Proposal for ILIAS (JRA1-JRA3)

TITLE

DEVELOPMENT OF SENSORS, SYSTEMS AND TECHNIQUES FOR LOW-FREQUENCY SEISMIC AND NEWTONIAN NOISE MONITORING AND FOR REDUCTION OF CONTROL NOISE IN UNDERGROUND GW DETECTORS

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Abstract

The fundamental noise sources that limit the design sensitivity of the first and second generation gravitational wave detectors are well identified. At very low frequency (1 – 10 Hz) the seismic noise plays a dominant role. It affects the detector sensitivity since seismic induced vibrations pass through the seismic filter chain used to suspend the main optics of the interferometer. In addition, the vibrating soil can directly couple to the suspended masses (the so called Newtonian noise (NN) or gravity gradient noise (GGN)). Furthermore, seismic noise complicates the control of the seismic filter chain (the so-called control noise).
The main goals of this activity are the development of suitable integrated sensors and techniques to quantify and reduce the low frequency noise contributions and the development of suitable position sensors and actuators for the last two stages of the suspension chain, that are the mirror and the marionetta, compatible with the requirements and sensitivity foreseen for the third generation of underground and cryogenic interferometric detectors.

Outline

Seismic Noise (SN) plays a relevant role in the sensitivity of interferometric detectors of gravitational waves at frequencies lower than 10 Hz. In fact, although SN is largely attenuated through the seismic filter chains used to suspend the main optics of the interferometer, the residual motion induced to the suspended masses of the interferometer is a noise wall for any sensitivity improvement in the low frequency band.

There are many noise sources acting at surface level, classically classified on their frequency range. Below ~1 Hz the noise (`microseismic' noise) is dominantly natural dependent on oceanic and large-scale meteorological conditions (*e.g.* monsoons and cyclones), around 1 Hz wind effects and local meteorological conditions show up, while above ~1 Hz the noise (`cultural noise') is mainly related to human activity. A synthetic noise power spectral density for frequencies up to 10 Hz was evaluated by Peterson from 75 seismic stations distributed worldwide. From a combined fit of data from the surface and borehole sensors (100 - 340 m depth) he derived a new low noise model (NLNM) that can be useful as a first insight in the frequency range 1 - 10 Hz for the Einstein Telescope. In particular, the lowest possible displacements according to the NLNM are about 0.1 nm/sqrt(Hz) at 1 Hz and decrease with f^2.

The reduction of seismic noise through only an improvement of the mechanics and control system of the seismic filter chains is a real challenge, because they are already very effective, so that it is very difficult to foresee the required strong improvements in their performances. Therefore, it becomes imperative to identify sites with relatively low seismicity suitable for the installation of a third generation GW detector, and the obvious choice is an underground site. In fact, many of above mentioned seismic noise sources are largely attenuated underground, where the effects of the “cultural noise” and of the surface seismic waves are reduced. This choice has the advantage to relax the requirements of the seismic filter chains making possible to adapt and optimize the one developed for the first and second generation of GW detectors.

Measurement of ground motion in various underground sites have been already carried out in Europe for different scientific goals (*e.g.* by the DESY ILC group). The PSD distribution of the Asse rocksalt mine for measurements at a depth of 900 m has an average rms (at $f > 1$ Hz) of 0.5 nm. Asse together with the Moxa seismic station near Jena with a 38 m horizontal borehole (rms of 0.6 nm) constitute quiet sites. In the ET frequency region of interest PSD values at HERA yield an rms of 51.8 nm. The HERA ring at DESY is situated in a shallow tunnel in close proximity of the densely populated city of Hamburg. The geology of the area is dominated by alluvium: quaternary sand and marlstone. Even worse performance was found for ESRF Grenoble (71.6 nm). Lower PSD values are obtained for the CERN LHC tunnel. LHC is situated in a ~100 m deep tunnel in stable bedrock. The rms vertical motion of the LHC tunnel is 1.8 nm at 1 Hz. The PSD spectra of the relatively deep LHC tunnel are about 3 orders of magnitude lower compared to the surface.

