parabola for many years in the future. The VLA is viewed by most radio astronomers as the national instrument that will keep the U.S. competitive in centimeter wave radio astronomy in the 1980's.

In 1972 American astronomers summarized their recommendations for major new programs for the coming decade in what is commonly referred to as the Greenstein Report. The VLA received highest priority by this Astronomy Survey Committee. The Committee agreed that funding was urgently needed for the construction of a large millimeter wavelength antenna, which appeared as one of seven additional programs, but they cautioned that such funding should not create a delay in funding the VLA.

PRESENT STATUS: Figure I summarizes the highest operating frequency that can be utilized on existing and proposed radio telescopes. We note that the two telescopes having the largest diameter that can operate in the 3-10 mm wavelength range are both located outside the United States and that the NRAO 11 m telescope is preeminent only in the range ~110-150 GHz if one discounts the receivers and auxilliary equipment on the antennas at lower frequencies. Confining the discussion to antennas larger than 10 m, we see that only seven antennas in the world can operate at long millimeter wavelengths and, of these, only two are capable of operating below 3 mm. Only three out of these seven systems are in the United States.

FUTURE SYSTEMS: Several possibilities for new millimeter wave telescope systems have been proposed or discussed recently. Table 1 summarizes these proposals according to whether the development involves the NRAO, a US, but non-NRAO development or a foreign development. Before discussing these suggestions and proposals, let us attempt to organize our thinking by the following quantitative but crude analysis.

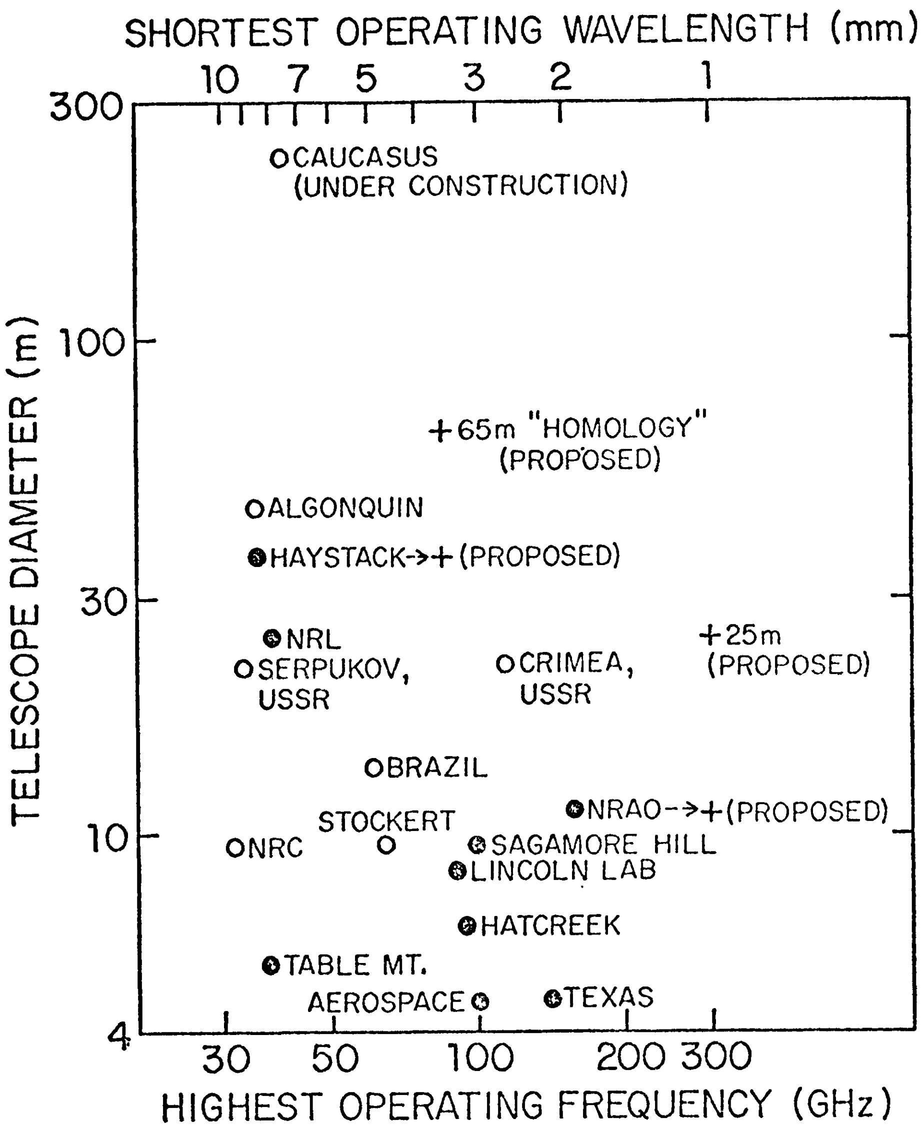
SHORTEST OPERATING WAVELENGTH (mm)
10 7 5 3 2 1
300
100
30
10
4
TELESCOPE DIAMETER (m)
CAUCASUS (UNDER CONSTRUCTION)
+65m "HOMOLOGY" (PROPOSED)
ALGONQUIN
HAYSTACK->+(PROPOSED)
NRL
SERPUKOV, USSR
CRIMEA, USSR
+25m (PROPOSED)
BRAZIL
NRAO->+(PROPOSED)
STOCKERT
NRC
SAGAMORE HILL
LINCOLN LAB
HATCREEK
TABLE MT.
AEROSPACE
TEXAS
30 50 100 200 300
HIGHEST OPERATING FREQUENCY (GHz)

