

## GRAIL R&D proposal

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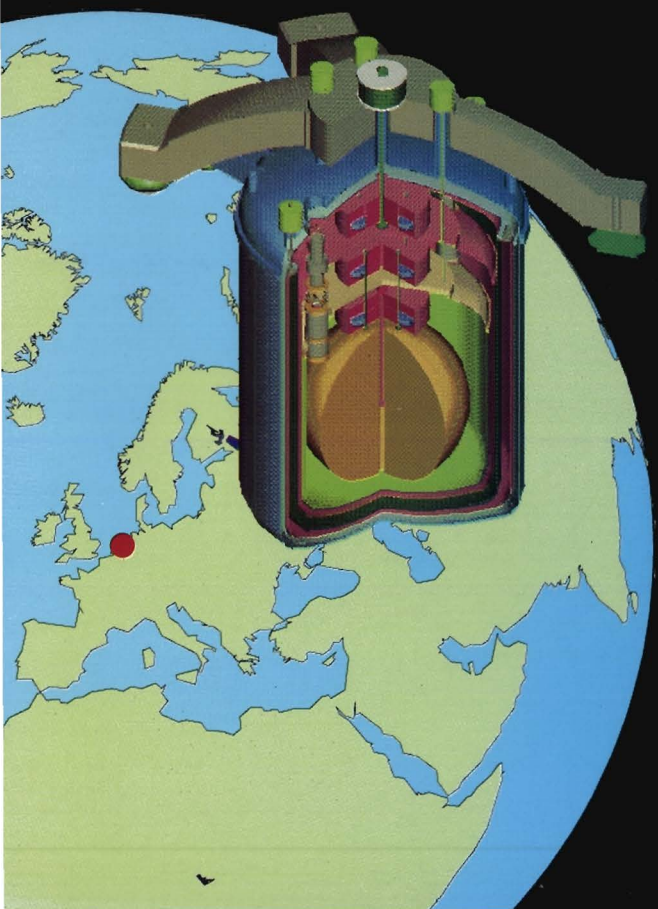
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# GRAIL

*An Omnidirectional Gravitational Wave Antenna*



May 1997

The GRAIL Collaboration

## GRAIL R&D Proposal

May 1997

D. van Albada, Universiteit van Amsterdam  
J. Flokstra, Universiteit Twente  
G. Frossati, Rijksuniversiteit Leiden  
E.P.J. van den Heuvel, CHEAF/Universiteit van Amsterdam  
J.W. van Holten, NIKHEF Amsterdam  
A.T.A.M. de Waele, Technische Universiteit Eindhoven  
P.K.A. de Witt-Huberts, NIKHEF Amsterdam

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# 1 Introduction and overview

## 1.1 The aim

The aim of the GRAIL project is the detection of gravitational waves from astrophysical sources. This is to be achieved by the development and operation of an omni-directional ultra-cold spherical resonant mass detector capable of detecting gravitational waves with a spectral noise amplitude<sup>1</sup> at the peak of the resonance of  $\tilde{h}(f) \leq 5 \times 10^{-24} / \sqrt{\text{Hz}}$ . Depending on the material the fundamental quadrupole frequency of the sphere is between 650 and 800 Hz.

Signals from this detector can prove the existence of gravitational waves and provide information about their properties, like the number and character of polarization states, and the direction of propagation. Such elementary properties test some of the essential ingredients of General Relativity as a description of the dynamical gravitational field.

Once the detection and reconstruction of gravitational waves has been proven feasible, the study of the astrophysical sources of gravitational radiation can be taken up. The science of gravitational-wave astronomy will provide a new window on the universe. In particular the properties of compact objects like neutron stars and black holes become open to investigation. Gravitational radiation can provide information on their structure and, for neutron stars, on their equation of state. Possibly there are unknown sources, e.g. dark matter, emitting measurable gravitational waves. Moreover, as the universe became transparent to gravitational waves long before it became transparent to light, gravitational radiation may yield new information on the very early universe.

The design sensitivity of GRAIL presents a great challenge to instrumentation physics. An improvement of 2 to 3 orders of magnitude in strain amplitude over existing instruments must be implemented [1]-[11]. An intensive research and development effort is needed to achieve this.

In this document a proposal for such an R&D program is formulated. It has been set up in a way that its successful completion is proof that a GRAIL detector is feasible. The duration of the R&D program is two years. After that the construction of the detector could be completed in three more years.

This document is organized as follows. In chapter 2 astrophysical sources of gravitational waves are briefly discussed. A research program for a modest gravitational wave astronomy activity during the R&D phase (phase A) of GRAIL is sketched. In chapter 3 we describe the international context of the project, and outline the networks that would provide the optimal environment for the construction and operation of the 3 meter diameter spherical GRAIL detector. We discuss the detector concept and the challenging instrumentation requirements

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<sup>1</sup>Defined as the square root of the noise power per unit of bandwidth

in chapter 4. The design objectives for GRAIL are spelled out and the specific research goals and methods for phase A of the project are discussed. Finally, chapter 5 presents the projected manpower and a budget request for phase A of GRAIL, and a description of the organisation- and management structure of the GRAIL collaboration.

## 1.2 The concept

Briefly, the GRAIL detector works as follows. A gravitational wave excites vibrations in a large sphere which are to be detected by motion sensors placed on its surface. The sensors are optimized to detect radial motion and are tuned to the frequency of the fundamental quadrupole mode, as this mode is expected to be the most sensitive to tensorial gravitational waves. Sensors tuned to one of the other modes can be added, for example to search for scalar wave components, or to monitor non-gravitational background.

A complete measurement of the quadrupole vibrations of the sphere requires a minimum number of five sensors. With the data from these sensors, having identified a gravitational-wave signal one can then reconstruct the direction and polarization of the radiation. To suppress thermal noise the detector is operated at a temperature close to 10 mK, and equipped with low-noise sensors. A limit on the sensitivity to be reached by conventional methods is provided by the energy of a single quantum of frequency 650 Hz:  $0.43 \times 10^{-30}$  J, or  $0.4 \times 10^{-7}$  K in thermodynamic units.

At the projected frequency and sensitivity one has to deal with a large background of vibrations from external sources. These include seismic background, atmospheric background and cosmic ray background. To reduce the seismic background to manageable proportions the suspension is to include a vibration isolation system capable of at least 320 dB attenuation at the resonant frequency. For suppression of the cosmic ray background it is desirable to operate the detector in an underground laboratory.

Careful calibration of the system components is indispensable for the proper processing and interpretation of the antenna signals. For interpretation and identification of events input from astrophysical models for sources of gravitational radiation is needed. Signal processing requires fast analysis and reconstruction algorithms. The development of correlation techniques like those used in radio astronomy is necessary for operation of GRAIL in a future world-wide network of gravitational wave detectors.

## 1.3 The challenge

The GRAIL detector is to achieve an over-all improvement in burst amplitude sensitivity of 2-3 orders of magnitude compared to existing resonant bar detectors. This formidable challenge to instrumentation science can be realized by a

combination of four improvements:

1. spherical geometry:
  - (a) a spherical detector is at all times optimally oriented for any source; on the average this leads to four times as many sources being visible by a sphere compared to a hypothetical bar detector at the same amplitude sensitivity;
  - (b) spherical geometry also gives the largest mass for fixed linear dimension: at least fourteen times more than any operational bar detector;
2. operation at temperatures close to 10 mK, as compared to 100 mK for the best cryogenic bars;
3. multi-stage sensors, allowing a ten times larger bandwidth with a hundred times better amplitude at the same time.
4. improvement of the coupling between the detector and sensor, in particular the efficiency ( $\beta$ ) of energy transfer to the transducer, and a better amplifier designed for operation at mK temperatures; the improvement factor envisaged for  $\beta$  is in the range 5-10.

In this document we describe the research and development program necessary to realize the improvements in system performance. The program should prove each of the critical issues to have at least one practical solution.

## 2 The physics of gravitational waves

Starting with the work of Weber [12], forty years of developments in instrumentation have brought us on the brink of observing gravitational radiation. The studies of the binary pulsar [13] discovered by Hulse and Taylor [14] have confirmed the theoretical expectations about the strength and efficiency of the emission process as predicted by General Relativity [15]. Therefore we are rather confident about the instrumental improvements necessary to cross the threshold of observability.

As the emission of gravitational waves is most efficient for massive compact objects accelerating at relativistic rates, it is likely that gravitational wave astronomy will focus first on the abundances and properties of systems consisting of one or more neutron stars or black holes. Indeed, many of the properties of such systems can in principle be studied best, or even exclusively, through the gravitational radiation they emit: the formation of black holes, the rotation rates of neutron stars not observable as pulsars, the inspiralling and collapse of a binary black hole and/or neutron star system, etc.

However, once gravitational wave signals are detected and identified, new and unexpected sources may turn up. In the past new windows on the universe, like radio and X-ray astronomy, have always yielded surprises. All forms of electromagnetically dark matter in the universe are potentially sources of gravitational radiation. There may also be cosmological backgrounds from very early epochs in the evolution of the universe. Until we observe gravitational radiation we can only speculate about what to expect.

From the point of view of fundamental physics, detection of gravitational radiation will teach us important new things about the fundamental interactions and about new, very dense states of matter:

- The properties of gravitational radiation like the number of polarization states and the velocity of propagation can be determined.
- The quadrupole nature of gravitational radiation, and the presence of conjectured scalar components of the gravitational field can be investigated.
- Gravitational radiation from spinning neutron stars, being a function of their asphericity, carries information about the equation of state of superdense nuclear matter.
- Gravitational radiation from black holes, or from the scattering of other compact objects by the field of a black hole, carries information about the gravitational field, and therefore the structure (i.e. the ergosphere and horizon), of the black hole.

Thus the detection of gravitational radiation will be a very rewarding breakthrough for fundamental physics as well as astronomy.



## Sources

Astrophysical sources for gravitational waves can be classified by the type of signal they produce. Two broad classes can be distinguished: *burst* sources, which emit a pulse of gravitational waves of finite duration, and *continuous* sources, which can be *periodic* or *stochastic*. The search for and identification of each type of source requires specific data analysis procedures: periodic sources can be searched for in principle by single antenna techniques, whilst burst sources or stochastic sources require correlation of antenna signals. A review of types and characteristics of sources with estimates of their signals can be found in [9].

Typical burst sources are connected with processes of gravitational collapse, like supernovae or the formation of black holes. Burst-like gravitational wave signals will also be emitted in the end phase of coalescing compact binary systems, composed of neutron stars or black holes. Continuous sources may be expected in the form of stable compact binary systems, like the binary pulsar [14], or rotating neutron stars with a slight asphericity in directions transverse to the rotation axis.

As GRAIL is expected to have its optimum sensitivity in the frequency range between 650 and 800 Hz, it is suited for finding burst sources or periodic sources like spinning neutron stars with periods shorter than 3 msec. While the identification of burst signals requires correlations with other detectors, periodic sources can be identified in principle by a spherical detector in single antenna mode, as the diurnal variation of the direction of the source w.r.t. the antenna causes a variation in the signals recorded by different sensors with a 24-hour period.

### Bursts from gravitational collapse

A rough estimate for the strain amplitude from a burst source can be obtained by the following elementary consideration. In the gravitational collapse of an object, gravitational waves are excited predominantly in the region of strong gravitational field, which typically has the dimension of a few times its Schwarzschild radius  $R_S = 2GM/c^2$ , with  $M$  the mass; as a conservative estimate we take the relevant distance equal to  $2R_S$ . The characteristic time scale for the generation of a pulse of gravitational radiation then is

$$\Delta\tau = \frac{2R_S}{c} = \frac{4GM}{c^3}. \quad (1)$$

A single pulse can be characterized as a pulse with central frequency  $f_0 = 1/2\pi\Delta\tau$  and width  $\Delta f \approx f_0$ . As the solar mass  $M_\odot$  is  $2 \times 10^{30}$  kg, eq.(1) then gives

$$f_0 \approx \Delta f \approx \frac{c^3}{8\pi GM} = 0.8 \times 10^4 \frac{M_\odot}{M}. \quad (2)$$

Thus  $f_0 \approx 800$  Hz for a black hole of ten solar masses. Taking the spectral

density  $\mathcal{E}(f)$  of the radiation to be flat in the bandwidth  $\Delta f$ , the emitted energy as fraction of the mass is

$$\varepsilon = \Delta f \frac{\mathcal{E}(f)}{Mc^2}, \quad (3)$$

The average energy flux per unit of frequency at a distance  $d$  then is

$$\frac{\varepsilon Mc^2}{4\pi d^2 \Delta\tau \Delta f} = \frac{f_0}{2d^2} \mathcal{E}(f). \quad (4)$$

The corresponding spectral amplitude of the pulse becomes

$$\begin{aligned} \tilde{h}(f) &= \sqrt{\frac{Gf_0}{\pi c^3 d^2 f^2} \mathcal{E}(f)} \\ &\approx 0.5 \times 10^{-18} \left(\frac{10 \text{ kpc}}{d}\right) \left(\frac{800 \text{ Hz}}{f}\right) \left(\frac{\varepsilon}{0.01}\right)^{1/2} \text{ Hz}^{-1/2}. \end{aligned} \quad (5)$$

Hence a gravitational collapse near the center of the galaxy of a mass equal to 10 solar masses, of which 1 per cent is converted into gravitational radiation, gives a gravitational wave signal with frequencies in the 0.1-1 kHz range, with an amplitude spectral density of about  $10^{-18}/\sqrt{\text{Hz}}$ . For the same event in the Virgo cluster, about 1000 times further away, we get an estimate for the spectral amplitude of the order of  $10^{-21}/\sqrt{\text{Hz}}$ .

For supernovae, in which a stellar core collapses to a neutron star, assuming a modest asphericity one expects gravitational wave signals to be typically one or two orders of magnitude smaller. For a supernova in the Virgo cluster this would produce a spectral amplitude in the range  $10^{-22} - 10^{-23}/\sqrt{\text{Hz}}$ . The frequencies and spectral amplitudes are well in the window of the projected GRAIL sensitivity of  $\tilde{h}(f) \leq 5 \times 10^{-24}/\sqrt{\text{Hz}}$  near the quadrupole resonance.

