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Plans for a large gravitational wave antenna in Germany

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Abstract

After encouraging progress with the 30 m prototype, the GW group at the Max-Planck-Institut für Quantenoptik are increasing efforts towards a full-sized antenna. A definition phase is being started, in the duration of which (1 to 2 years) various questions are to be clarified.

Size: Arms 3 km in length are proposed, as a trade-off mainly between cost and the influence of thermal mirror motion. Tunnels, completely or partly below the surface, are to house the vacuum tubes.

Configuration: Besides the standard single 90° interferometer, a redundant triangular configuration consisting of three 60° interferometers is also being considered.

Optics: The size of the mirrors will depend on the choice between delay lines and Fabry-Perot cavities. A set of relatively large mirrors is to be manufactured and tested. Components for light modulation and guiding need research.

Techniques: Light power enhancing techniques (injection locking, recycling) are to be investigated. Improved frequency stabilization is to be developed, and phase modulation of the laser light (to reduce noise due to scattered light) is to be tried.

Vacuum: On the basis of given vacuum requirements, the design of the vacuum system (choice of material, pumps) will have to be made by an industrial firm.

Site: Possible sites found in a topographical survey must be re-assessed in respect of seismic and traffic noise, accessibility, ownership and current use.

Cost: A reliable estimate of the main cost items (construction, vacuum system, and power and cooling water supplies) will come from a design study to be made by an engineering consultant; such a study will also allow an estimate of the time scales in planning and construction.

1. Introduction

1.1 Background

A search for gravitational radiation has a reasonable chance of success only if a major effort is made, in antenna size as well as in technology. This is not a recent discovery; it has been known for years.

It was, however, the policy at the Max-Planck-Institut für Astrophysik to postpone the planning of such a large antenna until certain intermediate goals had been reached in our 30 meter prototype. Among these goals were: achieving again, as in the previous 3 m apparatus, the shot noise limit, now corresponding to ten times lower strain noise, and ascertaining that no new serious problems had arisen. The time had come some time last year, and we then started with the preparation of a proposal for a large antenna [1].

1.2 Requirements

Let us start off with a brief recapitulation of what the *minimum* requirements of a large gravitational antenna are. In the back of our minds, we and some of our colleagues may have even more ambitious goals for the future. (Among the considerations given here, some are relevant only if the optical delay line scheme is used.)

(1) From the expected signal strengths of likely sources (figure 1, taken from reference [1]), it becomes clear that a search for gravitational waves makes sense only if strains h of 10^{-21} , preferably even smaller, can be detected.

(2) The strongest sources of such radiation will have only short duration, and therefore the search must be made in a relatively wide frequency band.

(3) A limitation of the usable frequency range is given at the low-frequency end by the steep increase of many optical and mechanical noise contributions, particularly of the seismic noise. To extend the frequency range to a lower limit of 100 Hz will already be a very difficult task.

(4) At the high-frequency end, the decreasing strength of the expected signals and the increasing noise level of the antenna set a limit at several kHz.

(5) For measuring in such a frequency region, say around a central frequency f_m of 1.5 kHz, the appropriate optical path L would be $L = c/(2f_m) \approx 100$ km, or a mean storage time of $\tau = 1/(2f_m) \approx \frac{1}{3}$ ms; this storage time τ can be realized either with optical delay lines or with Fabry-Perot cavities.

(6) The influence of mirror motions, whether seismically or thermally driven, can be reduced by choosing a larger mirror distance. Seismic noise can be kept low by choosing a quiet site and by using passive (and perhaps even active) isolation schemes.