Figure I.

Table 1

SUGGESTIONS OR PROPOSALS FOR FUTURE MILLIMETER WAVE TELESCOPE SYSTEMS
(Estimated Costs in parentheses for US proposals)

US (NRAO)	US (non-NRAO)	Foreign
1. Resurface the 11 m telescope to double the highest operating frequency ($0.3M).	1. Resurface the Hay-antenna for ~90 GHz operation ($2.5M).	1. French 3-element interferometer (funded).
2. Build the proposed 65 m "homology" antenna ($12M).	2. Acquire single 3-6 m antennas at universities ($0.2-0.8M).	2. Designs of ~25 m antennas in Australia and W. Germany.
3. Build a 25 m antenna capable of performance at 1 mm ($3.5M).	3. Build one or more university-based millimeter-wave interferometers using 4-10 m antennas ($0.8-3M).	3. Construction of ground plane reflector in Caucasus, USSR for operation to 8 mm.
4. Build a millimeter-wave interferometer ($1-4M).		4. Discussions involving joint US-foreign design, construction and operation of telescope in US or So. Hemisphere site.
5. Acquire a 10 m "Leighton" IR antenna and equip it for mm work ($1.5M).		5. Other discussions in England, Japan and Sweden.

<u>THE (65-m, 3.5 mm) "HOMOLOGY" TELESCOPE AND THE (25-m, 1 mm) TELESCOPE:</u>
Let us assume that it will take five years to construct either of these instruments. We may ask what receiver noise temperatures we might expect at 1, 3.5 and 9 mm wavelengths five years from now and then compare the performance of each of these instruments in terms of what we can presently accomplish on the 11 m telescope near Tucson. Present system noise temperatures are of the order of 1200 K at 9 and 3.5 mm and 5000 K at 1 mm.