The limiting factor for observing these events is therefore not primarily the amplitude or typical duration of the burst, but the event rate. For supernovae this rate is estimated with some accuracy at about 1 per 30 - 40 years for a galaxy like ours. Going out to distances of the Virgo cluster which brings into view more galaxies, with correspondingly weaker signals, the rate is expected to go up to between one and ten per year.

### Coalescing binaries

Coalescing compact binaries are a potentially important source of gravitational waves. Their signals are relatively strong and well-defined, allowing to use wave-form templates for enhanced signal recognition and reconstruction. For systems containing white dwarfs the frequencies are generally below the window of observability of terrestrial detectors. Binaries containing neutron stars are ideal, as the frequency domain of the last stage of coalescence before collapse is right

Astrophysical event rate = $1/y@45$ Mpc	$f_r = 600$ Hz	$f_r = 700$ Hz	$f_r = 800$ Hz
$\sqrt{S_0} = 4 \times 10^{-24}/\sqrt{\text{Hz}}, B = f_r/3$	4.8	3.6	2.7
$\sqrt{S_0} = 4 \times 10^{-24}/\sqrt{\text{Hz}}, B = f_r/6$	1.6	1.25	0.9
$\sqrt{S_0} = 10^{-23}/\sqrt{\text{Hz}}, B = f_r/3$	0.31	0.23	0.17
$\sqrt{S_0} = 10^{-23}/\sqrt{\text{Hz}}, B = f_r/6$	0.1	0.08	0.06

Table 1: Detection event rate per year for GRAIL at an SNR = 5.

on top of that of terrestrial detectors: the initial stage at lower frequencies can be followed for many periods by the laser interferometers, whilst the last few orbits at high frequency can be observed with better sensitivity by a 3 m diameter resonant sphere as proposed here [18].

The gravitational wave-form of coalescing binary neutron stars is shown as a function of time in fig.(2.1).

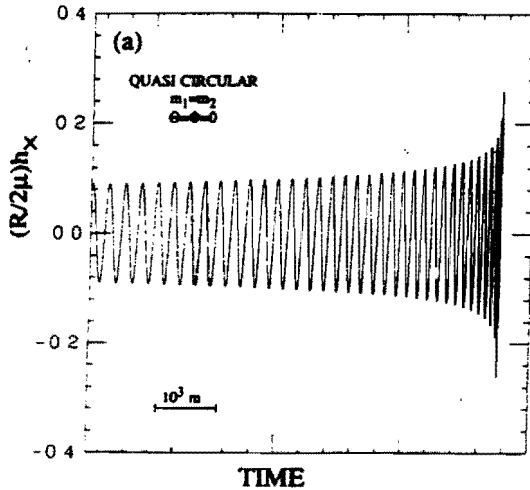


Fig.(2.1): Gravitational wave form of coalescing binary neutron stars.

In table (1) the estimated number of coalescences observed per year by the proposed GRAIL detector is given for a signal-to-noise ratio  $SNR = 5$  and an assumed astrophysical event rate of one event per year up to a distance of 45 Mpc, for various values of the detector parameters: the spectral noise density  $S_0$  in the bandwidth  $B$  around the central frequency  $f_r$ .

For systems containing coalescing black holes the parameters characterizing the emission of gravitational radiation are not known accurately. The problem of numerically following the phase of coalescence of two black holes according to general relativistic principles requires a handle on the full non-linear complications of the theory, and is considered one of the grand challenges in the field.

## Periodic sources

The signals from periodic sources are usually much weaker and have a much narrower bandwidth. They are correspondingly more difficult to detect, but because they can be integrated over long periods of time to reduce noise, the required amplitude spectral density is also much lower.

For a source characterized by a mass  $M$ , a length scale  $R$  and an angular rotation frequency  $\omega = 2\pi f$  the luminosity is given by the Einstein relation

$$W = \eta \frac{G}{c^5} M^2 \omega^6 R^4, \quad (6)$$

where  $\eta$  is a dimensionless constant of proportionality which depends strongly on the geometry of the source; in particular for spherically symmetric sources  $\eta = 0$ , as the variation of their quadrupole moment vanishes. Again a simple example allows to determine orders of magnitude of possible signals. Consider a rigid ellipsoid of mass  $M$ , with semi-major axes

$$a_i = (1 + \epsilon_i) R, \quad i = 1, 2, 3, \quad (7)$$

where  $R$  the average of the three semi-major axes, i.e.  $\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$ . Let the body rotate about the third axis with rotation frequency  $f_{rot}$ . Then it emits gravitational quadrupole radiation of frequency  $f_{gw} = 2f_{rot}$  and a total power given by eq.(6,) with  $\omega = 2\pi f_{rot}$  as before, and

$$\eta = \frac{128}{125} \Delta\epsilon^2, \quad \Delta\epsilon = |\epsilon_1 - \epsilon_2|. \quad (8)$$

Thus for the axially symmetric case  $\epsilon_1 = \epsilon_2$  no radiation is emitted. For non-axially symmetric systems the average power radiated per second and per square meter at a distance  $d$  is

$$\langle \Phi(2f_{rot}) \rangle = 10^4 \eta \left( \frac{10R_S}{4.5R} \right)^2 \left( \frac{f_{rot}}{300 \text{ Hz}} \right)^6 \left( \frac{R}{10 \text{ km}} \right)^6 \left( \frac{1 \text{ kpc}}{d} \right)^2 \text{ Wm}^{-2}. \quad (9)$$

Here  $R_S$  denotes the Schwarzschild radius as before, and therefore contains the dependence on the mass of the ellipsoid. All numbers inserted are typical for a millisecond pulsar in our galaxy. As GRAIL is only sensitive to frequencies  $f = 2f_{rot} \geq 600 \text{ Hz}$ , their rotation period should be less than 3 msec.

The energy absorption cross section of a GRAIL sphere with  $Q = 10^7$  is of the order of  $10^{-19} \text{ m}^2$  near the resonant frequency. Hence the energy absorbed from the flux (9) in time  $\tau$  is given by the product

$$\Delta E_{abs} = 2.4 \times 10^{-12} \Delta\epsilon^2 \left( \frac{\tau}{\tau_{rel}} \right) \left( \frac{10R_S}{4.5R} \right)^2 \left( \frac{f_{rot}}{300 \text{ Hz}} \right)^6 \left( \frac{R}{10 \text{ km}} \right)^6 \left( \frac{1 \text{ kpc}}{d} \right)^2 \text{ J}, \quad (10)$$

where  $\tau_{rel} = Q/2\pi f \approx 40$  min is the relaxation time of the antenna quadrupole mode, i.e. the average time in which an energy  $kT_{th}$  is dissipated. With  $f_{rot} \geq 300$  Hz, an energy  $\Delta E_{abs} \geq 2.4 \times 10^{-12} \Delta\epsilon^2$  J is absorbed every 40 min. from a standard source *at the resonance frequency* of the detector at a distance of up to 1 kpc. To get above the thermodynamic noise at 10 mK this should be larger than  $kT_{th} \approx 10^{-25}$  J; then we find  $\Delta\epsilon \geq 3 \times 10^{-7}$  for integration periods of the order 40 min. For a neutron star with radius 10 km this would imply a deformation of 3 mm in the radius along one of the transverse axes. Integrating over  $N$  periods  $\tau_{rel}$  improves the sensitivity by a factor  $\sqrt{N}$ . On the other hand, away from the resonance frequency the absorption rate falls rapidly. Typically the average absorption cross section in the bandwidth is about  $10^5$  to  $10^6$  times smaller than the peak value. To reach the same sensitivity of  $\epsilon \approx 10^{-7}$  then requires integration times of the order of 100 - 250 days.

The event rate for sources of this kind is determined by the number of millisecond neutron stars per unit of volume in our galaxy. It is estimated that there are about 120 ms pulsars within a sphere with radius 1 kpc from our solar system, of which about 1/3 have periods shorter than 3 ms [16, 17]. Which fraction of these are in the bandwidth of the detector and have an asphericity of the order of  $\Delta\epsilon \geq 10^{-7}$  is not known.

## Stochastic radiation

Stochastic radiation consists of continuous, non-periodic signals. It can be generated either as a superposition of many weak, uncorrelated sources, or exist as a cosmic background from an earlier epoch of the universe [19].

An example of the first type would be gravitational radiation generated by gravitational *bremssstrahlung* from the scattering of compact objects, like white dwarfs, with massive bodies, e.g. black holes, at close range. Such a kind of stochastic background should be confined predominantly to the galactic plane. Here the directional sensitivity of GRAIL would be a clear advantage.

A cosmic background which might be measurable is predicted by superstring cosmology, in the form of radiation with spectral density proportional to  $f^3$ , reaching its maximum in the kHz region [20].

To find stochastic signals over the detector noise, correlations between two or more detectors over long periods of time are required.

## Research objectives

### *Astrophysics*

During the initial R&D phase of GRAIL a modest research program on astrophysical sources of gravitational waves is to be carried out. Much expertise is available elsewhere and must be integrated in the project.

1. Target expected sources of gravitational waves and investigate their signal

characteristics, using analytical and/or numerical approaches.

2. Estimate event rates of various candidate sources, by studying the abundances and birth rates of these systems.
3. Develop search strategies for various kinds of sources, exploiting to the full the omni-directionality, the very good peak sensitivity and the relatively broad-band frequency sensitivity of GRAIL.

*Deliverables*

1. An estimate of the rate and type of sources for GRAIL.
2. Strategies and algorithms for performing efficient searches.

## 3 Long-term outlook and international context

### 3.1 International context

Worldwide several projects are underway aiming at the detection of gravitational waves and the study of their sources. Most of the detectors presently in operation are cryogenic bar detectors, routinely reaching burst strain sensitivities of the order of  $h \approx 10^{-19}$ . New detectors under construction are of the laser-interferometer type and aim at burst strain sensitivities of the order  $h \approx 10^{-22}$ , comparable to GRAIL. It is therefore necessary to sketch the international context in which GRAIL operates and the specific features that make the GRAIL detector a particularly strong player in any worldwide network of gravitational wave detectors.

Cryogenic resonant bar detectors like NAUTILUS and EXPLORER in Europe, ALLEGRO in the U.S., and NIOBE in Australia have shown that these detectors can be operated reliably over long periods of time. Presently these detectors have not yet reached the quantum limit of sensitivity; continual improvements of these instruments are foreseen, in particular through improved sensor technology. Clearly, connecting with the knowledge base present in the groups working with these detectors is important for the design and development of GRAIL.

A spherical resonant mass detector comparable to GRAIL has been proposed by the Gravity Wave Co-op in the U.S. [22]. However, construction of this detector is not scheduled in the foreseeable future.

The completion of the GRAIL detector in five years is in line with the time-schedule for the large interferometers, which are planned to become operational with an initial strain sensitivity  $h \approx 10^{-20} - 10^{-21}$  [21] by the year 2002. Instruments of this type presently under construction are GEO600 (a 600 m armlength German-British interferometer), VIRGO (a 3 km French-Italian instrument), and LIGO (two 4 km interferometers in the US). In an advanced stage, planned several years later, VIRGO and LIGO are to reach their final design strain sensitivity  $h \approx 10^{-22} - 10^{-23}$ .

Comparing the features of a spherical resonant mass detector with those of laser interferometers, we observe that the omni-directionality of a detector like GRAIL and its ability to reconstruct the full quadrupole signal allows it to search for sources anywhere in the sky with equal sensitivity, and to fully reconstruct the plane, degree and character of polarization of the gravitational radiation they emit. As a result GRAIL can locate sources with a resolution matching that of a network of four laser interferometers. Moreover, the sensitivity of GRAIL in the region near the resonance frequency is superior to that of the interferometers, even in their advanced stage.

The bandwidth of GRAIL at a spectral noise amplitude of  $\tilde{h} = 10^{-21}$  is planned to be  $\geq 130$  Hz around the resonance frequency near 700 Hz. The large interferometers should be able to reach bandwidths of about 200 – 800 Hz at this level of spectral noise amplitude in the initial and advanced stages, respectively. Their initial sensitivity will however be at considerably lower frequencies, between 50 and 250 Hz; fig. 3.1 shows the projected sensitivity for LIGO.

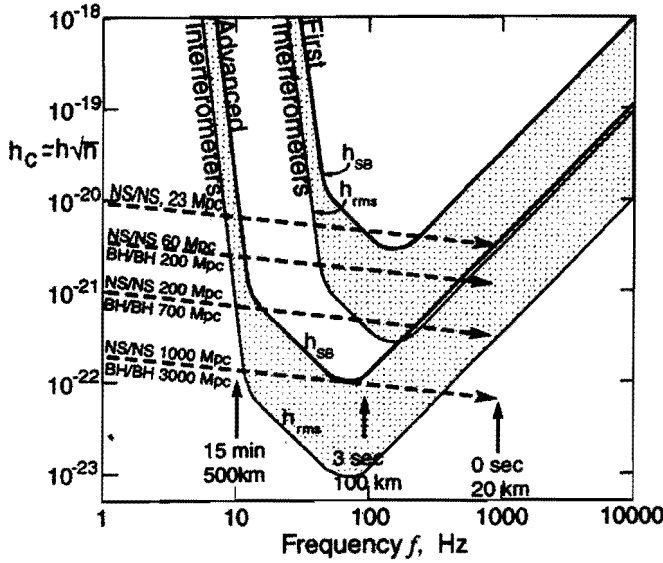


Fig. 3.1: LIGO's projected broad-band noise  $h_{rms}$  and sensitivity to bursts  $h_{SB}$ .

As this comparison indicates, laser interferometers have features complementary to those of spherical resonant mass detectors at comparable sensitivity. A complete gravitational wave observatory must combine these features to extract the maximum of information about their properties and sources. Moreover, the weakness of gravitational radiation calls for coincidence methods to establish unambiguously the arrival of a gravitational wave signal. Therefore the development of international networks is essential for the operation of gravitational wave detectors; it is a necessary part of the preparation for the commissioning and exploitation of GRAIL.