(7) To keep the thermally driven noise low, one has to choose mirror masses (of up to several hundred kg) that have a high mechanical quality factor ($Q \approx 10^5$). But even then, the (sub-resonant) thermal mirror motions $\delta\ell$ will still be so large

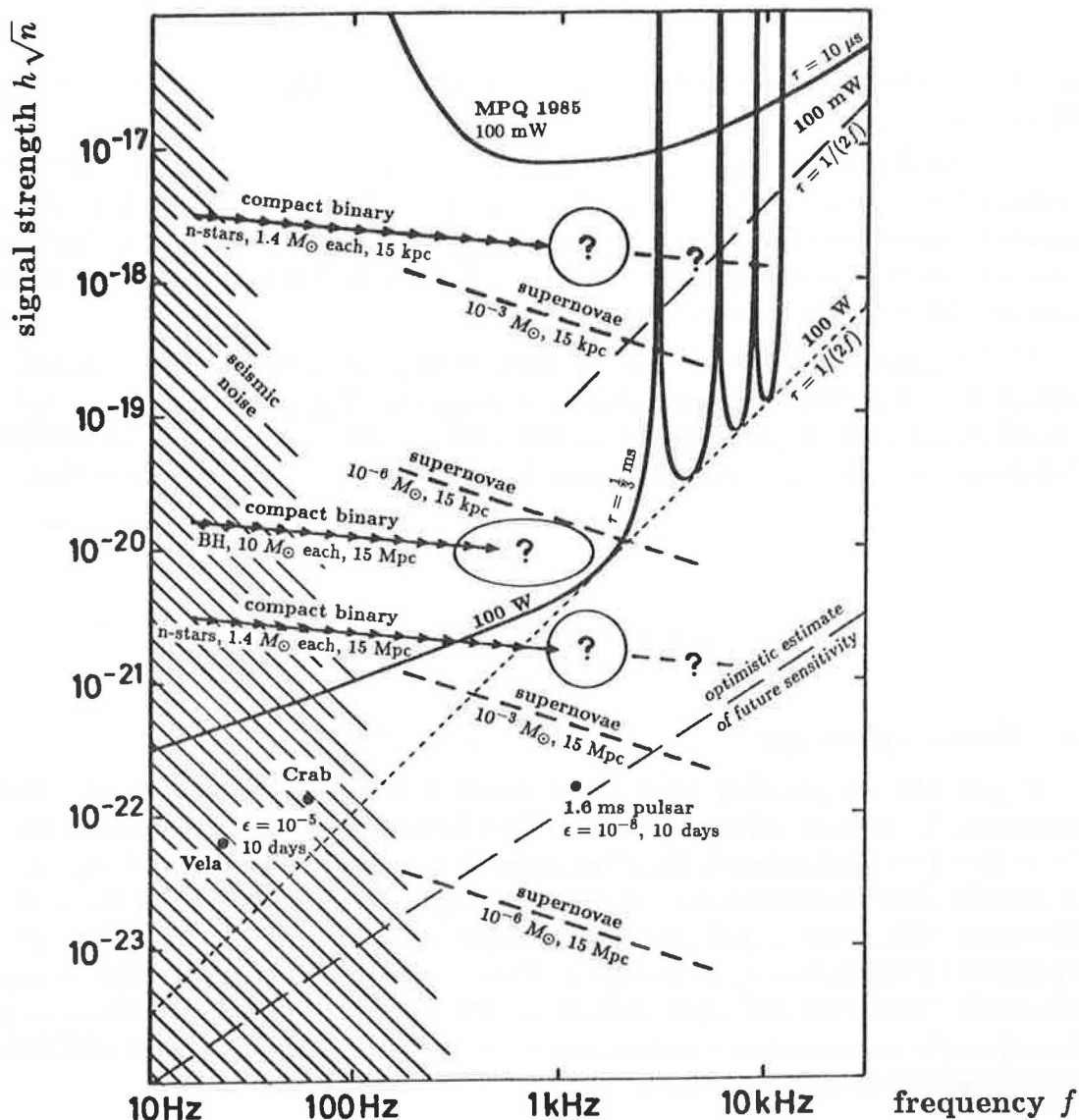


Fig. 1: Signal strengths expected from some more likely sources, expressed as product $h\sqrt{n}$ versus frequency f , where h is the gravitational wave strain and n is a quality factor specifying the number of oscillations near the frequency f . Examples are supernova events with emitted g.w. energies of 10^{-3} or $10^{-6} M_{\odot}$, and the evolution of compact binaries; in both cases they are given for distances to the galactic center (15 kpc) and to the Virgo cluster (15 Mpc). As examples of periodic sources, some pulsars are indicated.