In five years, S. Weinreb estimates that the receiver noise will be reduced to 100 K, 100 K and 200 K, respectively. If we add an additional 30, 35 and 40 K for other sources of antenna and background noise, we have predictions of 130, 135 and 240 K for system noise temperatures in five years. In terms of the time taken to reach a given sensitivity, and taking the bandwidths of the receivers to be the same, we anticipate improvements of factors of $(1200/130)^2 = 85$ at 9 mm, $(1200/135)^2 = 79$ at 3.5 mm and $(5000/240)^2 = 430$ at 1 mm. Similarly, improvements in time needed to reach the same sensitivity will be achieved because the antenna will be larger. These factors are $(25/11)^2 = 5.2$ for a 25 m antenna and $(65/11)^2 = 35$ for a 65 m antenna, assuming that the antenna surface accuracies are identical to the accuracy of the NRAO 11 m antenna. The total improvement in the time needed to reach a given sensitivity is the product of the receiver and antenna-size factors and these are summarized for each antenna and at each wavelength in Table 2, together with the improvements that might be realized by improving the surface of the Haystack (36.5 m) antenna--relative to the 11 m antenna system performance at present.

Table 2

RELATIVE IMPROVEMENTS IN SYSTEM PERFORMANCE FOR PROPOSED TELESCOPES
(Improvement is expressed in reduction of time
required to obtain a given sensitivity)

Antenna Diameter (m)	$\lambda = 9$ mm	$\lambda = 3.5$ mm	$\lambda = 1$ mm
65 , in five years	3000	2800	(1500)
36.5 , in five years	940	870	(470)
25 , in five years	440	410	2200
11 , in five years	85	79	850†
11 , now	1	1	1

† Assume resurfacing improves efficiency by a factor of 2.

The improvements to be expected at 1 mm operation on the 65 and 36 m telescopes are very uncertain since each will be operating essentially as a light bucket at that wavelength. We have assumed improvements of only 10% in antenna area due to the reduced aperture efficiencies anticipated. These "improvements" for the largest antennas at 1 mm may still be overestimated since the telescopes could be totally inoperative at that wavelength.

Tables 3 and 4 give the beamwidths that would be achieved and the pointing accuracies that would be required on each of the telescope systems at each frequency. Table 4 assumes that the pointing accuracies should be 0.2 beamwidth and errors due to pointing will be approximately 4% in flux density for a point source. If the tolerable error is only 1%, one would need 0.1 beamwidth accuracy in the pointing (i.e., 0.1 the values given in Table 3).

	Table 3			Table 4		
	BEAMWIDTH AT WAVELENGTH:			POINTING REQUIREMENT AT WAVELENGTH:		
Antenna Diameter (m)	9 mm	3.5 mm	1 mm	9 mm	3.5 mm	1 mm
65	35"	14"	4"	7"	3"	0".8
36.5	1'	24"	7"	12"	5"	1".4
25	1'.5	35"	10"	18"	7"	2"
11	3'.5	1'.3	23"	42"	15"	5"

DISCUSSION

A. Comparisons: It is clear from Table 2 that the impact of building the 65 m telescope affects the middle-to-long millimeter wavelength region rather than the short millimeter region where its operating characteristics are questionable. It is also clear that the major impact of building the 25 m telescope will be at the short millimeter wavelengths. In effect, resurfacing the Haystack antenna will result in a system that is about twice as good as the 25 m antenna at the mid-to-long millimeter wavelengths, but is only about one-third as effective as the homology telescope would be. We assume that the Haystack radome will cause no serious attenuation down to 3 mm.

From Table 4 and Table 2 we see that the pointing requirements of these systems are all in excess of about 2" arc and when the antenna surfaces do not permit observing at 1 mm wavelength (viz, for the 36.5 and the 65 m antennas), the pointing requirements also exceed the capabilities of the antenna (viz, about 3" arc for both antennas).

The case for acquiring a 10 m "Leighton" IR antenna is not a strong one. The diameter would not be larger than the present NRAO 11 m antenna and, although the antenna may be relatively inexpensive, the costs rise as one mounts it, equips it and starts a separate site. Regardless of where that site would be, we would probably want to continue the operation of the 11 m antenna and the NRAO would find itself with two antennas of roughly equal capability. Cost considerations would probably rule out an undeveloped site and thus only two sites would be in contention, Kitt Peak and the VLA site. In terms of today's monetary climate and the fact that construction at the VLA site is still in its very early stages, any near-term acquisition of a "Leighton" antenna for that site, independent of the VLA as a system, appears unwarranted. Resurfacing the 11 m NRAO antenna appears to be more attractive and it will accomplish better 1 mm results at lower cost.