In fig. 3.2 we compare the design strain sensitivity of GRAIL with the GEO600 interferometer, operated in a dedicated detection mode designed for optimal sensitivity around a frequency of 600 Hz. Because of the overlap in bandwidth, correlation of the outputs of GRAIL and GEO600 will yield a combined bandwidth of 200 Hz at a level of sensitivity that is substantially better than the initial design sensitivity of the other large interferometers, with the added advantage of GRAIL providing good directional resolution.

A network including GRAIL in combination with GEO600, VIRGO and/or LIGO would result in further improvement of the figures of merit of all these detectors as they provide different and complementary information about gravitational wave events.



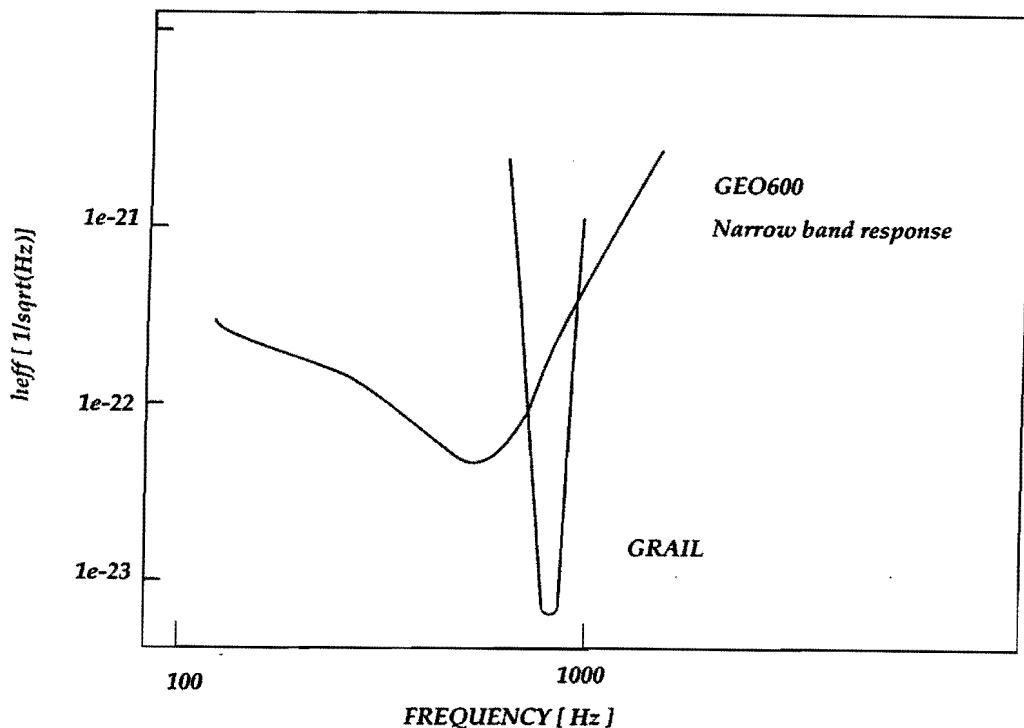


Fig. 3.2: Projected spectral noise amplitudes for GEO600 and GRAIL.

### 3.2 Networks

It is of paramount importance to work right from the start on developing a collaboration network for instrumentation, and also for the (astro)physics exploitation of GRAIL, that will start once the device has been commissioned to the sensitivity level required.

In the Netherlands there is a strong and active radio-astronomy community that is expected to participate in due course in the scientific exploitation of the GRAIL antenna. In the research of the best sensor technology we intend to collaborate among others with colleagues involved in the exploitation of the Dwingelo radiotelescope (ASTRON).

A well-developed knowledge base for resonant mass gravitational wave detectors exists in Italy. We have submitted a Network Proposal called GRACE<sup>2</sup> with partners from Italy, France and Spain in the frame of the EU programme Training and Mobility of Researchers (TMR) in the beginning of 1997. In phase A of the GRAIL project collaboration with the partners in this network on the development of improved transducers of the inductive and optical variety is planned. Joined work on data analysis procedures and backgrounds will be initiated.

The abstract of the GRACE proposal, its research objectives and a precise list of the participants of the EU network is appended to the present proposal.

<sup>2</sup>Gravitational Radiation Collaboration Europe; participants: AURIGA, GRAIL, NAUTILUS, Univ. of Barcelona, Univ. Alfonso X (Madrid), Astrophysical Institute (Paris).

### 3.3 Construction phase

Upon successful completion of the R&D of phase A of the GRAIL project, the construction phase of the 3 m diameter resonant mass detector (phase B) is planned to be completed in three years. Phase B is structured as follows.

- The construction of GRAIL with technologies based on the Technical Design Report, as elaborated in the first (R&D) phase.
- Further development of the technology for the transducer and amplifier in order to install the optimal sensor in the final phase of the construction period.
- Preparation of the site for installation of the detector at NIKHEF.
- Initial commissioning of GRAIL with application of techniques to correlate GRAIL signals with other gravitational wave detectors.

The duration of phase B of three years is based on quotes from the industries that have capability to build the large cryogenic installations required for the detector.

### 3.4 Costing of phase B of GRAIL

We present a breakdown of the expenditures for the 3 meter diameter detector, its control systems, infra-structure and installation costs in phase B of GRAIL. The large entries, (cryogenic mainly) are costed on the basis of quotes from industries.

The total investment for the project amounts to 30 Million Dutch Guilders. The large parts of the detector can be accommodated by Dutch Industry and the necessary knowledge base pertaining to essential research on high power dilution refrigerator technology is available in this country. In first approximation the total annual exploitation budget for phase B is foreseen to be similar to that of phase A. This figure is presented in the table following chapter 5.

ITEM	INVESTMENT (Mf)
<b>Mechanics</b>	
Casting, machining of Sphere	3.2
Suspension	1.5
<b>Cryogenics</b>	
Main Cryostat	4.9
Dilution Refrigerators	1.9
Helium Liquefier	2.7
Helium Recovery system	0.7
Nitrogen precooling	0.3
Liquid Helium	0.6
Helium-3	0.7
Liquid Nitrogen	0.1
<b>Sensors</b>	
Mechanical amplifiers	1.2
Transducers	1.8
<b>Backgrounds</b>	
Cosmics monitor	1.0
Noise monitors	0.6
<b>Data acquisition and analysis</b>	
Computer hardware	1.0
<b>Equipment and materials</b>	
Electronics	1.5
Consumables	1.5
<b>Station infrastructure</b>	4.0
Networking/Intl. collaboration	0.8
<b>TOTAL</b>	<b>30.0</b>

GRAIL investment budget for phase B

## 4 Design and research objectives

The design of the GRAIL detector is guided by four principles:

- Good energy absorption from gravitational waves.
- Effective noise temperature close to the quantum limit.
- Minimal interference from non-gravitational backgrounds, such as internal, seismic, cosmic or atmospheric disturbances.
- Optimal signal recognition and reconstruction capability.

Design and research work heavily relies on the use of accurate numerical modelling of the complete system as well as subsystems. The following list summarizes the research objectives for the instrumentation work during phase A of the GRAIL project:

1. Show the feasibility of a 3 m diameter CuAl sphere with a objectives mechanical resonance quality factor of  $Q \geq 10^7$ .
2. Development of ultra low-noise suspension, with external vibration attenuation better than 320 dB near the resonance frequency, and compatible reduction of the influence of internal noise sources.
3. Development of a pre-cooling system capable of cooling 100,000 kg of CuAl to the 4 K range within three weeks.
4. Development of a dilution refrigerator with a cooling power of 100  $\mu$ W at  $T = 10$  mK.
5. Development of a motion sensor ultimately capable of determining surface displacements of the order of a several times  $10^{-22}$  m.
6. Development of methods and controls for suppressing interference from non-gravitational background events to the same level of sensitivity.
7. Development of a calibration system to measure the transfer function of signals passed on from the sphere to the read-out system.
8. Development of a data acquisition system and signal processing capability for taking and analyzing data from five sensors at a rate of 3 kHz, plus control and housekeeping data from external devices.
9. Development of a numerical simulation model of the complete system for design tests, and accurate numerical modelling of the signal transfer function of the system for the reconstruction of signals from the sensor output.

In this chapter we discuss each of these instrumentation aspects in detail. A modest research program on astrophysical sources, event rates and signals of relevance to the project was outlined in chapter 2.

## 4.1 Design and material properties of the sphere

There are several criteria for the selection of the best detector material. We discuss them in turn.

a. The mechanical  $Q$ -value, a dimensionless number representing the decay time of the quadrupole vibration measured in number of cycles. A high  $Q$ -value implies a large absorption cross section for gravity waves at the resonance frequency. As all excitations of the vibration modes decay by the same mechanisms, the  $Q$ -value also determines the relaxation time of thermal fluctuations. Therefore if the sampling rate of the sensors is sufficiently high—such that the sampling period is short compared to this relaxation time—then a change in amplitude and/or phase of the quadrupole vibration can be determined even if it is much smaller than the average size of a thermal fluctuation. In this way the effective noise temperature of the detector can be much lower than the actual thermodynamic temperature. If this is matched by an equally low noise temperature of the transducer-amplifier system a detector at a thermodynamic temperature of 10 mK can operate close to the quantum limit. Quantitatively the effective temperature is given by

$$T_{eff} = \frac{T}{\beta Q} + 2T_n. \quad (11)$$

Here  $\beta$  is the coupling parameter of the transducer, the efficiency with which it transforms mechanical into electrical energy, and  $T_n$  is the noise temperature of the amplifier. It follows, that for  $T = 10$  mK and  $\beta Q = 10^5$  the effective temperature is  $T_{eff} = 10^{-7}$  K, provided the noise temperature of the amplifier is of the same order of magnitude.

b. It must be possible to cast the material into a sphere of 3 m diameter. LIPS Bronze Casting Industries has expressed interest in manufacturing a sphere of this size, with a corresponding mass of well over 100,000 kg, from a suitable copper alloy such as CuAl.

c. The thermal properties of the material, like specific heat and thermal conductivity, determine the rate at which the sphere can be cooled and the size of thermal gradients over the volume of the sphere. Low specific heat requires absence of magnetic impurities, and good thermal conductivity excludes superconducting materials.

### State of the art

a. Present detectors like NAUTILUS and ALLEGRO reach  $\beta Q$  values of the order  $10^3$ . For GRAIL a CuAl (94/6) alloy has been identified with a  $Q = 1.5 \times 10^7$  for a frequency of 29 kHz at  $T = 15$  mK [38].

b. Pieces of 50,000 kg and more have been cast by LIPS, though never in spherical form. No qualitatively new difficulties are expected during the casting and cool-

down of the sphere.

Machining of a 3 m diameter sphere can not be done at LIPS. RDM ship-building industries have been approached for this part of the work. It is expected that machining at RDM can be done with a tolerance of better than 0.1 mm, which is adequate. The allowed degree of roughness of the surface is presently not known. It must be determined by measuring its influence on the  $Q$ -factor of the sphere.

## Research objectives

*Design of sphere, material science and material selection.*

1. At low temperatures the  $Q$ -value, the thermal conductivity and the specific heat of CuAl alloys are strongly influenced by the presence of impurities. The surface conditions may influence  $Q$  as well. The allowed level of impurities and surface roughness must be determined. For this,  $Q$ -values and thermal properties should be measured at 10 mK for small spheres containing known, controlled amounts of impurities, after various kinds of surface treatment and with known residual radioactivity.
2. The dependence of  $Q$  on the frequency is to be established by testing samples of larger dimension.
3. The influence of sensors and the suspension on the  $Q$ -value is to be determined by simulation and laboratory experiments.

*Deliverable*

Production and test specifications for a 3 m sphere with  $Q \geq 10^7$ .

## 4.2 Suspension

The suspension of the sphere is an important part of the design; see fig.(4.1). It must support the sphere in such a way that it transfers the smallest possible amount of external vibrations while causing negligible loss of internal vibration energy stored in the detector. This is best achieved by suspending the sphere in the center, where the amplitude of the quadrupole and monopole vibrations is minimal. Therefore it is necessary to drill a hole through the center of the sphere.

The weight of the sphere is to rest on a support, such that up-conversion of low-frequency vibrations by grazing surfaces is minimized. At the same time, this support also acts as heat contact through which heat will be extracted from the sphere by the dilution refrigerator (DR). Therefore it must provide optimal heat flow.