For comparison, the fundamental limit due to shot noise is shown, for an effective light power of $P = 100 \text{ W}$. The dotted line indicates the sensitivity limit obtainable if for each frequency f the storage time τ were optimized: $\tau = 1/(2f)$. The solid curve touching this line describes the proposed delay-line antenna (at $P = 100 \text{ W}$), optimized for $f_m = 1.5 \text{ kHz}$, i.e. $\tau = \frac{1}{3} \text{ ms}$. In the vicinity of the even harmonics of f_m , the antenna becomes particularly insensitive.

A corresponding limit for 100 mW of light power is given by the upper dashed line, and the top curve (MPQ 1985) indicates the best experimental results so far, achieved in the 30 m prototype operated with $\tau = 10 \mu\text{s}$ [2].

The lower dashed line indicates a sensitivity limit conceivable under very optimistic assumptions upon 'recycling' of light at an input power of 100 W (and upon suppressing all other noise sources sufficiently) [3].

that the required strains $\delta\ell/\ell$ can be reached only with mirror distances ℓ greater than 1 km.

(8) A fundamental noise contribution is the shot noise introduced in the conversion of the output light into electrical signals. To keep the spurious signals caused by shot noise in a frequency bandwidth of 1 kHz below the gravitational wave signals from a strain level of $h \approx 10^{-21}$, one will need light power of the order of 500 W in the interferometer.

(9) To guard against spurious signals due to local noise sources, verification with at least one further interferometer is required. The interferometers used in coincidence should – if possible – be separated by distances in the range of 1000 km. Collaboration with experimental groups in other countries is highly desirable.

2. Preliminary Design

2.1 General Features

A possible design of a large interferometer is sketched in figure 2. Only schematically, the central vacuum tank (V) is indicated, housing the beam splitter S and the two near mirrors M, all separately suspended. Only one laser (L) is shown; the interferometer output is monitored by a detector D. The vacuum tubes (T) connect the central tank (V) with end tanks situated in the end houses (only one shown in the distance to the right). The arm length envisaged is 3 km, a compromise between cost and noise reduction. Houses at intermediate distances (as shown) might be required for pump stations, early tests, and perhaps for additional interferometers of reduced length.