The case for starting a few millimeter-wave single dish systems at universities appears to be relatively strong. They are inexpensive and can be exceptionally useful as test-beds for millimeter-wave instrumentation. The successful organizations will probably be those who have already exhibited a strong millimeter-wave program or who have the potential of combining the efforts of capable electronics and astronomy-physics teams from various departments in the university.

B. Single-Dish vs. Interferometer: Under the basic assumption that the general levels of effort in support of any new area of science should require a small number of large, unique instruments supported by a larger number of smaller systems, we find it hard to avoid the conclusion that there will be fewer interferometers than single antennas, particularly at the early stages of development of millimeter wave astronomy. This is presently the case. Only now are millimeter-wave interferometers being constructed or seriously proposed after more than five years of exploration by single antenna systems. Because of this time lag, less is known of the potentialities of interferometric techniques in this wavelength region than is known of the potentialities of larger, single antenna systems. Because millimeter-wave interferometry is still relatively undeveloped, because the NRAO is heavily committed to centimeter-wave interferometry and because US universities (e.g., Berkeley, Cal Tech, U. Mass., MIT, etc.) are already proposing or constructing millimeter-wave interferometers and have shown both interest and competence in building these systems, it is proposed that NRAO not become engaged in millimeter interferometry for the next few years. After the potentialities of the technique are proven and when sufficient US-user demand has been generated as the science progresses, it would then be appropriate to re-open the question of the development of a flexible, national, visitor-oriented millimeter wave interferometer system. In the interim we should encourage university-based efforts in order to explore and develop the technique.

C. Some Non-Scientific Considerations: It is quite clear that within the period 1973-1981 the major funding for new construction in radio astronomy will go almost exclusively to the VLA, at an anticipated rate of $10M annually. The NRAO, NSF and the Greenstein report recommendation are in good agreement on this point. Yet if sufficient pressures are brought to bear from within the scientific community, it may be possible to fund a limited number of relatively low-cost projects in the millimeter wave area while funding for the VLA continues. With this expectation in mind, let us explore some of our previous considerations in terms of cost-effectiveness as well as in terms of absolute cost.

Let us return to Table 2 and adopt the cost estimates given in Table 1. Based on certain assumptions, the numbers in Table 2 represent performance estimates for each telescope at each frequency in the table. Let us somewhat naively take these estimates and divide them by the cost involved in producing the increase in millimeter-wave capability. These improvement-per-dollar estimates are given in Table 5. The result in Table 5 is striking. First, resurfacing the NRAO 11 m antenna is markedly cost-effective at the very short wavelengths where no other radio

Table 5

RELATIVE IMPROVEMENTS-PER-DOLLAR
IN SYSTEM PERFORMANCE FOR PROPOSED TELESCOPES

Antenna Diameter (m)	$\lambda = 9$ mm	$\lambda = 3.5$ mm	$\lambda = 1$ mm
65	250	230	(125)
36.5 (resurfaced)	380	350	(190)
25	130	120	630
11 (resurfaced)	85	79	2900

telescope now operated. While the 25 m telescope is over 2.5 times better in absolute terms (Table 2), the cost-effectiveness of resurfacing the 11 m telescope seems beyond doubt. Similar reasoning leads us to conclude that resurfacing the Haystack antenna gives us the greatest step-per-dollar at the middle-to-long millimeter wave region of the spectrum. In terms of cost effectiveness, then, the two resurfacing proposals appear to be the most economical steps to take in the immediate future. Table 2 shows them to be among the least expensive alternatives as well--a fortunate coincidence, since it enhances the chances for funding.

