PROPOSED DESIGN

The design study which is described in this volume has had two major aspects: consideration of the physical nature of the performance limits of a large gravitational wave antenna system, and the conceptual engineering design of a complete system which could attain a high sensitivity for a reasonable cost. The scientific issues, such as sensitivity and the antenna noise sources, have been discussed in the sections I through V and in the appendices of the report written by MIT in consultation with the CalTech group. The conceptual design of the high capital cost parts of the system (which involve for the most part only well-known technology) is described in the sections written by the industrial consultants (section VI on the vacuum system by Arthur D. Little, Inc., and Sections VII and VIII on the siting and installation by Stone and Webster Engineering Co.).

In this final section of the report we describe the estimated total cost of a gravitational wave antenna system. At a minimum, such a system includes two large antennas, since detection of burst events or stochastic backgrounds is impossible with only one antenna. Preferably these two antennas should be separated by distances of continental scale. Thus, to arrive at a total system cost we must multiply the cost of a single antenna by a factor nearly equal to two. (The factor would be exactly two if there were no ways to share costs between the two installations.)

For discussion purposes, the system costs can be divided into capital costs and operating costs. Operating costs include the salaries of the scientific and technical staff, in addition to maintenance costs and the costs of consumables such as power and water. Capital costs consist of the cost of the vacuum system and the installation, detailed in the sections written by the industrial consultants, and also the costs of the scientific apparatus, estimated below. The funding schedule for the project can be derived by spreading the capital costs over the construction period, then adding the appropriate operating cost for each year of construction, instrument start-up, or scientific operation.

Throughout the work of the industrial consultants, the arm length of the interferometer was left unspecified within the range of 1 to 10 km, and the vacuum tube diameter was allowed to be anywhere from 12 to 48 inches. To arrive at a final estimated cost for the system, we are required to specify these dimensions of the apparatus. In making this decision, there is no unarguably right answer, although there are some wrong ones. The main reasons for this are the trade-offs that must be made between performance, risks and cost.

Three principles have guided our choices,

1) The antenna should not be so small that the fundamental limits of performance can not be attained with realistic estimates of technical capability. The question of system noise as a function of antenna length was addressed in detail in the discussion of the noise budget, section V. There it is shown that in order to reach

a regime where the system performance is independent of arm length (the shot-noise limit), the length must be greater than some minimum, which is itself a function of frequency, circulating light power and the assumption made regarding the suppression of the effect of stochastic forces. If performance at 1 kHz is the issue, noise within a factor of three of the shot noise limit of present laser intensities could be attained, in principle, with arms 500 meters long. However, the advent of increased circulating light powers would not improve the antenna sensitivity at 1 kHz in a 500 meter system, since the stochastic forces would dominate the noise budget with the present assumptions concerning our ability to reduce their effects. Reduction in risk and planning for the future argues for longer antenna length even at 1 kHz. At 100 Hz or below, where the electromagnetically coupled antenna is most promising, the noise is still decreasing nearly as the inverse first power of the length even at a length of 5 km.

2) The scale of the system should be large enough so that further improvement of the performance by a significant factor requires cost increments by a substantial factor. This means simply that it is unwise to build a system so small that the total cost is dominated by the fixed costs instead of by the variable (length-dependent) costs. As the discussion of the installation and vacuum system, sections VI and VIII, show, antenna lengths of several kilometers satisfy this condition.

3) Within reason no choice in external parameters of the present antenna design should preclude future internal design changes which, with advances in technology, will substantially improve performance. Examples of such planning are the following. The vacuum system is designed for operation at 10^{-6} mm Hg but no elements in it preclude operation at 10^{-8} mm Hg. The diameter of the vacuum tube should be large enough to allow future operation of multiple interferometers within the same tube or the implementation of the scheme to interchange beams in a search for periodic sources as proposed by Drever. In the long run a generous decision on the tube diameter will certainly pay off.

With these guiding principles in mind, we have chosen to propose two antennas each with 5 km arms using vacuum tubes of 48 inch diameter. The proposed construction technique is to bury the pipes below ground surrounded by a cover, option 3 of the Stone and Webster Engineering Study.

The decision to choose 48" diameter tubes is not mandated by the needs of a first generation design but follows guiding principle number three and furthermore appears prudent in considering the costs. In a 5 km antenna the difference in overall costs in going from the minimum usable diameter of 24" to 48" is a 15% increment in capital costs of the system giving a factor of 4 increase in beam area and considerably more safety in alignment sensitivity and the effects of light scattering.