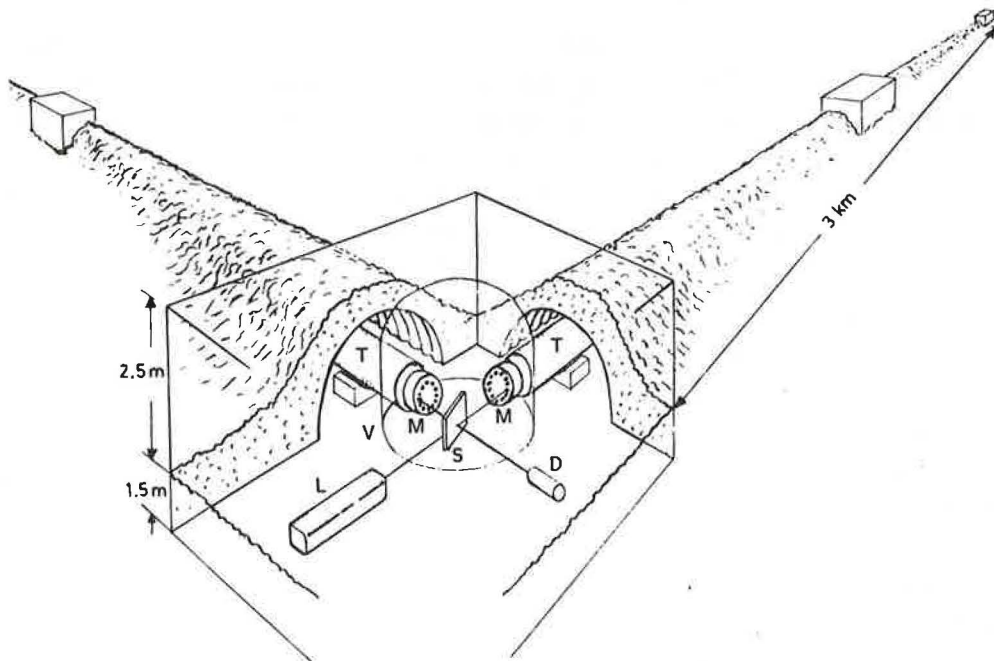


Fig. 2 : Sketch of an interferometer with arms of $\ell = 3$ km.

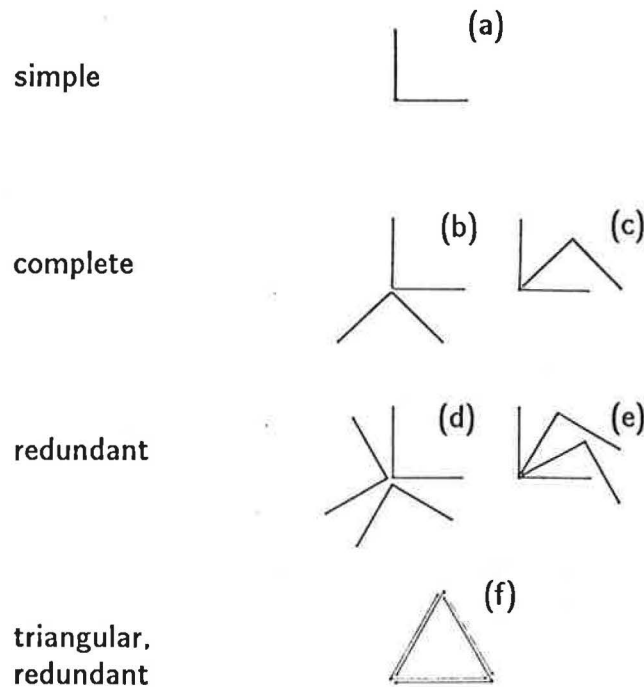


Fig. 4 : Configurations of simple (a), complete (b, c), redundant (d, e), and triangular redundant (f) receiving stations.

Actually, one would like to go even one step further. An ideal receiving station would incorporate some redundancy, as can be had with two additional interferometers, rotated, say, through 30° and 60° with respect to the first one. Two possible configurations of such 'redundant receiving stations' are shown in figures 4d and 4e.

Such a redundancy would have several great advantages. An obvious one is that even during failure or maintenance of one interferometer, the detectability of either polarization is ensured.

The other advantage of such a redundant station is the mutual verification of the interferometer signals. A signal seen in one interferometer will always have a sizeable counterpart (of no less than 50%) in at least one of the other two interferometers.

The individual interferometers can be considered independent with respect to disturbances from the vacuum, from shot noise, from fluctuations in the lasers, and from thermally induced noise. Thus, the mutual verification in such a redundant station might even allow some data reduction on-line, i.e. before the data are scanned for possible coincidences with data from other laboratories. The signals in the three interferometers are practically simultaneous, i.e. no unknown time delays have to be fitted.

The individual interferometers are, however, not independent as far as seismic, acoustic and electromagnetic perturbations are concerned, but these noise contributions are the ones that are most easily detectable. Thus, by monitoring them one could guard against misinterpretations.

There is, of course, a price to be paid for this redundant arrangement; in the configurations shown here, the expenses for end houses, tunnels, and vacuum tubes would be practically tripled.