The suspension rod must be strong to support the weight of the sphere. As the connection between the sphere and the dilution refrigerator it must be a good

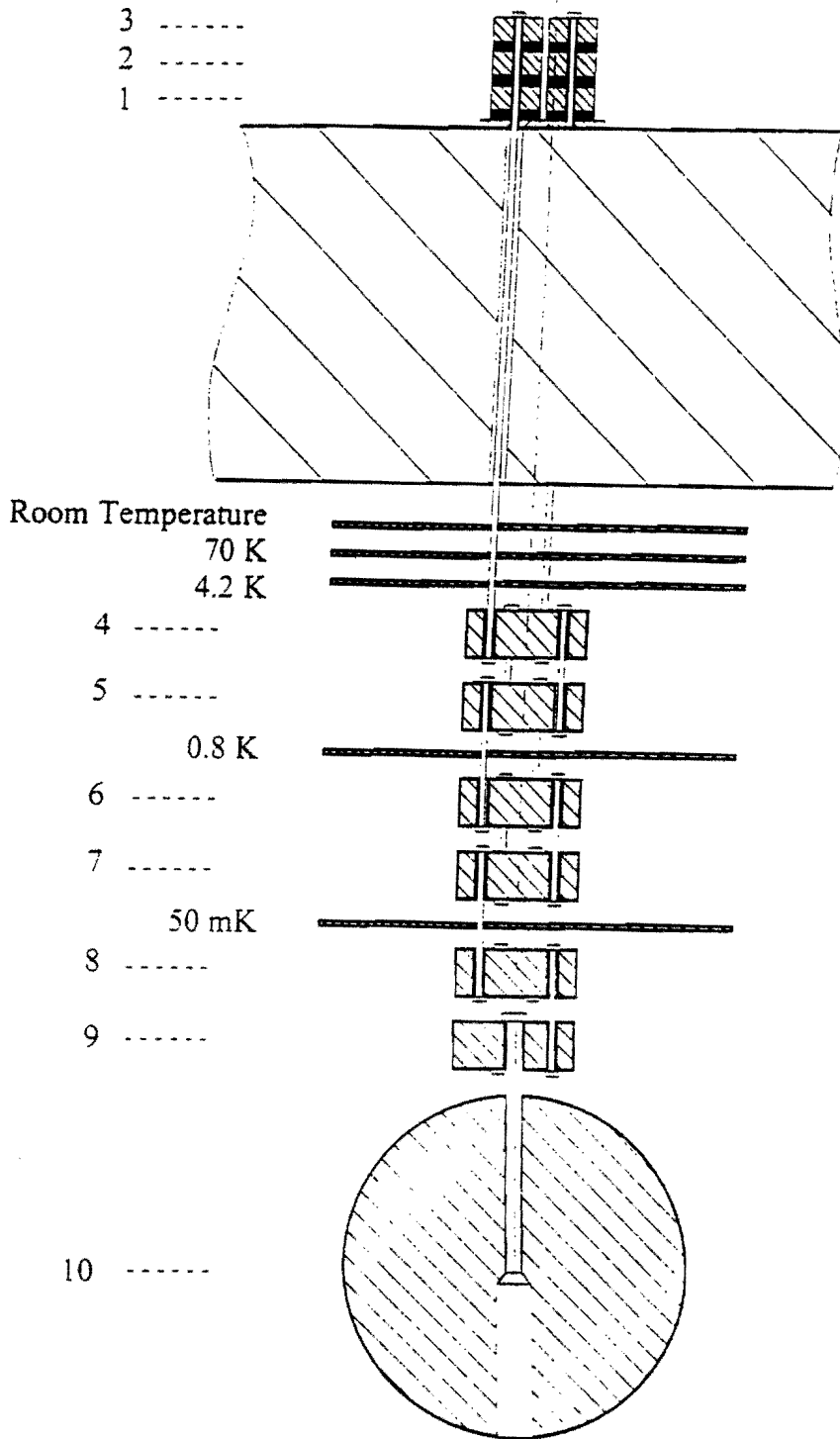


Fig. 4.1: Schematic diagram of the GRAIL suspension system. At room temperature a stack of rubber and steel plates provides the first vibrational isolation; not shown is a 1000 kg mass halfway the long rod between room temperature and the 4.2 K region.

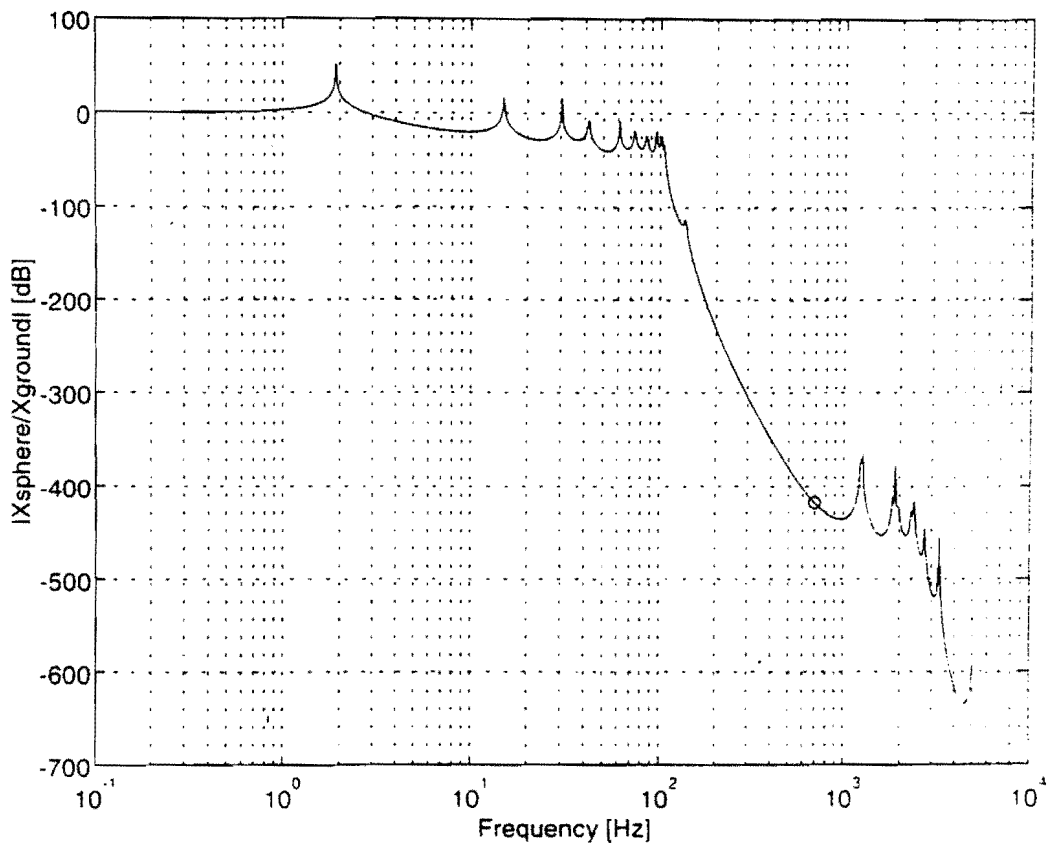


Fig. 4.2: Transfer function of the system represented in fig. 4.1. The 1000 kg mass halfway the long rod (not shown in fig. 4.1) was necessary to obtain a quiet region near the resonance frequency of the sphere, represented by the small circle.



heat conductor. The most critical mechanical contact is the thermal connection to the mixing chamber of the DR. The vibrations of the pumps of the DR must be eliminated at the source. Dangerous resonances of the coupled sphere-rod system are to be avoided, as these are sources of up-conversion of externally induced low-frequency motion.

External vibrations must be prevented from reaching the suspension rod by an efficient vibration isolation system. Analytical as well as finite-element calculations, supported by small-scale experiments, have shown an attenuation of 320 dB at the resonance frequency of the detector to be feasible using chains of solid rods and masses [38], fig.(4.2).

## Research objectives

### *Suspension and vibration isolation.*

1. Investigate materials and designs for the suspension rod and the support, minimizing the amount of internal vibrations and up-conversion.
2. Measurement of up-conversion noise at low temperatures.
3. Design a full-scale vibration isolation system capable of attenuating vibrations by 320 dB. Construct and test scaled-down components of the system, at room temperature and at low temperatures down to 4.2 K.

### *Deliverables*

1. Validation of a numerical simulation model of the vibration isolation.
2. Validation of the design of a 320 dB attenuation system for frequencies in the bandwidth of GRAIL.
3. Demonstration of the feasibility of an up-conversion noise spectrum of internal suspension commensurate with 320 dB attenuation.

## 4.3 Cryogenic aspects of GRAIL

Efficient operation of GRAIL requires a cryogenic system capable of cooling 100,000 kg of copper rapidly to 10 mK, and maintaining that temperature for long periods of time with high reliability and low mechanical vibrations. The cooling of the sphere and the attached apparatus proceeds in two stages: first pre-cooling to liquid He temperature, and then the final cooling to 10 mK using  $^3\text{He}$ - $^4\text{He}$  dilution refrigerators.

The first stage determines almost entirely the cool-down time. Calculations show, that with a heat transfer rate of  $500 \text{ W/m}^2$  the pre-cooling lasts about two weeks. Such a rate can be obtained by forcing He gas directly on the surface of the sphere. To this end the 50 mK shields are placed close to the surface, at a

distance of about 5 cm. The resonant transducers and SQUIDs must be properly protected against the high-speed gas flow. The heat transfer depends on several parameters like the speed and the pressure of the gas; target values are 1 m/s and 3 bar. A commercial 150 l/hr He liquefier provides sufficient cooling power.

When a temperature of 6 K has been reached the pre-cooling phase ends, the inner space of the cryostat will be evacuated and the He bath will be filled with liquid He. From that point on the dilution refrigerators take over and the final cooling stage is entered. On extrapolating the measured heat leak of the NAUTILUS detector at 100 mK, a cooling power of 100  $\mu\text{W}$  at 10 mK is a safe design value for the dilution refrigerators. There are however some uncertainties in the extrapolation, depending on parameters like the temperature of the last shield —targeted at 50 mK— and possibly unknown volume effects.

The necessary circulation rate of  $^3\text{He}$  in the DR's is 20 mmol/s, which can be achieved with a 20,000 l/s booster pump backed by a cascade of Roots pumps and a dry rotary pump. The recirculating oil is to be eliminated by a series of filters like those used in turbine He liquefiers, which are very sensitive to impurities. Great attention must be paid to vibration attenuation. Special heat exchangers of spiral geometry can be used; lacking sharp corners they are expected to contribute minimally to the hydrodynamic noise.

The design of the cryostat is largely determined by the choice of the cooling method, by the requirement of long-term operation at mK temperatures, and by the design of the low-noise suspension system. It must also take into account the assembling on a sphere equipped with sensors. Finally, it must allow for an over-pressure compatible with the integrity of the sealing of the inner vacuum vessel.

## State of the art

Commercially available dilution refrigerators typically have a cooling power of about 5  $\mu\text{W}$ ; the most powerful machines constructed in the Kamerlingh Onnes Laboratory in Leiden attain 25  $\mu\text{W}$  at 10 mK.

## Research objectives

### *Cryogenics*

1. Develop and test a circulation system for the forced He gas. Measure the exchange coefficient of He gas with the CuAl material of the sphere as a function of the design parameters, such as the position of the 50 mK shields, using a 15 cm diameter prototype sphere.
2. Design a cryostat housing the entire system of 3 m sphere plus sensors and suspension.
3. Develop a prototype dilution refrigerator with a power of 100  $\mu\text{W}$  near 10 mK. Low-noise operation of the system is to be demonstrated. The

prototype DR equipped with a large mixing chamber of 40-50 cm is to be used for testing components for GRAIL.

#### *Deliverables*

1. Demonstration that forced He gas circulation is capable of reducing cool-down times for the 3 m sphere to periods  $\leq 3$  weeks from room temperature to 6 K.
2. A prototype dilution refrigerator with a power of  $100 \mu\text{W}$  in the 10 mK range.
3. Demonstration of mechanical and fluid noise level of DR commensurate with external vibration isolation.
4. Production specifications of the cryostat for the 3 m sphere.

## **4.4 The motion sensors**

A solid spherical resonant-mass detector can vibrate in a large number of modes, either of spheroidal or toroidal type, characterised by a specific frequency and a specific multipole moment [24, 27, 28]. Tensor gravitational waves excite only spheroidal vibrations; therefore motion sensors that detect the vibrations induced by gravitational radiation must be designed to couple selectively to these modes.

A pure gravitational tensor wave excites the lowest spheroidal quadrupole modes if the frequency in the wave matches that of the quadrupole modes to within the bandwidth of the detector. All components of the wave can then be measured in principle with optimal sensitivity, provided there are at least five suitably positioned independent sensors on the surface of the detector to determine the full set of quadrupole amplitudes [25]. The polarization of the wave and its direction can be reconstructed [5, 6, 7], modulo a reflection in the transverse plane: opposite directions of the sky are indistinguishable. Correlation of the GRAIL data with another gravitational wave detector at sufficient distance would remove the ambiguity if differences in arrival time were measured.

A possible scalar wave component can be measured using a sixth sensor tuned to the fundamental monopole mode [26]. For a sphere with a fundamental quadrupole mode around 650 Hz, this monopole frequency is about 1.54 kHz [27, 28]. From the monopole signal by itself no directional information can be obtained.

The motion sensors of a resonant mass gravitational wave detector are critical components in determining its strain sensitivity. Basically they consist of three subsystems:

1. a mechanical motion amplifier designed to match the mechanical oscillation to the electrical read-out;

2. a transducer, transforming the mechanical oscillation into an electric signal;
3. a low-noise electronic amplifier for the electric signal.

Electro-mechanical transducers exist in three categories: capacitive (passive: SQUID, or active: microwave), inductive (passive: SQUID) and optical (active: laser resonant cavity).

There seems to be concensus in the literature, based on practical experience to date, that inductive transducers may ultimately reach the best energy resolution in particular when coupled to a SQUID, that itself an inductive device. However, the NIOBE antenna of the University of Western Australia is equipped with a sensitive microwave parametric transducer, whilst an optical transducer has recently been proposed in the context of the large Interferometer projects (LIGO and VIRGO) as a sensor with great promise to achieve sensitivities near the Standard Quantum Limit (SQL).

Because the sensor is a critical component of the GRAIL antenna we will briefly review the state of the art in each of the sensor categories, following the literature and results of our own research, obtained in the pilot study for GRAIL [38].

### Mechanical Motion Amplifier and Transducer

The quality factor of a sensor is characterized by two parameters – sensitivity and bandwidth. An important improvement in sensitivity is achieved by coupling the antenna to a mechanical motion amplifier, consisting of an oscillator with a small mass  $m$  in resonance with the large effective mass  $M_{eff}$  of the antenna [31]. The amplitude of the motion of the small mass will be increased by a factor  $\sqrt{M_{eff}/m}$  relative to the amplitude of the antenna. The transducer is then coupled to the small mass, rather than to the antenna itself. Practical amplification factors have been achieved in the range 300 – 500.