Newtonian noise, instead, couples directly to the suspended masses of interferometer. In fact, the mechanical perturbations on the GW detector test masses due to the seismically

induced fluctuations of Earth's gravitational field, have been calculated to impede detection of Gravitational Waves at frequencies significantly lower than ~20 Hz.
The reduction of the effects of the seismic noise should clearly put in evidence the NN as a further limiting noise source. The problem is that its different way of coupling with the suspended masses clearly requires the study and development of special techniques for its reduction. Preliminary theoretical studies are in progress and some ideas are circulating among the scientific community on possible techniques for its measurement and reduction. Again, all the theoretical approaches indicate that the reduction of the NN passes through a suitable choice of the site composition and geometry and it seems convenient to go underground,
The theoretical calculations assume an infinite and completely uniform bedrock around the cave, they do not take into account the effects of the surface above, and consider uniform and frequency-independent seismic excitation. The simulation also considers either complete coherence between modes or no coherence at all. In all cases this crude estimation gives cancellation factors of the order of 10^3-10^4 for caves of 30 m diameter and 60 m long. These strong cancellation factors, in addition to the 10^2-10^3 seismic attenuation factors due to the lower seismic noise level in deep caves, and with an assumed f^{-4} slope of the NN LF wall, imply a large gain of GW detection bandwidth, allowing GW detection possibly to as low as 1 Hz. Further analytical calculations are ongoing to include the effects of the surface and to make a more direct comparison to the case of existing interferometers.
It is clear that a numerical, finite-element model of the cave, including effects of stratification, seismic noise reduction as a function of depth, varying speed of sound, varying coherence levels and the effects of the surface above, needs to be implemented to have a more accurate NN reduction estimation or a direct NN evaluation. At present, the models are not yet supported by suitable experimental measurements that must provide all the necessary preliminary information to make these evaluations reliable.

In synthesis, the sensitivity requirements at low frequencies for third generation ITF imply the need to develop suitable tools (sensors and techniques) for the measurement, analysis and compensation of Seismic and Newtonian Noises, aimed to define the physical and geological characteristics of candidate underground sites in Europe to host the Einstein Telescope.
Along these directions initial steps have been done, to perform preliminary measurements and to test the sensitivity of the present instruments for seismic noise measurement and the technique to be used to validate the theoretical model or to get empirical models.
In particular, preliminary measurements were made in the Realmonte (Agrigento, Sicily, Italy), an Italkali salt-mine, in 2004. Since the end of 2008 a measurement campaign is ongoing in the Homestake (South Dakota, USA) mine, chosen to host the Deep Underground Science and Engineering Laboratory (DUSEL).
The main goal of this experiment is to understand the present technical limits of the new monolithic accelerometers under development and to characterize the Homestake site in the frequency band 10^{-4} – 30 Hz, providing also preliminary information to understand the feasibility of underground GW interferometric detectors sensitive at 1 Hz and below. This measurement campaign is important to understand the real technical limits of the tunable monolithic sensors in terms of displacement sensitivity (10^{-12} m/√Hz is theoretically obtainable, in the band 0.01 – 30 Hz) and in terms of useful band (10^{-6} – 30 Hz).

If the theoretical sensitivity and bandwidth are reached, these new sensors will give more complete information, necessary for the ongoing studies, improving the results obtainable from commercial instruments.

According to the measurement planning, two tunable mechanical monolithic horizontal sensors, located in a tunnel 2000 ft. deep in the mine, will be characterized and by the end of the year another two sensors will be located in a tunnel 4000 ft. deep.