If we confine our attention for the moment to the issue of the (65 m, 3.5 mm) telescope vs. the (25 m, 1 mm) telescope, we find from Table 2 that our choice, in NRAO terms, is one of deciding whether to replace the 140 foot or the 36 foot telescope. If the 25 m telescope is built, it will render the 36 foot telescope obsolete since its performance throughout the spectrum will be superior. Similarly, if the 65 m were built, it would render the 140 foot obsolete for the same reason. However, in the absence of the 25 m telescope, a 65 m telescope would also take all the proposals longward of 3 mm, absorbing the 140 foot and many 36 foot programs. While there may be strong economic reasons for substituting one antenna for two, it is doubtful that such a move would be wise in view of the strong pressures for observing time on both telescopes that are still anticipated in the future. In short, the 65 m telescope is not large enough to satisfy the steerable, single dish enthusiasts at centimeter wavelengths and does not operate sufficiently well at the very short millimeter wavelengths to satisfy the enthusiasts at short millimeter wavelengths. While well-conceived in its design prior to the discovery of the CO line at 2.6 mm, it is not an optimum compromise for the future, which seems to involve the construction of smaller antennas with surfaces of higher precision. Indeed, looking even farther into the future, it would not be surprising to see the evolution of our arguments complete a cycle and begin again with new reasons to build a very large centimeter-wave steerable telescope. But for the present, the trend is toward the 1 mm wavelength region.

It is intuitively obvious that if the design goal of, say, a 25 m telescope is efficient operation at 1 mm wavelength, the telescope should be located at a relatively dry, cloud-free site, and this probably means the southwestern United States. The site selection criteria for a larger millimeter-wave telescope are less clear, however. Provided the diameter of the large antenna is large enough to attract observers at centimeter wavelengths, only a fraction of the antenna time will be devoted to millimeter-wave observing. If that fraction is less than the fraction of clear days at a potential site, the site is still a viable one as long as the operating frequency can be changed relatively quickly (i.e., in about an hour), even though the site may be non-optimum from the point of view of rain or cloud cover. This means that the Haystack site or Green Bank remain in contention for resurfacing or for new antennas that have diameters equal to, or exceeding 35 m, as long as the time-weather fractional criterion is met. Weather contingency scheduling is the answer in this case.

D. A Suggested Design and Building Program: The following schedule in Table 6 is based on the preceding arguments and considerations. Foreign efforts are shown for comparison and represent only estimates of what may happen abroad.

Table 6

DESIGN AND CONSTRUCTION SCHEDULE FOR MILLIMETER WAVE TELESCOPES

Year	NRAO Effort	Non-NRAO, US Effort	(Foreign Effort)
1973	1. Begin Design to Resurface 11 m Telescope. 2. Begin Design of (25 m, 1 mm) Telescope. 3. Investigate Re-design of (65 m, <3 mm) Telescope.	4. Design to Resurface Haystack.	5. Continued Design of ~25 m Antenna.
1974	6. (Continue Designs Above).	7. Begin University Interf. #1 Construction. 8. Begin 1 or 2 Small Univ. Telescope.	9. Begin Construction French Interf. 10. Begin Construction 25 m Telescope.

Table 6 (cont'd)

Year	NRAO Effort	Non-NRAO,US Effort	(Foreign Effort)
1975	11. Resurface 11 m Telescope. Complete (25 m, 1 mm) Design. 12. Finalize 65 m Design.	13. Begin Resurface, Haystack. 14. Begin University Interf. #2 Construction.	15. Completion of 8 mm Caucausus Reflector.
1976	16. 11 m, Resurfaced, in Operation. 17. Begin Construction (25 m, 1 mm) Telescope.	18. Complete Interf. #1. 19. Resurfaced Haystack Operating. 20. 1 or 2 Univ. Telescopes in Operation.	21. 25 m in Operation. 22. French Interf. in Operation.
1977	23. Begin Eval. Next NRAO Step (Interf. vs. Single Larger Dish).	24. Complete Interf. #2.	
1978	25. (25 m, 1 mm) Telescope in Operation. 26. Begin Construction of Second 25 m or 65 m Antenna.		
1979	27. (Continue Construction).		
1980	28. Complete 65 m or Interferometer.		