Multimode motion amplifiers using  $n$  coupled harmonic oscillators of decreasing mass have been developed by Richard [32]. These devices have the same high gain, determined by the square root  $\sqrt{M_{eff}/m_n}$  of the ratio of the effective antenna mass and the effective last resonator mass  $m_n$ , whilst the bandwidth — taken as the range of resonances of the coupled oscillator system— approaches the resonance frequency of the antenna. In fact the theoretical fractional bandwidth is given by  $\delta = (m_n/m_1)^{1/(2n-2)}$ , where  $n$  is the number of masses in the multi-stage amplifier. It should be noted, however, that the relevant bandwidth of the detector is that of the signal-to-noise ratio (SNR), which can differ appreciably from the range of mechanical resonances [29, 30].

For a sphere with a typical Poisson ratio of  $\nu = 0.3$ , the effective mass is  $M_{eff} \approx M/3$  for the radial modes, whilst  $M_{eff} \approx 4M$  for the tangential modes. The mass of the resonators should be optimized in order to minimize the thermal noise coupled back into the antenna (back action).

The motion amplifier is followed by a transducer converting the motion of the last mass into an electromagnetic signal. In passive transducers this is usually a SQUID, because of the low noise it can achieve in principle. The signal is further amplified electronically before being read out. Most currently operating resonant mass detectors NAUTILUS (INFN, Rome), EXPLORER (INFN, CERN) and ALLEGRO (LSU) use passive transducers with dc-SQUID amplifiers that are optimized for use at  $T = 4.2$  K. The SQUID amplifier at the NAUTILUS antenna has thusfar reached an energy sensitivity of  $1000 \hbar$ . A two-stage SQUID amplifier has been investigated at Louisiana State University with a best sensitivity reported of  $50 \hbar$ .

In the GRAIL pilot study we have investigated the properties of inductive transducers, focussing on the propagation of mechanical and electrical noise in the tightly-coupled system of mechanical amplifier and SQUID. From the simulations we extracted optimal parameters for a design of a multimode transducer. The calculated noise performance of a three-stage mechanical amplifier with a last mass of 0.5 kg and an intermediate mass of 122 kg, inductively coupled to a SQUID amplifier, is shown in fig. 4.3. The mass ratios have been optimized by varying the energy sensitivity of the SQUID and the antenna mass.

We have also developed and tested dc SQUIDS and double relaxation-oscillation (DROS) SQUIDS and have observed a noise level near the SQL at 100 mK. Further development of both types of SQUIDS carries promise to reach quantum limited sensitivity at 10 mK, the operational temperature of GRAIL.

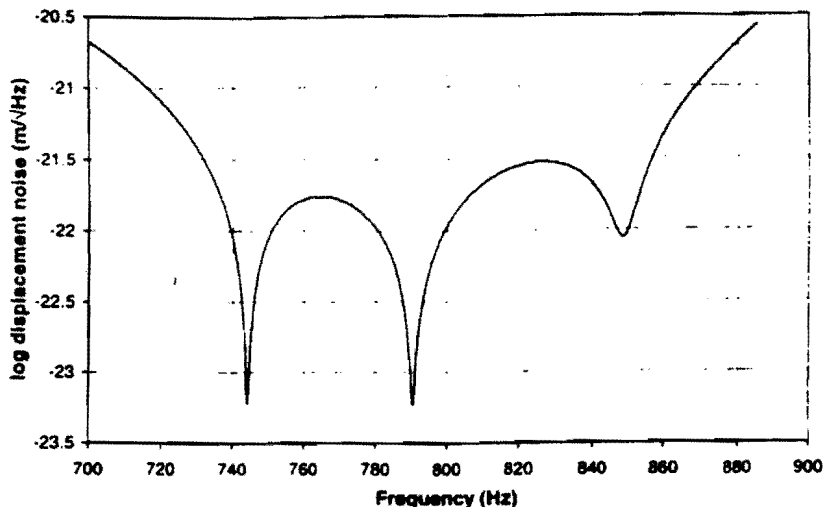


Fig. 4.3 Noise spectrum of 3-mode inductive transducer for  $m_3 = 0.5$  kg

Passive transducers based on an inductive or capacitive SQUID coupling are relatively straightforward, linear devices, holding considerable promise for further improvement towards the quantum limit in the near future. A possible second option for the read-out of a resonant gravitational wave antenna, which may also

be of interest for the long-term development of GRAIL, is provided by active parametric transducers. Parametric transducers are electro-magnetically resonant devices with a characteristic frequency modulated by the motion of the resonant mass antenna. A low-noise pump oscillator provides an incident carrier signal to the transducer at its resonant frequency. The frequency-modulated signal is extracted from the reflected or transmitted carrier signal. Parametric transducers working at microwave or optical frequencies have been developed [34, 35]. Because the measurement is based on the measurement of an incoming radiation field, these transducers can be operated without any wires contacting the transducer, allowing improved mechanical-vibration isolation.

### Optical transducer

In an optical transducer two mirrors are mounted to form an optical cavity: the reference mirror is mounted on the antenna, the second mirror is mounted on the last mass of the mechanical amplifier. An RF, phase-modulated laser beam, stabilized in both amplitude and frequency, traverses a high-finesse Fabry-Perot cavity which forms the transducer. The demodulated RF signal drives a feed-back system coupled to the cavity in such a way that it remains at resonance. The antenna signal is extracted from the demodulated RF signal.

The minimum detectable variation in the distance of the mirrors of a Fabry-Perot cavity is a function of the line-width of the cavity (determining factor: finesse), the linewidth of the laser (frequency noise) and the noise in the light detection system (shot noise, modulation noise).

Extrapolations based on Richard's measurements [34] at 4 K imply that it may be possible to reach broad-band signal amplification with nearly quantum-limited sensitivity, if a multimode transducer with an optical cavity cooled to 10 mK can be operated with submicrowatt dissipated power.

Notice that in the readout scheme, projected for both LIGO and VIRGO interferometers, similar requirements concerning stable laser operations have to be met with the added challenge of extremely large laser power and stability.

### Microwave Transducer

Another option for an active parametric transducer worth investigating is the superconducting cavity, as used by the NIOBE team. It has been shown to achieve good sensitivity levels using a 10 GHz microwave resonator at 5 K [36].

The NIOBE antenna consists of a high- $Q$  superconducting Nb-bar of 1.5 ton with a resonance frequency of 700 Hz. The bar is coupled via a mechanical amplifier with a mass ratio of 3000 to a non-contacting microstrip antenna. The vibration is monitored by a superconducting re-entrant cavity whose capacitance is modulated by the relative motion of the bar and the antenna.

The minimum noise temperature, achieved when contributions from the narrow-band noise equal the broad-band noise, amounts to 1 mK with optimal noise

filtering applied.

From straightforward extrapolation it is claimed that by reducing the oscillator AM noise an effective noise temperature of 0.3 mK can be reached. We intend to investigate the applicability of the superconducting parametric-transducer option in the 10 mK temperature range for GRAIL, making use of the knowledge base developed over the past few years in the field of superconducting Nb-technology for high-energy accelerator RF-cavities, e.g. at CEBAF, HERA and CERN.

## Research issues for sensors

### a. Mechanical motion amplifier

Transducers must be compact in order that, when positioned on the sphere, the size and hence the cost of the cryogenic system is not substantially increased. Together with the required large values of the quality factor  $Q$  and the coupling factor, this makes the design of the mechanical motion amplifier quite challenging. The transducer should be strongly coupled to the vibration of the sphere in the radial direction and be insensitive to motion in the transverse direction.

Two types of cylindrical multi-mode amplifiers satisfying these requirements have been designed: the *diaphragm* and the *mushroom* type. The *mushroom* type is not very suitable for the construction of multi-mode resonators.

## Research objectives

### *Mechanical motion amplifier for SQUID transducer*

1. Improve the coupling factor of the mechanical amplifier by loss-reduced coupling to the sphere surface. Special metal to metal joining techniques will be investigated, applicable at 10 mK temperature. The quality factor  $Q$  of the sensor must match that of the antenna, and a bandwidth of  $\Delta f \geq 130$  Hz at a strain level  $h = 10^{-21}$  implemented.
2. Optimize a 3-mode mechanical motion amplifier as to gain and bandwidth, together with the inductive coupling to the SQUID amplifier.

### *Deliverables*

A full-scale model of the mechanical amplifier, with coupling to a transducer, such that for the complete system the expected  $\beta Q \geq 10^5$ .

### b. SQUID transducer

The energy of the last mass of the mechanical transducer is transformed into electrical energy with an efficiency given by the energy coupling parameter  $\beta$ . The system components are the last mass (superconducting) of the mechanical transducer, the superconducting loop that carries the persistent current and an

inductive network, parallel to the loop that couples flux to the SQUID. We intend to fabricate and test quantum limited SQUIDs, both in dc-SQUID and DROS configuration. In the development phase we will vary the SQUID hole size, the critical current (related to the junction size and the critical current density) and the shunt resistors; for the DROS the shunt inductor and the damping resistor will be optimized. We will investigate properties of the devices such as the transfer function and the noise characteristics as a function of the temperature. For this the development of a local facility to test SQUIDs at mK temperatures is planned. Tests of larger components with integrated SQUIDs can be done at the facility to be developed in Leiden. Attention will also be paid to the dissipation in practical devices. In addition to the bare SQUID we will study the effect of the input coil on the SQUID washer.

A key research objective is to produce robust and sensitive devices that have a long lifetime and operational stability in the millikelvin domain.

We will investigate the following design parameters, directed towards optimizing the energy transfer function and the noise characteristics.

- The shape, material and topology of various types of coils with a flattened surface to allow distances to the resonant mass of 10-20  $\mu\text{m}$ .
- The loop current in order to optimize the displacement-current transformation factor, which is proportional to current.
- Match the mechano-electric transformer to the impedance characteristics of the SQUIDs. Variables here are the number of transformers, coupling factors and the input-coil inductance of the SQUID.
- Fabrication of the circuitry including the persistent current-mode facility.
- Develop practical engineering solutions for SQL sensitivity and robust sensor devices.

## Research objectives

### *Inductive SQUID transducer*

1. Implement a bare energy sensitivity of the SQUID sensor of  $20 \hbar$  and a bandwidth of  $\geq 130$  Hz.
2. Test the flux transformer circuit and the SQUID in an adequate cryogenic test facility at temperatures below 1 K .

### *Deliverable*

A prototype inductive SQUID transducer with coupled sensitivity of  $40 \hbar$ .



### c. Optical transducers

The AURIGA group in Legnaro (It.), a partner of GRAIL in the GRACE proposal for a TMR network, will study the feasibility of optical transducers for resonant-mass detectors.

It is proposed to follow the development of optical transducers by the AURIGA group in Legnaro as described in the GRACE proposal, and assess their suitability for the GRAIL detector.

### Research objectives

#### *Optical transducers*

1. Test of optical transducers developed by the AURIGA collaboration.

#### *Deliverable*

Assessment of an optical transducer for GRAIL.

### d. Microwave transducer

Expertise on RF microwave cavities and Nb technology is available in the GRAIL collaboration. The applicability of the technology to resonant mass detectors depends on the attainable noise level and the power dissipation in the sensor.

The three fundamental noise components: thermal (white) noise, shot noise (in particular  $1/f$  noise), and transition noise, are to be reduced to roughly equal values at operating conditions. While thermal noise can be reduced by lowering the operating temperature, transition noise and shot noise must be minimized by careful design of the microwave parametric amplifier system. Dissipation can be lowered by lowering the energy density in the cavity. The corresponding decrease in the  $Q$ -value must be compensated by improved transducer efficiency  $\beta$ .

Reduction of the  $1/f$  noise will be the major research effort. Substantial improvements have been achieved over the past several years in low-noise microwave amplification, superconducting Nb accelerator cavity technology and ultra-stable microwave pumping sources.

### Research objectives

#### *Microwave transducer*

1. Development of a, possibly mono-crystalline, microwave cavity with strong, low noise, coupling to the mechanical motion amplifier in the 10 mK range.
2. Selection of a microwave frequency in the range used in radio astronomy (1-5 GHz).
3. Development of a low-noise amplifier for operation below 1 K.

### *Deliverable*

Feasibility proof of a microwave transducer operating at  $T < 4K$ , with the following specifications:

1. An integrated system consisting of a mechanical resonator, cavity, compensation circuits and amplifier.
2. Extrapolated dissipation  $< 10 \mu W$  in the 10 mK range.
3. A calibrated conversion of mechanical to electrical energy.
4. Bandwidth  $\Delta f \geq 50$  Hz.
5. Shot noise ( $1/f$ ) comparable to the extrapolated thermal noise limit.
6. Calibrated sensitivity to disturbing mechanical noise sources.

## 4.5 Cosmic ray background

Without massive shielding cosmic rays will deposit substantial amounts of energy in GRAIL and cause on average an increase of the effective noise temperature  $T_{eff}$  of the antenna. At the sensitivity level that we aim for with GRAIL the effect of cosmic-ray impact might seriously impair its operational characteristics. Quantitative data on the effect of cosmic impact on GW detectors is scant at present. The team at the NAUTILUS detector have investigated to some extent the issue of the impact of cosmic rays. NAUTILUS is presently operating at a noise temperature  $T_{eff} \approx 10^{-3} K$ . A recent, preliminary analysis by the NAUTILUS group of GW antenna signals in coincidence with cosmic rays signals, generated in particle detectors positioned above and underneath NAUTILUS, indicates that the extensive air-shower component of cosmic rays might lead to signals, mimicking gravitational waves, at a level above  $T_{eff} \approx 10^{-3} K$ . [39]

Here we discuss the issue of cosmic rays, using results obtained with computer modeling of the impact of cosmic rays in GRAIL, both at surface level and deep underneath, at a site as provided for instance by the GRAN SASSO Underground Laboratory in the vicinity of Rome. Research objectives for Phase A of the project are subsequently presented.

### State of the art

Particle composition, energy spectra and fluxes of cosmic rays impinging on the earth surface and after penetrating through a fat layer of rock into an underground laboratory have been well established experimentally [40]. The well-known process of energy deposition of cosmic rays in the detector and a Thermo-Acoustic Conversion (TAC) Model [42] have been used to estimate the effect on noise temperature level. Cosmic rays basically lead to ionization in the vicinity of

the track, heating the material locally. This is followed by localized thermal expansion, which excites the vibration modes of the sphere and contributes to the non-gravitational background signal.