2.4 Triangular Configuration

This is where the idea of a triangular configuration (figure 5) comes in. One noticeable change is that the individual interferometers now form angles of 60° instead of 90° . This has the disadvantage of reducing the signal by 13%, which is regrettable, but by no means prohibitive.

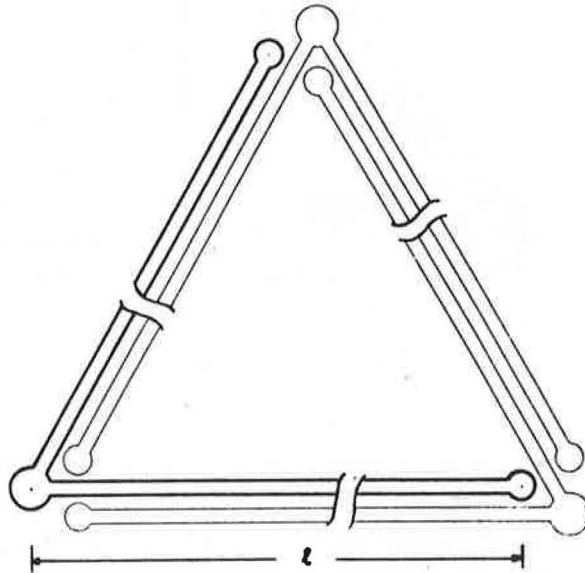


Fig. 5 : Triangular receiving station, consisting of three interferometers of angle 60° . In a first construction phase, only one interferometer would be realized (heavy lines).

The advantage of such 60° interferometers is, however, that they lend themselves to a redundant configuration that allows considerable savings in the number of end houses (now only three are needed) and connecting tunnels (also only three now). In the configuration indicated here, the vacuum tubes remain separate, so that index fluctuations due to the residual gas remain uncorrelated in the three interferometers.

The redundant configuration of three 60° interferometers is seen as an advanced stage in the development of a large antenna station. One would – in all probability – start out with a single interferometer. But at that point, a choice between a standard 90° interferometer and the 60° type must have been made.

Such a choice would also involve the end houses, a plan view of which can be seen in figure 6. The interferometer having its central tank in this house (indicated with heavy lines) is fixed in its location. The end tanks of the (other) interferometers are clamped on to rails. By inserting additional tubes, their distance from their central tanks can be adapted to possible deviations in the radii of curvature of the mirrors. To allow for such longitudinal adjustments, the houses must have dimensions as indicated here, say 20 m to a side.

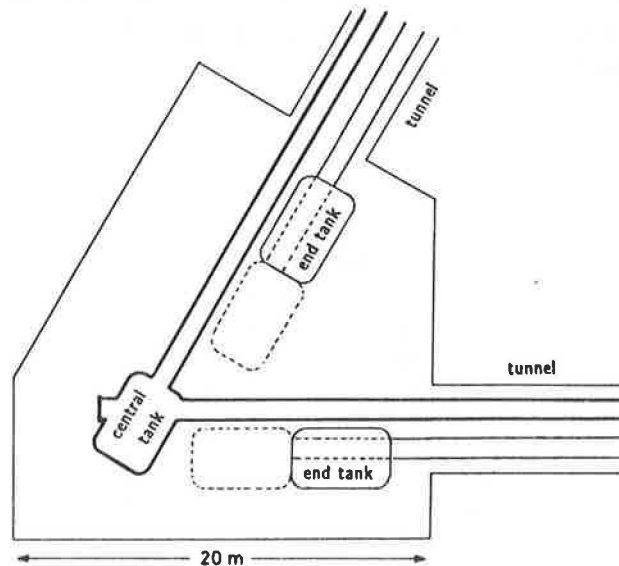


Fig. 6 : Sketch of a corner house in a redundant triangular receiving station. The dimensions are chosen large (20 m to a side) to allow coarse adjustment of mirror distances by moving the end tanks by several meters (dotted). For a fine adjustment, the mirrors can be moved inside the cylindrical end tanks.