Another source of noise in the low frequency range is the so called control noise, in particular the noise introduced by the system used to align and position the last stages of the suspension chain, i.e. the mirror and the marionetta. Two different kinds of sensing systems are used for the last stages. The first one is used before the lock acquisition of the interferometer, when no error signal is available from the interferometer's output, neither for the longitudinal nor for the angular degrees of freedom. This sensing system is in fact mainly used for the preliminary alignment of the interferometer's mirrors and for the damping of their normal oscillation modes. Once the lock is acquired, the second sensing system becomes available. This is constituted by the set of photodiodes and quadrants placed at different output beams of the interferometer, that provide, respectively, the longitudinal and angular error signals for the position of the mirrors. The actuators used for the marionetta and mirror, are instead always the same, despite of the sensing system used. The first position sensing system, together with the actuation system located at marionetta and mirror levels, constitute the local control system, while the second set, sharing the same actuators, is the global control system.

In principle, during the science mode operation of the interferometer, all the local control systems have to be disabled, since their sensitivity cannot be compatible with the requirements on the linear and angular displacements of the mirror during linear operations ($\sim 10^{-12}$ m rms and $\sim 10^{-8}$ rad rms for first generation detectors). This is due to the intrinsic lower sensitivity of the local sensors and mostly since they are always referred to a ground based system. This means that their final sensitivity is limited by the seismic noise directly affecting the local sensing components. Nevertheless it is important to improve the sensitivity for local sensors for two main reasons. The first reason is due to the most stringent requirements on the mirror longitudinal and angular displacements to reach before the lock acquisition, due to the higher finesse of the arm cavities. The second motivation is linked to the ultimate seismic noise background, that is expected to be significantly lower, as stated in the first part of this outline, for underground operating detectors. This will allow to put in operation more sensitive position sensors. For the actual VIRGO local position sensor, based on optical levers with all the hardware components placed outside the vacuum chamber, the longitudinal and angular sensitivity are $\sim 10^{-7}$ m rms and $\sim 5\cdot 10^{-7}$ rad rms respectively, but a sensitivity of $\sim 10^{-9}$ m rms and $\sim 10^{-8}$ rad rms was already demonstrated for similar sensors arranged with different topology and optimized conditioning electronics.

Of course a strong effort is needed for the integration of the sensing system in the suspension chain, and for the compatibility with cryogenic operations. The interferometric facility available at the INFN VIRGO Napoli laboratory, consisting of a three suspended optic interferometer in Michelson configuration, represents a perfect bench for this task. Each suspension is composed by an inverted pendulum and two attenuation stage for the seismic reduction, plus the suspended payload, constituted by marionetta and mirror. This facility constitute a very useful hosting apparatus for prototype characterization since all the most relevant characteristics of a true suspension for gravitational wave detectors are implemented, even if at reduced scale. Similarly, the cryogen compatibility of the sensing system can be effectively tested on the cryogenic facility operating at INFN VIRGO Roma Tor Vergata laboratory. This facility is able to host all the required hardware, including space for probe beams, test mirrors and cabling, making the system working at low temperatures, miming the payload conditions foreseen for third generation detectors.

The last problem arises from the choice and design of the actuators used for the mirror control. These actuators are the direct source of the control noises. The first contribution to this noise comes from the local or global sensing and can be reduced by acting on that system. Another contribution comes from the actuation chain: digital control system, actuator drivers and transducers. Each one of these components adds a characteristic contribution to the final control noise. In particular, by using a digital control system implies a large freedom to easily implement many kind of filters and also a very simple way to mix signals coming from the different subsystem of the interferometer. On the other side there are at least two disadvantage for this approach. The first one is the limited dynamic range due to the finite number of bits available to perform the analog to digital and the digital to analog conversions. The second one is due to the finite bit arithmetic used to implement the digital filtering. The first effects has the major implication on the actuation system, in fact the dynamics of the actuators need to cover a wide range of control forces, that cannot be employed directly by the digital system. This imply the use of different actuator driving modes, depending on the status of the interferometer, to enhance the actuation during the lock acquisition steps or to reduce the control noise during the linear phase. Finally the actuator itself add its contribution to the control noise, since it can be sensitive to uncontrollable events, like the electromagnetic noises for the coil-magnets actuators or the electrical stray charges for the electrostatic actuators.