For the NAUTILUS antenna the calculated rates as a function of threshold are very low, and the effect on the noise temperature is found to be sufficiently small not to impair proper operation of the antenna at the present noise temperature of 3 mK.

The situation may well be different for GRAIL with its two orders of magnitude larger sensitivity. At earth surface the total calculated rate of cosmics depositing an energy  $\Delta E/k \geq 10^{-7}$  K amounts to  $10 \text{ s}^{-1}$ . At the depth of about 1.5 km under rock in the Gran Sasso laboratory the total incident rate of muons on the sphere would be less than about  $0.004 \text{ m}^{-1}$  [40, 41]. Cosmic hadrons will not reach the antenna, having been completely absorbed. In practice the remaining detected muons can be used to veto the GW-antenna signal, without causing a dead time problem.

The key question in modeling the effect of cosmics impact is to understand what fraction of the energy deposited in GRAIL is transferred at the resonant frequency to the quadrupole vibration mode, characteristic of GW radiation.

Tools, based on available knowledge, have been used in computer simulations to calculate cosmic ray effects in the recent GRAIL pilot study [38]. These calculations are still too crude to draw precise quantitative conclusions as to the background level generated by cosmics in GRAIL when the detector is positioned at sea level.

We have also carried out experiments to calibrate the TAC model calculations by bombarding a test sphere with bunches of  $\approx 10^{10}$  electrons with an energy of 700 MeV per electron and measuring the acoustic energy detected by piezoelectric sensors attached to the surface of the sphere. A preliminary analysis of the measurements yield the following qualitative observations.

1. The impact of electrons does excite the quadrupole mode at a significant level. It seems therefore unlikely that cosmics impact can be discriminated on the basis of a multipole analysis of the antenna signal from GW wave impact.
2. At sea level, if all cosmics impinging on GRAIL would be used to veto the antenna an unacceptable level of dead time would result.

In the conjectured circumstances, operation of GRAIL in coincidence with other GW detectors would not be helpful because of the dead time problem. This might be alleviated by substantially increasing the detection threshold; however this would result in an undesirable loss of sensitivity.

If indeed GRAIL-antenna signals, induced by cosmic rays, turns out to disturb the gravitational wave analysis, GRAIL should ultimately be set up in an underground laboratory that provides for sufficient shielding from cosmic rays. A definite operational conclusion should await the supplementary research to be performed during Phase A of the GRAIL project.

## Research objectives

### *Cosmics background*

1. Join the NAUTILUS data analysis effort to obtain cosmics- and antenna-signal correlations.
2. Extend the mini-sphere tests in the MEA electron beam. Establish the fraction of the vibrational energy transferred to the quadrupole vibrational mode of the sphere. Compare the measurements on the test sphere with the results of full-scale computer simulations.
3. Measure the Grueneisen parameter of the materials selected for GRAIL below 100 mK. This is the relevant material property governing the thermo-acoustic conversion efficiency.
4. Investigate strategies for discriminating cosmics-induced signals from GW induced signals.
5. Design of a cosmic ray detector system for a surface-based and an underground GW experiment.

### *Deliverables*

1. A validated model for the energy deposited in the quadrupole mode by charged particles at room temperature.
2. The value of the Grueneisen parameter as a function of temperature below 100 mK.
3. A reliable estimate for the number of accidental coincidences between two or more detectors due to cosmics, above and underground.

## 4.6 Calibration

The output of the motion sensors is a measure for the displacement of the surface of the sphere. The quantitative relation between displacement and output is represented by the transfer function of the sphere-plus-read-out system. Because of the complex nature of the full apparatus, which defies a completely analytical representation, and the unknown influence of small imperfections and mismatches in the system, the transfer function must be determined empirically. The results form the input for a numerical simulation model of the system, which is important to set up data analysis procedures. The calibration is done by the application of a local impulse to the sphere and registration of the respons of the sensors.

The relative sensitivity of the motion sensors is of importance. For example, an accurate knowledge of the relative amplitude and phase of the output of

the sensors suffices to determine the direction and polarization of a gravitational wave. Such a relative calibration of sensors can be achieved by swapping their positions, for example in a set up in which their gain is measured. For measuring background levels, like cosmics, absolute calibration is necessary.

## Research objectives

### *Calibration*

1. Test of calibration procedure on a small sphere including transducers at room temperature.
2. An impuls generator which can apply local impulses to the 3 m sphere is to be designed and constructed.
3. A calibration station for the measurement of vibration amplitudes by the sensor/transducer system is to be developed. A numerical model for the read-out transfer function is to be constructed.

### *Deliverable*

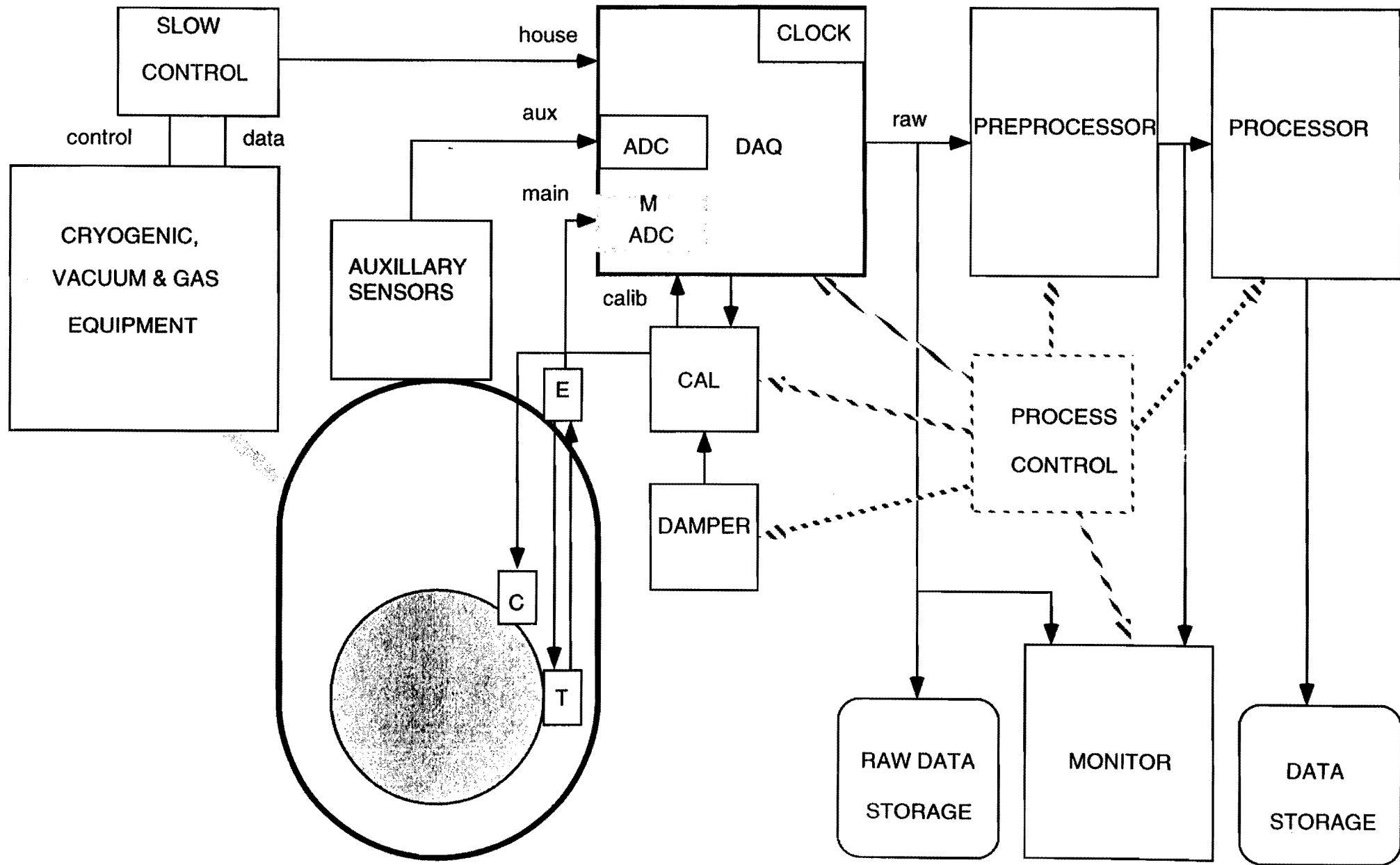
A validated calibration procedure of the transfer function of the read-out system.

## 4.7 Data acquisition and processing

After electronic amplification, the data from the sensors has to be sampled and processed. In addition there are other data necessary to identify external noise events and to monitor the state of the apparatus. In the diagram the system of detector, cryostat and auxiliary apparatus is shown, indicating the flow of data and signals.

The following data streams can be discerned:

1. Signals from the SQUIDs: the six mechanical transducers (T) together with the SQUIDs and the associated electronics (E) produce the *main* data.
2. Signals from the auxiliary sensors (*aux*) which are necessary to interpret the main data, such as
  - (a) cosmic ray signals;
  - (b) signals from seismic sensors on support, cryostat, etc.;
  - (c) signals from e.m. antennas;
  - (d) clock signals for accurate timing.
3. Signals from other equipment, such as temperature and pressure monitors in the cryostat, and status information (housekeeping data: *house*).



4. Control signals for valves, heaters etc. (*control data*)
5. Calibration signals (*calib*) from the calibration process (CAL) controlling a calibration device (C) on the sphere.

The PROCESS CONTROL function synchronizes the various processes, starts and stops data taking runs. The SLOW CONTROL function receives data and sends control signals to the control devices inside the cryogenic, vacuum and gas equipment, and produces status information for the Data Acquisition System (DAQ).

### Sensor Data

In order to achieve the best possible sensor performance, the digital quantisation noise of the analog-digital conversion (ADC) should be smaller than the noise of the sensor itself. Assuming a bandwidth of 200 Hz for each of the six sensors of GRAIL we estimate that the number of ADC bits required to avoid digitalisation noise is 20.

The data-acquisition equipment should not induce RF interference in the SQUID electronics. This implies separate grounding and power supplies for the electronics and the ADC. The digital read-out and the triggering of the converter is best implemented by fiber optics.

The sensor signals are to be digitized and stored in memory. All processing will be done on the digitized data. For minimal loss of information the *main* and *aux* are to be sampled with at least the Nyquist frequency. To accomodate both the fundamental quadrupole and possibly the monopole mode, we need a minimal sampling rate of 3 kHz, with appropriate anti-aliasing. To avoid problems with random background like cosmics, accurate time labels of background events are to be stored with the data.

Correlation of motion-sensor and other data requires accurate knowledge of relative phases. All sampling and time labelling is therefore to be done with the same clock. For correlation with other gravitational-wave detectors it is necessary to refer this clock to absolute time-standards. Commercially available hardware like GPS-based clocks provides absolute time references to within 100 ns resolution.

In order to continuously assess the proper functioning of the instruments some signals have to be processed in real time. In the diagram this function is indicated by MONITOR. Automatic alarms must be given on the basis of the raw *house* data, e.g. when critical temperatures are reached. A small sample of the preprocessed data stream is to be used for monitoring. For example, the signals of the SQUIDs will be processed to determine an absolute noise level which can be compared with earlier data. Noise spectra of the *main* data must be continuously available as a monitor of the health of the instrument.

## Data processing

In the block labeled PREPROCESSOR two functions are performed:

- Sorting: *main* and *aux* data will generally not need to be processed when the *house* data indicate malfunctioning of the instrument. On the other hand, such data can be used for failure diagnosis. The *house* data are further used to separate the data streams according to status bits indicating that the instrument is in measure mode or calibration mode. Vetoing for random background like seismic or cosmic ray events is to be done at a later stage.
- Conversion: the raw data, represented only by bits, have to be converted to physically meaningful data. This applies to all three data streams. Here the input of the calibration is used to process the data, for example by using the measured transfer function of the detector to convert SQUID data to displacements.

## Further processing

The PROCESSOR further handles the data as necessary for signal analysis, both for gravitational waves and background. Specifically we indicate two important functions.

- Filtering: by restricting the data to lie in specific bands of frequencies noise can be reduced (near an eigen-frequency of the sphere) or measured (away from the resonances). The corresponding reduction of the bandwidth may allow a lower sampling rate. The depth of the samples may be changed as well. The total data rate will then be much less than that of the raw data.
- Correlation: data from the various sensors are to be combined into mode channels to obtain the amplitudes of the normal modes of the detector. Correlation with *aux* data like cosmic-ray events is needed. All meaningful signals, possibly representing gravitational waves, are to be identified and stored.

## Estimated size of the data streams

<i>main</i>	6 SQUIDs, 20 bits at 3 kHz	360 kbit/s
<i>aux</i>		
cosmics	(unless underground)	2 Mbit/s
seismics	10 sensors, 16 bits at 3kHz	480 kbit/s
e.m. background	10 sensors, 16 bits at 3 kHz	480 kbit/s
<i>house</i>	100 sensors, 8 bits at 1 Hz	800 bit/s

## 4.8 Signal analysis

The final step in the processing of the data is signal analysis. As is the case with most radio-astronomical antennas, GRAIL and other gravitational-wave detectors will be looking for the slight changes in the detector noise that signify the presence of an astrophysical source. In order to make this search successful, we



must obtain the best possible understanding of the antenna, its noise characteristics and transfer function, and of the sources. We must extend existing analysis procedures, and where possible/necessary develop new procedures.

### **Transfer function and noise characteristics**

The transfer function and the noise characteristics of the read-out system of the antenna are determined by the complete chain of (slightly) dissipative resonators formed by the antenna and sensors. Including the additional complications of back-action of the transducers, the result will be quite complex. The modelling of the system is a challenge to the applicability of theoretical procedures and requires empirical input.