The most controversial decision is to use a cover for the vacuum tube. Approximately $14M is tied up in the cover for two 5km arm length antennas. Several factors are involved in this decision. First, the study of mine sites, which would eliminate the need for a cover, is not at present sufficiently definitive in costing and in determining mine site availability or tunnelling accessibility to be a strong candidate for a realistic proposal. This will be studied further with the hope that the detailed investigation of specific mines may uncover means of saving over the generic tunnelling costs used in the Stone and Webster report.

Second, once having decided to bury the pipe which is driven by considerations of thermal stability, reduction of wind induced noise, apparatus safety and environmental impact; the cover could become unnecessary. The utility companies regularly bury gas pipes in shallow trenches backfilled with soil.

The concept of burying the gravity antenna vacuum tubing directly without a cover is being studied further but at present the best engineering judgement is to employ the cover. It eases the difficulties of leak testing and alignment during construction, it reduces the risk of injury during backfilling operations and facilitates the ability to repair leaks and maintain alignment during antenna operation.

Finally, approximately $7M is included in the estimated budget for power transmission and distribution costs to two antennas. These are fixed costs independent of antenna length and may not be needed if both sites are already developed and there is sufficient power available.

The design and construction of a pair of large antennas will require more people than currently work on the MIT and CIT gravity experiments. An efficient effort will necessitate separating the job into several tasks among which are: data acquisition and analysis, optics, and suspension systems. We expect each task will require two to three Ph.D.'s during the initial design and additional staff during the later stages of design and construction. The additional people added would be postdocs, graduate students, and technical and administrative support. We estimate that nearly thirty people will be needed for the project, more than doubling the current total effort at both institutions. The details of our personnel projection are presented in the project budget.

COST ESTIMATES FOR THE PROJECT

CAPITAL COSTS

Costs Independent of Antenna Length/Antenna

Vacuum System

3 end stations and pumps	945K	
Isolation valves	280K	

Construction

Support buildings	112K	
End station buildings	864K	
Cooling system	250K	
Transmission line to site	680K	6.16 M
Power sub station on site	1831K	
Power line tie in	950K	
Wiring to antenna	250K	

Instrumentation

Lasers	300K	
Optical components	500K	
Vibration isolation system	400K	2.5 M
Machining costs	500K	
On site control computer and data storage	300K	
General laboratory instrumentation	500K	

Total length independent costs per antenna	$\boxed{\text{8662K}}$

Capital Costs Linear in Antenna Length

Vacuum System

48" tubing, valves, bellows, alignment jigs, welding, ion pumps, roughing pumps	1007K/km

Construction

Cleaning & grading	28K/km
Trenching, backfill, bedding	249K/km
Supports	66K/km
Housing	689K/km

Construction (continued)

Electrical wiring	100K/km
Subtotal cost/km	2139K/km
Subtotal cost 2 x 5km	21390K
Subtotal capital cost/antenna	30.05M
Subtotal capital cost for 2 antennas Assume 1.9 factor for shared facilities such as cleaning station, alignment jigs, welding equipment etc.	57.10M

ADDITIONAL COSTS COMMON TO BOTH ANTENNAS

Data Analysis Center - Central computer, array processor, display equipment, large scale data storage equipment	600K
Engineering - Estimated at 1% of construction costs	500K
Total additional fixed cost	1100K
Total cost two antennas	$58.2M

RECURRING COSTS

Operations Costs at Both Antennas/Year

Maintenance	100K/yr.
Laser tubes	260K/yr.
Power	130K/yr.
Travel - 10 persons/100 days/yr. $40/day/person $400 airfare/10 trips/yr.	85K/yr.
Subtotal operations cost/yr.	575K/yr.

Personnel Costs/Year

6 faculty	100K/yr.
8 research physicists	240K/yr.
8 graduate students	120K/yr.

Personnel Costs (continued)

4 electronic instrumentation technical support staff	140K/yr.
2 mechanical instrumentation technical support staff	70K/yr.
2 optical instrumentation technical support staff	70K/yr.
1 computer programmer	30K/yr.
1 project manager/administrator	40K/yr.
Total personnel salaries and wages/yr.	810K
Employee benefits and overhead S & W x 1.25	1012K
Total personnel cost/yr.	$1.82M/yr.

Estimated Material and Services Costs

	200K/yr.
Total estimated recurring costs/year	$2.60M/yr.

CAPITAL

8.6M/ANT [illegible]

$6 [illegible]

25M/ANTENNA

50 TOTAL

10 M ANCILLARY COST

60M TOTAL