PROPOSAL

This study integrates theoretical and experimental activities: characterization of possible underground sites, development of sensors and actuators to be optimized for this specific study and use and a clear understanding of the effects of their integration in the mechanical suspension chain under vacuum and/or in cryogenic systems.

One of the points is the development and integration of prototypes of unidirectional opto-mechanic monolithic sensors and tiltmeters to be used both for low frequency seismic noise measurement and for the control of the mechanical suspensions of GW interferometric detectors. These sensors are being developed by the INFN groups of Napoli (monolithic sensors) and Roma Tor Vergata (tiltmeters) and must be optimized to be used as stand alone sensors for both seismic noise monitoring and geophysics applications, with particular attention in their design to the necessary immunity to environmental noises. The test of these monolithic sensor prototypes will be performed in the lab and, as soon as possible, in the INFN Gran Sasso Laboratory, that will be used as a facility to quantify and optimize their performances and sensitivities in the low noise band. Further tests will be performed in suitable chosen sites, at different levels of depth, with the double goal of understanding their behavior and characterizing the site for possible implementation of the Einstein Telescope.

At the same time, while the laboratory activities are ongoing, field studies of ET candidate sites will be performed by NIKHEF with an array of commercial seismic sensors and the already operational unit of monolithic sensors. The array will be upgraded as soon as new improved sensors are available and validated in the Gran Sasso INFN National Laboratory.

Data from this array will provide information about attenuation of seismic noise with depth, dependence of geology, *e.g*. sediments, hardrock and salt, and coherence length of signals between various sensors. We will attempt to decompose seismic noise according to surface waves, such as Rayleigh and Love waves, and body waves. Furthermore, daily variations will be exploited in order to estimate contributions from cultural noise. Although sporadic seismic information is available from a variety of sites, the proposed studies will include long-term observations. The proposed studies will aid to identify a possible R&D path to seismic isolation systems, while its data will be used as input to underground-surface site decision making process. It will allow to identify time-dependent contributions in Newtonian background from surface seismic compression waves, weather activity (variations in atmospheric pressure), ground-water dynamics, slow gravity drifts of geophysical origin, cultural noise (moving object: humans, machines, etc.). The proposed study will quantify these various contributions and identify approaches to limiting gravity gradient noise and active correction systems with data from seismic sensors, accelerometers, strainmeters, tiltmeters, rock thermometers and piezometers.

Finally, due to the high quality of the commercial sensors used and those developed within this R&D, geophysical analysis will be also performed in the very low frequency band, where portable instrumentation, with performances comparable with the big scientific instruments, does not exist. In this way, the data acquired in the different sites explored during this scientific research program will be very useful for geophysicists.

In parallel, the translation and rotation sensors developed in this research program, being fully scalable and adaptable in terms of dimensions and sensitivity, will be tested in a suspension chain. It will be necessary to modify and adapt their design, characteristics and materials for the use in control systems for both cryogenic and room temperature suspension chains. The tests of the prototypes will be performed using the two facilities already existing in the INFN VIRGO Lab of Roma Tor Vergata (cryogenic facility) and in the INFN Napoli Lab (3 m interferometer in vacuum with TAMA suspensions). The outcome of this study will be the development of suitable sensors in connections with real and up-to-date facilities.

Regarding the development of a suitable sensing and control system for the mirror and marionetta, in order to simplify the local control design and to limit the engagement of internal oscillation mode of the whole suspension chain, it is useful to refer the mirror and the marionetta positions to the ground. This choice on one hand reduces the ultimate sensitivity of the local position sensors, because of the seismic noise of the reference frame, but, on the other hand, makes it possible to employ simpler sensors and to ensure an easier integration in the suspension.

Such a system can be developed by using optical levers and position sensing photodiodes. The most important points to investigate are the compatibility with the cryogenic environment and the required sensitivity.

The first point is connected with the possibility to integrate the detectors inside the vacuum chamber, by realizing a suitable optical path in the cold shields to allow the beam propagation, or, alternatively, to use fiber-taper, with appropriate geometry to guide the light on detectors located outside the vacuum chamber. Both the solution have to be investigated to evaluate their effectiveness.