The behaviour of perfect as well as deformed spheres, with holes for suspension and sensors mounted on the surface, can be modeled by a combination of analytical and numerical methods [24, 27, 28, 43]. The most versatile and powerful computational techniques applied are the finite element methods. Implicit methods allow us to find the vibration modes and frequencies for undamped systems and eventually, to determine the transfer functions even for slightly damped systems. They require that the eigenmodes of very large sparse matrices are determined. Explicit methods use a time-integration approach for the equations of motion for the system. They can more easily be applied to the study of transient phenomena, and their greater algorithmic simplicity makes them more attractive for very-high resolution studies. A suitable high-resolution finite element method (FEM) code was developed at the University of Amsterdam that can be run on the available parallel computer systems.

A sphere with six three-mode sensors has seventeen resonant modes, with frequencies spread over a range of more than 100 Hz. Depending on the achieved symmetry, some of these modes are degenerate in frequency with other ones. Not all of the modes need to interact with gravitational waves. An analysis of these modes is important, as it allows the application of the mode channel model proposed by Merkowitz et al.[5].

### **Data analysis**

Data analysis techniques depend on whether the data are from a single antenna, or from two or more correlated antennas.

*Single antenna techniques.* Techniques to recognize gravitational wave signals with a single detector are useful when correlating the gravitational antenna output with non-gravitational data, e.g. gamma rays, neutrinos, optical or radio signals. If the form of the gravitational wave signal to be expected is known with some accuracy, one can use either of two complementary methods known as template matching in the time domain, or matched filtering in the frequency

domain. These techniques are applicable for example to the collapse of a compact binary star system, which has a very characteristic signal. The GRAIL antenna is expected to be able to follow binary neutron star collapses as far away as the Virgo cluster for several periods of revolution [18].

Applications of these techniques require good knowledge of the transfer function and noise of the antenna read-out. Signals must still significantly exceed the instantaneous antenna noise to be detectable, but the matched filtering can significantly increase the confidence in a detection. Challenges in this area are the modelling of the signal sources and the development of fast and reliable strategies to correlate the continuous stream of antenna data with the large number of possible signal footprints.

Periodic signals from continuous sources like slightly aspherical millisecond pulsars can be integrated in a phase-coherent way over long periods of time by correlation with radio data. For such a source the relative phase of the expected signal can be accurately corrected for the diurnal, monthly and annual motions of the antenna with respect to the source. Therefore even very weak signals can be reconstructed in principle.

This becomes much more difficult for unknown sources of periodic signals. Because of the many parameters involved, including the celestial coordinates, the period and the spin-down rate, the search space becomes very large. Divide-and-conquer techniques or maximal-entropy methods will be studied to find efficient strategies.

*Correlated antenna techniques.* The multiplicative correlation technique widely used in radio interferometric applications can in many ways be transplanted to the GW domain. It requires the simultaneous operation of two or more antennas in the same frequency range, and preferably having comparable sensitivities. Correlation experiments can be performed off-line if desired, as long as a recording of the antenna signals with sufficiently accurate timing information is available. Gravitational wave experiments can benefit strongly from transfer of expertise available in radio astronomy.

Correlations between nearby antennas allow to search for coincidences with strong suppression of the uncorrelated noise. The technique is suitable for establishing burst sources as well as stochastic background.

Correlations between distant antennas (one or more wavelengths apart) in an interferometer set-up and using variable delays further improves the directional information about the sources by comparing arrival times of signals. Moreover a further reduction of external noise, e.g. from cosmic ray showers or thunderstorms, can be achieved.

## **Research issues for GRAIL**

*a. The transfer functions of the GRAIL antenna.* For many of the techniques described above it is necessary to have an accurate knowledge of the transfer

function of the antenna, from GW input (including direction and polarisation) to the digitized output signal, for each frequency. The large number of resonant components and the sharpness of the resonances due to the high  $Q$  of the system will tend to lead to rapid changes in the gain and phase response with frequency. In radio-astronomy bright point sources are used to calibrate the response of the antenna. For GRAIL calibration procedures have been described in sect.4.5. Initially we have to rely on accurate modelling of the system and more indirect measurements of the transfer functions.

Apart from determining the transfer function itself, it is necessary to determine the inverse function as well to be able to determine the characteristics of the source from the output of the transducers. Template matching techniques provide a complementary approach. It is to be investigated how accurately the incident signal can be reproduced from the detector output under various circumstances.

Using the modelling and analysis tools developed during for the feasibility study a complete input-output model of the GRAIL system will be constructed. Additional tools will be developed as need arises.

## Research objectives

### *Transfer functions*

1. Develop and test a complete input-output model for the GRAIL sphere with motion sensors, including a realistic noise model.
2. Develop the input-output model for the proposed calibration system. Collaborate in developing the calibration method.

### *Deliverables*

1. A parametrized program to generate simulated observations including noise, for calibration, testing and modelling.
2. A first version of calibration software

*b. Data analysis and search techniques.* Both for the template matching for events of short duration and for the search for unknown continuous wave sources, the search space is extremely large. Divide and conquer techniques of various kinds appear to be promising, but significant research is still required. From the source models and the knowledge of the transfer functions, the required templates can be constructed. Furthermore, the applicability of *maximum entropy* techniques, which can provide an optimum reconstruction of the input signal for noisy and patchy data will be studied.

## Research objectives

### *Data analysis*

1. Design and test data analysis procedures using the knowledge of source characteristics, transfer model and calibration procedures.
2. Study the implementation of correlation procedures with the other suitable GW antennas.

### *Deliverables*

1. A first version of a suite of programs to extract data from real/simulated observations.

*c. Other design considerations.* The available modelling tools will also be used to study other aspect of the GRAIL system. These will include design parameters, such as the optimal positioning of the suspension point within the sphere, and the signature of various noise sources, such as cosmic rays.

## Research objectives

### *Design issues*

1. Provide simulation support where needed and possible for other subprojects.

### *Deliverables*

1. As required by other project tasks.

## 4.9 GRAIL design and costing

Test results and production specifications for all components of the complete system including the full 3 m sphere, sensors, read-out and cryogenic apparatus as well as monitoring devices are to be integrated in regular updates of the GRAIL design. Assembly and integration of the components and subsystems are to be planned and prepared. The costing of the full system is to be updated accordingly.

### Design objective

#### *Design and costing*

Production and assembly specifications for the integrated GRAIL design.

#### *Deliverable*

An integrated system design and update of the costing for phase B.

## 5 The GRAIL Collaboration

The design, construction and scientific exploitation of a large and complex device such as GRAIL involves a major interdisciplinary effort encompassing physics, astronomy, computer science, and engineering. The successful realization of the project also requires involvement of industries specialized on a high technology level in large-scale mK cryogenics, ultra-pure metallurgy and casting of multi-ton pieces.

A substantial part of the required industrial capability is in principle available in the Netherlands, e.g. with LIPS Industries, Leiden Cryogenics, De Schelde and RDM. Specific scientific expertise is available in the domains of millikelvin physics and the related instrumentation, low temperature quantum electronics (SQUID devices), mechanical engineering science, microwave electronics and system engineering.

The universities and research institutes currently participating in the project are

- Rijksuniversiteit Leiden: Low Temperature Physics
- Universiteit van Amsterdam: Institute for Astrophysics/CHEAF
- Universiteit van Amsterdam: Computational Physics Dept.
- NIKHEF-FOM (Amsterdam): Theoretical and Experimental Physics
- Technische Universiteit Eindhoven: Low Temperature Physics and Mechanical Engineering
- Universiteit Twente: Quantum Electronics and Micromechanics

The teams involved will join the GRAIL collaboration by signing a memorandum of understanding. The management structure of the project and its governance is discussed in the next section.

### 5.1 Project management

Management of the GRAIL project is based on the concept of a formal collaboration headed by a project director (PD). The PD controls the budget, reports to the review council overseeing the project on behalf of the participating institutions, and represents the collaboration in all scientific policy matters.

A board of principal investigators advises the project director on all scientific matters related with the project and on internal matters of the collaboration.

Members of the review council are representatives of the institutions and institutes participating in the project. The council is advised by an international scientific advisory committee.

Participants join the collaboration upon signing a formal memorandum of understanding.

The technical project leader (TPL) reports to the project director and the board of principal investigators. He is responsible for the implementation of the GRAIL project. The project leaders of the sub-projects, that deliver parts and subsystems of GRAIL, report to the TPL. The collaboration will have meetings on a regular basis in which progress is communicated and scientific matters are discussed.

## 5.2 Project timelines

The GRAIL project has the objective to push the state of the art in GW detectors by two to three orders of magnitude in strain sensitivity. This involves extrapolation of current instrumentation technologies by a large factor, requiring several parallel instrumentation approaches to be pursued before a Technical Design Report can be delivered. The GRAIL Project will therefore be implemented in two phases:

- *Phase A*

Research and development of critical parts of instrumentation such as quantum limited sensors, minimization of internal noise sources, and the design of a large power dilution refrigerator.

Together with signal analysis and correlation strategies, deliverables of Phase A constitute the base for the engineering design of the 3 meter diameter GRAIL Antenna.

The planned duration of Phase A is *two years*.

- *Phase B*

Production, installation at NIKHEF and commissioning of GRAIL.

Prepare the initial programme of searches for GW burst sources.

Prepare for European Correlation network of GW detectors with appropriate sensitivity. Continuation of the R and D effort to improve the sensor technology even closer to the level of quantum-limited sensitivity.

The planned duration of Phase B is *three years*.

In the initial phase of GRAIL a test and development facility will be set up to perform research on critical instrumentation issues such as the sensors with the goal to continually improve the performance of the antenna and to develop special purpose devices. These activities will be coordinated in the frame of a European Network with the purpose to set up a correlated GW Antenna network and improve on the overall performance of the participating instruments.

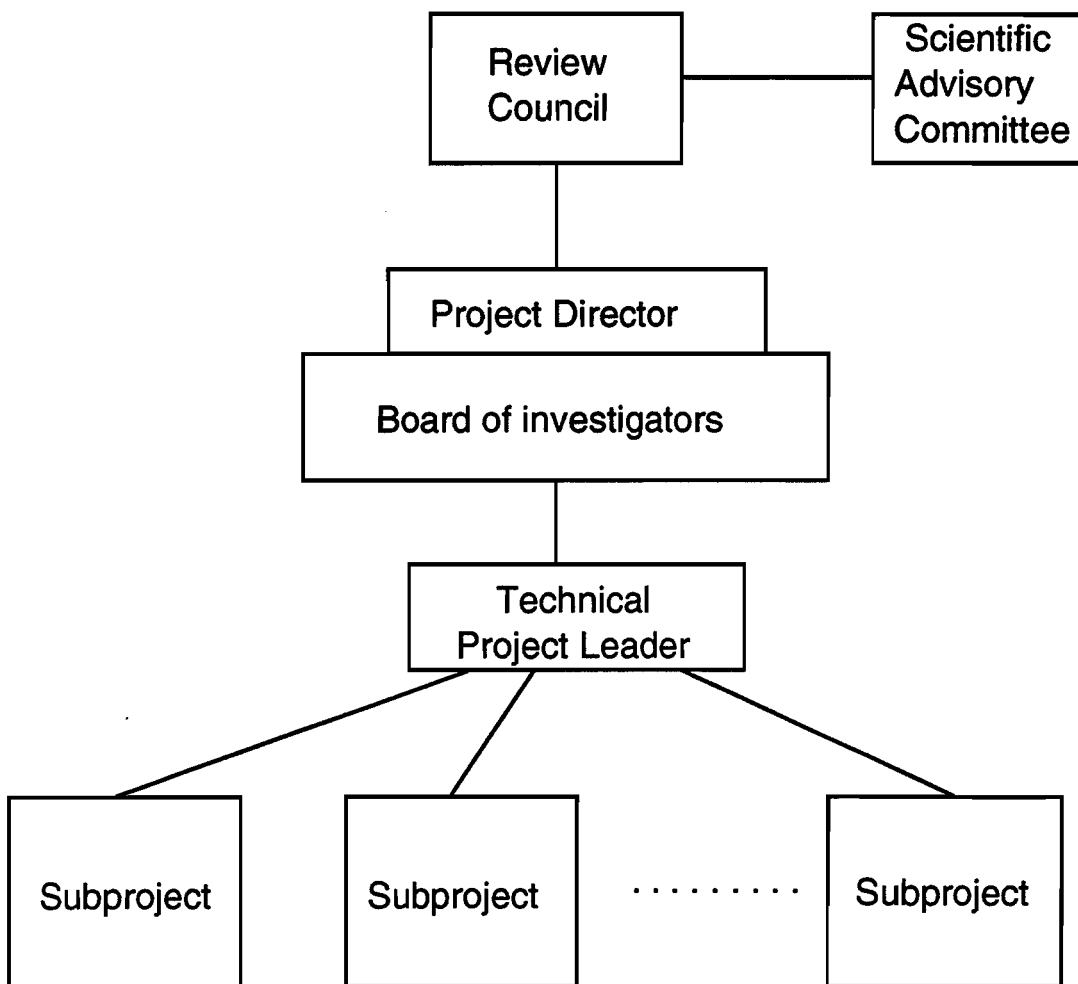


Fig.5.1: Organisation structure of the GRAIL project

## Budget for phase A of GRAIL

TEAM	Invest. <sup>a</sup> (kfl)	Expl <sup>b</sup> WP	Expl <sup>b</sup> TP	Matching <sup>b</sup> WP	Matching <sup>b</sup> TP	Expl. <sup>c,d</sup> Total (kf) FOM prg.	Expl. <sup>c,d</sup> Total (kf) Match.
RULeiden	1910	2.5	1.0	2.8	1.7	275	520
TUEindhoven	1050	5.0	1.5	2.1	0.4	490	320
UTwente	730	2.5	1.5	3.0	0.4	300	350
UvA	100	1.0		1.0		75	105
CHEAF	50	2.0		2.0		125	125
NIKHEF	910	5.5	3.5	incl.	incl.	1300	500
<b>TOTAL</b>	<b>4750</b>					<b>2565</b>	

### *Notes*

- a. Investment quoted in amounts for 2 years.
  - b. Personnel quoted in total number of man-years per year.
  - c. Exploitation expenditures in last 2 columns quoted in amounts per year.
  - d. Exploitation in last column includes infrastructure costs.
- legenda:* WP = Scientific Personnel; TP = Technical Personnel.