The triangular configuration lends itself to realizing a closed light path enclosing a very large area. This seems, at first sight, very attractive for applications of the Sagnac effect. Even though it would have unparalleled sensitivity, it would, however, probably not allow tests of relativistic theories. This is because there is no way to calibrate it with sufficient precision to separate the relativistic effects from the much larger classical effect due to the earth's rotation. But it might be a useful tool for measuring fluctuations of just this rotation with a very high time resolution.

3. The Definition Phase

The previous chapter – in a nut shell – described the concept of the large antenna proposed by the Max-Planck-Institut für Quantenoptik [1]. A definition phase is being started, with an expected duration of between one and two years. Let us just briefly go through the major tasks to be done during this definition phase.

3.1 Optical Methods

Among the optical methods, one very fundamental question has yet to find its final answer: which of the two possible schemes, *delay line* or *Fabry-Perot*, offers the greater chance of success?

Let us start with some obvious advantages of the delay-line scheme. It is particularly easy to align and is rather insensitive to lateral motions and tilts of the distant mirror. The storage time is determined solely by the geometrical mirror spacing ℓ and the number of beams, N ; the reflectivity of the mirrors, a value rather difficult to control, does not enter. It is less sensitive to index fluctuations of the residual gas in the vacuum tubes, and thus a poorer vacuum could be tolerated. Heating of the mirrors due to light absorption is distributed over a wider surface area (in a less symmetrical way, however). The substrate need not be of transparent material. So far, delay-line interferometers have been very successful in their operation [2].

But perhaps all of these advantages may be counterbalanced by the points where the Fabry-Perot is more favorable. Most prominent here is the mirror size: a Fabry-Perot will require mirrors a factor of about three to five smaller than in a delay line, resulting in greatly reduced cost, in mirror fabrication as well as in the construction of the vacuum system. The mirror size (proportional to the square root of the laser wavelength) would assume prohibitively large values if one were to operate a delay-line interferometer with the $1.06 \mu\text{m}$ line of Nd:YAG lasers.

Particularly via the mirror size, the choice between delay line and Fabry-Perot has a great impact on the engineering design and thus on the total cost: diameter of vacuum tubes, spacing of pumps, size of tanks, tunnels, houses.

No matter what method is to be used, a further improvement of the *frequency stabilization* will be required. Some techniques to be used here will pave the way for a recycling of light. Therefore, some investigation into both these methods is planned in order to determine their feasibility.

Various methods leading to *larger laser power* have been proposed by other workers in this field: coherent superposition of output from injection-locked lasers; use of Nd:YAG lasers, either at their natural wavelength ($1.06 \mu\text{m}$) or at the frequency-doubled line ($0.532 \mu\text{m}$). It is not likely that our group could look into more than one of these possibilities, but we hope that some will be pursued at other laboratories.

Several schemes of phase-modulating (or *whitening*) the laser light have been proposed to combat noise due to scattered light. The feasibility of such schemes should be assessed, particularly their compatibility with "recycling".

3.2 Optical Components

An important task will be to have specialized optical components manufactured and to test their properties.

Foremost among these components are the *mirrors* for delay lines or Fabry-Perot cavities, where experience with the quality and the equality of surfaces with 3 km of radius of curvature has yet to be gathered. The coating of the (relatively large) mirrors with highly reflective dielectric layers (99.5 % up to something like 99.99 %) will also require considerable development on the manufacturer's part. Fortunately, a company in Germany seems to have both the know-how and the willingness to enter into such a development venture. It is planned to start out with test mirrors of "only" 40 cm diameter, but even these will constitute an expensive investment; the cost will come partly from development yet to be done to devise testing and evaporation techniques, partly from the high price of highly homogeneous substrates having a Q of 10^5 .