Table 6 shows that by 1980 we might expect to have in operation the following millimeter-wave telescopes in the United States and abroad (Table 7).

Table 7

US (NRAO)	US (non-NRAO)	(Foreign)
• 11 m antenna, resurfaced.	• 36.5 m antenna, resurfaced.	• USSR Caucasus reflector.
• (25 m, 1 mm) telescope.	• 1 or 2 University telescopes.	• French interferometer.
• (65 m, <3 mm) telescope or interferometer composed of a. 65 m antenna or b. 25 m antenna.	• 2 Interferometers of 4-10 m antennas	• 1 or more single antennas of ~25 m size.

Note the advantages of the U.S. schedule:

1. The low-cost, cost-effective projects are done first.

2. Balance is achieved between NRAO and University-based efforts, at least to the extent experienced in the era 1965-1973.

3. NRAO continues to provide the large, costly facilities for visitor-use.

4. The Universities and foreign observatories explore interferometric techniques while NRAO concentrates in the early stages on large single dish design and construction.

5. There is little or no duplication of effort between NRAO and the University community.

6. The decision to build an NRAO millimeter wave interferometer is postponed until the technique has been explored. NRAO then builds an interferometer for general use <u>or</u> the 65 m telescope. The choice of interferometer component size is kept flexible as long as possible.

The total cost of this program, from Tables 1 and 6, is shown in Table 8, cumulative by year.

Table 8

By the Year	The Cumulative Funds Necessary to Complete the US Effort in Table 6 is:
1975	\$ 0.3M (11 m resurfaced)
1976	\$ 5.4M (Haystack resurfaced, \$2.5M + 2 antennas, \$1.0M + 1 interferometer, \$1.9M)
1977	\$ 7.3M (1 interferometer, \$1.9M)
1978	\$10.8M (25 m, 1 mm telescope, \$3.5M)
1980	\$14.8 <u>or</u> 22.8M (65 m telescope, \$12M <u>or</u> second 25 m, 1mm telescope, #3.5M)

Table 8 does not include instrumentation costs, estimated at less than \$1.0M, since many of these systems will be updated at NRAO as part of its normal operation of the 11 m telescope, nor does it include design costs for work done in the universities, also estimated at less than \$1.0M.

The proposal presented here would cost \$16-25M, spread over 7 years. It is an ambitious program and could be dropped to more modest proportions by eliminating one antenna resurfacing project, one university interferometer, one university antenna and by delaying the final 1980 NRAO effort. In this case the cost would approximate \$6-9M over the same time interval.

There is little doubt, as the arguments leading up to Table 2 have shown, that the major advances in millimeter-wave radio astronomy will be brought about largely through receiver improvements. We have chosen a five-year improvement interval in Table 2 because, for the optimum development of the science, the antenna improvements should be phased in with the receiver improvements and it takes aproximately five years, as a minimum, to conceive, propose, design, construct and start operating any new, state-of-the-art instrument.

This report has purposely not addressed its attention to the scientific programs to which these systems will be addressed. The reader is referred to pp 3-7 of the Findlay-von Hoerner monograph entitled "A 65-meter

Telescope for Millimeter Wavelengths" which has recently been given wide distribution, to various reports of observatories now engaged in millimeter-wave work or to write-ups on individual systems proposed here that go into the subject at length. In the era 1968-1973 during which the relatively modest NRAO 11 m system has been in operation, we have witnessed a virtual explosion of new scientific achievements and discoveries taking place. It is virtually impossible to predict the course of discoveries in the millimeter wave region through which instruments such as the ones summarized here will lead us. Perhaps this type of prediction and speculation may be the topic of a future "white paper" on the scientific future of millimeter-wave astronomy.