## Distribution of Tasks for Phase A of GRAIL

TASK	RUL	TUE	UT	UvA	CHEAF	NIKHEF
<b>1. Material science</b>						
Materials selection	✓					✓
Casting of Sphere						✓
<b>2. Suspension</b>						
Suspension		✓				✓
Vibration attenuator		✓				
<b>3. Cryogenics</b>						
Cryostat	✓	✓				
Cooling to 6 K	✓	✓				
Dilution Refrigerator	✓					
<b>4. Sensors</b>						
Mechanical amplifier		✓	✓			✓
SQUID Transducer			✓			
[Optical cavity]	[✓]					
Microwave Transducer						✓
<b>5. Signals and Backgrounds</b>						
Cosmics						✓
Calibration	✓	✓				✓
Response modeling				✓		
Noise		✓		✓		
<b>6. GW Signals/Sources</b>	✓			✓	✓	✓
<b>7. Design and costing</b>						✓

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## **Appendix: excerpt of the GRACE proposal**

In this appendix some selected pages of the GRACE proposal for a European collaboration on resonant-mass detection of gravitational waves are reproduced. The GRACE proposal has been submitted by NIKHEF to the TMR program of the European Union. It represents a collaboration of GRAIL (here represented by NIKHEF, and the universities of Leiden and Twente) with the universities of Rome and Trento (Italy), Barcelona and Madrid (Spain), and the Institute for Astrophysics of the CNRS in Paris (France). The selected pages show the involvement of the various participants, the project objectives and milestones to be reached by the end of the project, the training content for young researchers, and the way collaborations on sub-projects will be organised.

**1. GENERAL PROPOSAL INFORMATION (1)**

**TMR RESEARCH NETWORK PROPOSAL**

<b>Proposal Title (2)</b>	→	Gravitation Radiation Collaboration Europe
<b>Proposal Short Title (3)</b>	→	GRACE
<b>Panel (4)</b>	→	Physics
<b>Disciplines (5) (in order of relevance)</b>	→	1. <u>PO8</u> 2. <u>PO9</u> 3. <u>P10</u> 4. _____

**Name and Postal Address of the Proposal Coordinator (6)**

<b>Title, Family Name</b>	→	Dr. Van Holten
<b>First Name</b>	→	Jan-Willem
<b>Name of Organisation</b>	→	Foundation for Fundamental Research on Matter (FOM)
<b>Name of Department</b>	→	FOM Institute for Subatomic Physics/NIKHEF
<b>Street Name and N°</b>	→	Kruislaan 409
<b>Town/City</b>	→	Amsterdam
<b>Post Code/cedex</b>	→	1098 SJ
<b>Country Code (7)</b>	→	NL
<b>Telephone N° (8)</b>	→	(+31)20.592.5131
<b>Fax N° (8)</b>	→	(+31)20.592.5054
<b>E-mail</b>	→	t32@nikhef.nl

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1. (continued) GENERAL PROPOSAL INFORMATION

Proposal Short Title (3) →

GRACE

Partnership Summary (9)

Participant Number (coordinating partner as number 1)	Abbreviated Name of Organisation	Type Size of Organisation	Country Code	Less-Favoured Region (enter "LFR" when appropriate)	Young Researchers (man-months)	EC Funding Requested (kECU)
(10)	(11)	(12)	(7)	(13)	(14)	(15)
1	NIKHEF	ROR	NL		36	200
2	ULeid	EDU	NL		24	125
3	UT	EDU	NL		24	125
4	URROME	EDU	IT		24	150
5	UTRENT	EDU	IT		24	150
6	UBAR	EDU	ES		24	125
7	UMAD	EDU	ES		24	125
8	CNRS	ROR	FR		24	125
9						
10						
11						
12						
13						
14						
15						
<b>TOTALS</b>						1125

Project Duration (16) →

36 Months

I, the proposal coordinator, certify that the information contained here in Part 1 of the Proposal Form corresponds to the information contained in the Individual Participant Information Sheets.

Signature →

*Wim Hotten*

Date →

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**2. PROPOSAL SUMMARY (1)**

Proposal Short Title (3) →

GRACE

Give below a brief summary of the objectives and content of the joint research project that the network partners propose to carry out. Also describe briefly the training content of the proposed network. The whole summary must be a maximum of 300 words of plain typed text, avoiding formulae and any special characters, *preferably in English*.

**Research objectives and content (maximum 200 words):**

A network is proposed for joint studies on critical design issues related with the development of a new omni-directional gravitational wave detector. The ultimate goal is to design a new class of large-mass, nearly quantum-limited detectors of spherical shape. If successful such detectors could observe with isotropic sky coverage distant regions of the universe that include thousands of galaxies plus offer the capability to measure the polarization states of radiation and the source direction. We intend to develop a number of innovations: the solution of metallurgical problems in constructing homogeneous solid bodies with masses of ~ 100 tons, the development of refrigerators to cool them to temperatures in the range of 10 millikelvin in a reasonably short time, the improvement of vibration-isolation techniques, the development of motion sensors of quantum-limited sensitivity and the assessment of the effects of impact of cosmic rays on the detector. Resonant-mass detectors of cylindrical shape currently operating at 100 mK in Europe will provide a test bench for the proposed developments. Reaching the research objectives will allow these detectors to attain their ultimate sensitivity. The processing of signals and correlating these with signals from other GW detectors will be studied with the goal to reconstruct gravitational wave excitations and identify astrophysical sources.

**Training content (maximum 100 words):**

The combination of expertise and competence in the fields of astrophysics, low-temperature physics, computer modelling, quantum electronics, needed for the successful completion of the project makes the network cross disciplinary in character. This constellation will offer excellent training opportunities to young researchers. In several nodes of the network a combination of typically two out of the four key tasks in the network research are pursued.



Short title: **GRACE**

## 2. Project objectives

The research project proposed here hinges on the competence and collective experience of the teams required to resolve a set of joint problems related to the design of a large ultra-cool resonant-mass detector of spherical shape. We intend to tackle four problems with the following objectives:

### *Mechanics and Cryogenic systems*

The ultimate energy resolution of a resonant-mass gravitational wave detector of a given shape and material composition is proportional to its effective temperature  $T_{\text{eff}}$  and inversely proportional to the mass. Cooling 100 tons of metal (the ultimate spherical detector) to mK temperatures is a considerable challenge in cryogenics that we intend to address in two steps:

- a. Cooling to 4 K by direct-flow cooling with cold He in one month time.
- b. Cooling to 10-20 mK by designing a dilution refrigerator with a factor 5 larger power than is currently available. Integrate it with an acoustically silent suspension system providing 400 dB isolation.

### *Sensors*

Present read out systems are based on dc SQUID amplifiers. We intend to improve the sensitivity by optimising sensor geometry and coupling to the resonant detector, improve the noise performance of sub-micrometer Josephson junctions with high critical current density at low temperatures. As an alternative for the sensor technology, a laser-based sensor will be investigated. The sensor makes use of a double mechanical resonator to amplify the detector's vibration. The objective is to develop a displacement sensor with energy resolution better than  $20 \hbar$ .

### *Backgrounds*

Resonant detectors exhibit excess noise showing up as rare but large events. Plastic creep at microscopic level due to high loading of the suspensions is among the candidate sources for this phenomenon. The "unloaded" equilibrium counterpart of this kind of relaxation, is also suspected to limit the Q factor of the detector itself. A careful investigation of the material properties with respect to structural damping and visco-elasticity is crucial for second generation, heavy subK detectors. The impact of cosmic rays presumably prevent to reach the ultimate intrinsic sensitivity. This issue will be investigated by using data from the NAUTILUS and AURIGA detectors, with experiments using charged-particle beams and theoretical modelling of the transformation of thermal energy, deposited by the cosmic ray into acoustic energy.

### *Signal processing*

Data processing and data analysis are particularly demanding in GW detection because of the weakness of the signal and the magnitude of the noise background. We will develop techniques specifically adapted for spherical detectors equipped with more than one sensor, study the back action of the readout system and design schemes for a correlation analysis of signals from different GW detectors located in different sites. We will expand the present know how available in the network to cope with the more complex situations in the future.

Short title: **GRACE**

## 5. Workplan

The overall project comprises four (interconnected) main tasks.

- A. Mechanical and cryogenic systems
- B. Sensor systems
- C. Reduction of internal and external backgrounds
- D. Signal processing and correlation schemes

The distribution of tasks among the network teams is shown in the matrix below.

	A	B	C	D
	Mechanics Cryo	Sensors	Backgrounds	Signal Processing
NIKHEF	v		v	v
ULeid	v	v		
UT	v	v		
UROME	v	v	v	v
UTRENT	v	v	v	v
UBARC			v	v
UMADR		v		v
IAP			v	v

The milestone planning of the four tasks is shown in the time line diagram with the following major milestones for each task:

### Task A

M(ilestone)1: Assess best material and casting techniques; design cryostat

M2: Assess feasibility of detector with 3m diameter

### Task B

M1: Design and prototyping of alternative sensor and readout schemes

M2: Assess characteristics of sensor system with quantum limited sensitivity

### Task C

M1: Test the effect of cosmics and assess models for thermo-acoustic conversion

M2: Assess strategy for optimal (underground?) site of the ultimate 3m diameter resonant-mass detector

### Task D

M1: Design of the optimal technique for acoustic- electric conversion

M2: Assess optimal signal-correlation strategies

Short title: **GRACE**

The timelines of the project tasks are as follows:

Task	1997	1998	1999	2000
A		-----X-----		X
		M1		M2
B			-----X-----	X
			M1	M2
C		-----X-----		X
		M1		M2
D			-----X-----	X
			M1	M2

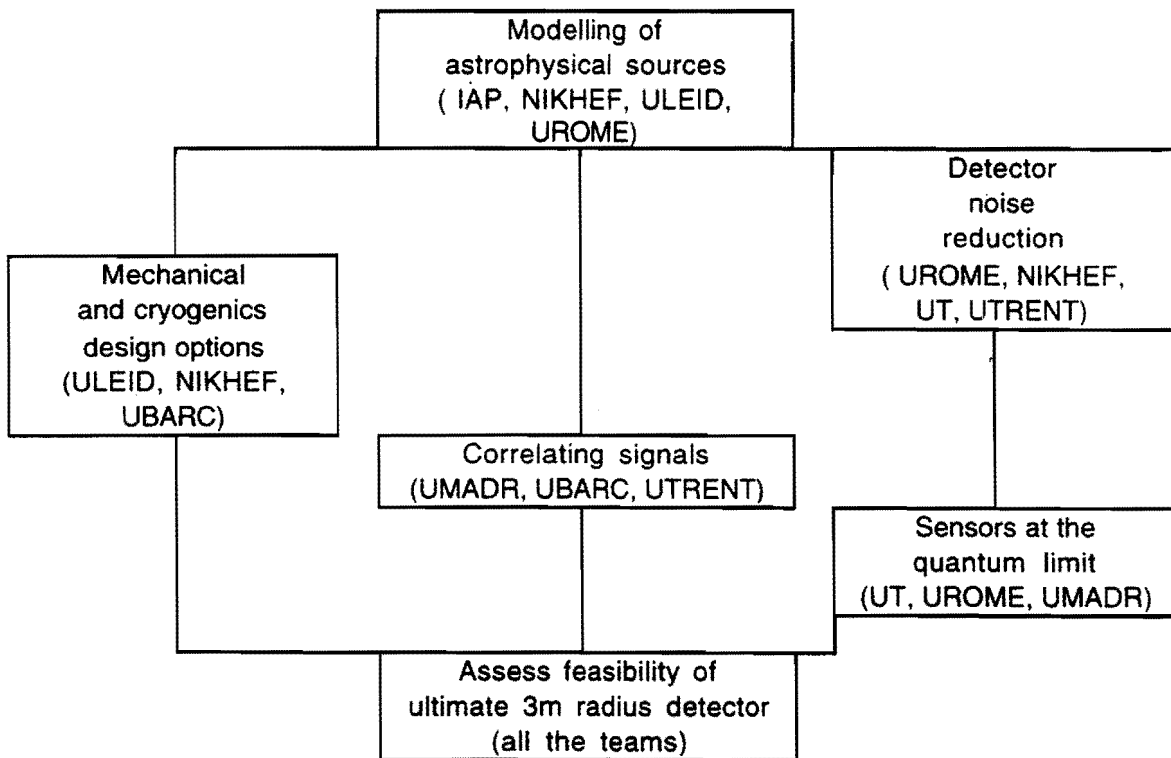
A summary of the effort planned for the network research is given below:

Team	Young researchers TMR	Researchers Local
NIKHEF	36	144
ULeid	30	160
UT	36	52
UROME	36	255
UTRENT	36	150
UBARC	24	80
UMADR	12	96
IAP	36	60

## 7. Collaboration between the teams

The network comprises experienced research teams reputable in their respective domains of specialisation. The Madrid team (participant number 7) is starting a new research direction in GW physics based on its previous space-based observational astrophysics programmes. Nikhef plans to extend its fundamental physics programme in subatomic physics into the direction of GW detectors utilising its experience in large-scale instrumentation projects and exploiting theoretical know how in the field of gravitation physics.

Young researchers shall be trained in the combination of techniques required for their experiments. Opportunities for training on the job will be provided by the relevant core team(s). For example investigating noise problems requires understanding cryogenics, mechanical design features and techniques to measure noise at ultra-low levels. The interaction structures in the network are summarised in the diagram below. For a given activity the acronym of the teams involved in that task are shown between brackets.



**Colofon**

Omslag: K. Huyser (NIKHEF)

Postbus 90159  
5600 RM Eindhoven  
Tel: 040 - 247 22 24



200610388