The use of mono-mode *glass fibers* has been very helpful in our experiments, both for 'mode cleaning' and for directing the beam [4]. For the envisaged light powers of the order of 100 W, special types of fibers (mono-mode, large core, polarization holding) would have to be developed and tested.

Of course, with the larger beam diameters, such components as Pockels cells, beam splitters for the 60° configuration, and polarizing prisms will also have to be developed and tested.

3.3 Site Selection

An important item during the definition phase will be to select a site for a 3 km installation. The final choice will have to be a compromise, since not all of the following criteria will be met simultaneously.

We want it to be *flat* (so that earth movement during excavation and construction can be kept to a minimum), and we would prefer it to be *level* (so that the optical axes are exactly horizontal). If one were to consider going deeper into the ground, say 5 to 10 m, which would have great advantages with respect to higher-frequency ground noise, both these considerations (flat, level) would play a lesser role.

The site should be *quiet*, i.e. have a low intrinsic seismic noise level; and to have a low level of man-made noise, it should be far enough away from sources of industrial and traffic noise.

We would want it to be uninhabited (not easily found in a heavily populated country). On the other hand we would prefer a site within at most a few hours' ride from the institute to save extra offices and workshops. And of course it would be helpful (though not absolutely mandatory) if the land were publicly owned. Agricultural use of the site could be continued, as it would cause strong disturbances on just a few days per year.

A search for sites is being started, and after a preselection on topographical and some general criteria, the seismic suitability will have to be investigated. The glacial till surrounding Munich seems geologically and seismically suitable, and this ground formation would ease excavation work.

Underneath the North German plains, huge salt deposits have been mined, and relatively long line-of-sight passages exist. Inquiries will have to be made, because the use of such salt mines should not be ruled out. They constitute a very stable, quiet environment, but it is likely that only orthogonal arms will be found.

3.4 The Vacuum System

The design of the vacuum system, starting out from given minimum requirements, will have to be made by a manufacturer or an engineering consultant. A first objective would be a critical comparison of various alternatives, e.g. in the choice of

- (1) the tubing material (probably aluminum),
- (2) processing of the finished tubes (thorough cleaning, filling with dry inert gas)
- (3) the environment, procedure, and machinery required for welding
- (4) the type and the required number of pumps (a function of, among other things, the tube diameter).

The respective costs, but also safety margins, maintenance considerations, etc. of such alternatives will have to be compared. Final decisions must then be made in an interactive process with the experimentalists.

3.5 Construction

A conceptual design of the construction (houses, tunnels, supply facilities) is about to be started by a consulting firm. Again, a number of alternatives will have to be considered, their respective merits compared, and their costs estimated. Deciding on a final design is not expected to be a straightforward proposition, but rather requiring several iterations.

Items to be clarified are

- (1) the interplay of trench digging, tunnel covering, and welding and aligning the vacuum tubes
- (2) dependence of cost on size of tubes and tunnels
- (3) dependence of building time and cost on soil formation and depth of trenches
- (4) cost of site development (roads; power, water supply)
- (5) cost comparison between simple detector (1 interferometer) and redundant station (3 interferometers).

3.6 Cost Estimates

It is on such data and cost estimates that a final proposal for a large antenna will have to be based. For the preliminary proposal, we had, of course, made some rough guesses of the cost to be expected, mainly to judge the relative contributions of the individual items.

For both configurations considered, it appears that the main contributions come from the length-dependent items, namely the tunnels and vacuum tubes, and they happen to be of similar order of magnitude in the simple interferometer. In the redundant case the tube length is tripled, whereas the tunnel length is multiplied only by one and a half, resulting in a total about twice that of the simple antenna.

When we quote some absolute figures, these should be taken *cum grano salis*: for the total cost of the simple interferometer we guess something like 30 to 50 million DM (10 to 15 million \$), and for the redundant station perhaps twice that amount.

With the designing and a more reliable costing now just beginning, we may well be in for surprises; let's be optimistic and hope they will be positive.

Acknowledgement

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