The second point, concerning the sensitivity, is mostly related to the conditioning electronic of the position sensing photodiode, that has to be carefully designed to avoid electronic noise introduction, and to the quality of the source to use for the optical lever, that has to be stable in order to avoid long term drift of the position signals. Moreover, since this local control system is disabled after the lock acquisition of the interferometer, the noise reintroduction, due to the seismic noise of the reference frame, can be tolerated.

Since the mirror will be controlled, in any case, with a hierarchical system, the larger part of the force will be exerted on the marionetta by using standard coil magnets actuators. On the other hand, the development of the actuation system for the mirror, should take advantage in leaving the mirror free from any additional element. In fact, in this way, a significant improvement of the mirror mechanical quality factor is demonstrated.

A possible solution, in this case, could be the use of an electrostatic actuation system. In fact such system does not require any additional element on the mirror and can be easily integrated on the recoil mass of the suspension. Moreover, since the mirror are closed in a metallic vacuum tank, the effect of the external electromagnetic noise is strongly reduced. An important point to investigate is the possibility to eliminate the recoil mass and to use a ground referenced electrostatic actuator. In this way the actuation on the mirror could be completely switched off after the lock acquisition, largely reducing the direct re-introduction of control noises on the test masses.

The reduction of the thermal noise through the cooling of the mirrors at low temperatures opens the possibility to use new materials and techniques for the development of sensing and control systems. In particular, a solution that is worth investigating is that based on superconducting devices for test mass and marionetta displacement readout and actuation.

The test of the proposed solutions will be performed in the facilities available in the Napoli and Tor Vergata Laboratories described above.

Tasks and Output

1) Acquisition of seismic data in different underground sites in Europe, to get information about attenuation of seismic noise with depth, dependence on geology, *e.g*. sediments, hardrock and salt, and coherence length of signals among different sensors.
2) Analysis and validation of seismic models and study of suitable underground architectures and sensors configurations for NN measurement and reduction in underground sites.
3) Development and validation of low-frequency, low-noise and large-band seismic sensors (seismometers and accelerometers) for Seismic and NN measurement;
4) Development and characterization of low-frequency, high sensitivity tiltmeters and performances test on inverted pendulum.
5) Optimization of the developed seismic sensors for their application in the control of the suspension chains through their characterization in the facilities of INFN – Napoli and INFN - Roma Tor Vergata.
6) Data Analysis of the acquired data for geophysical applications and modeling of the underground sites.

7) Development and characterization of contactless sensors for the test mass and marionetta position sensing, optimization and integration in the suspended chain and validation in cryogenic environment.
8) Development of actuators for test mass position control, characterization in different working configuration using the suspended chain, validation at cryogenic temperatures and optimization for cryogenic environment.

Task	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Napoli	x		x		x	x	x	x
Nikhef	x	x				x		
Roma TV				x	x		x	x

Involvement of the participants on the tasks

Planning

Year 1:

Half seismic array + data acquisition ready;

Preliminary characterization of actuators and position sensors in vacuum;

Year 2:

Position sensor with sensitivity better than $5 \cdot 10^{-9}$ m in the band 0.1-10 Hz in single sensor configuration;

Full seismic array installed for 1st measurement;

Monolithic sensors with sensitivity better than 10^{-9} m in the band 0.1-10 Hz;

Preliminary measurements of actuators and position sensors at low temperature

Year 3:

Integration of monolithic sensors in the suspension;

Comparison of the performances of ground based and suspended actuators for the test mass;

Characterization of tiltmeter in low frequency range;

Year 4:

Characterization of the underground sites on the basis of NN measurement; Suspension chain control with local controls based on the developed sensors and actuators;

Full characterization of the developed sensors and actuators in cryogenic environment;

Available know-how in the proponent groups

- high sensitivity-low frequency translation and rotation sensors
- cryogenics
- superconducting electronics
- electrostatic actuators
- optics
- control systems

Note

In Birmingham, sensors for the advanced LIGO GW detector suspensions have been developed. An interest for a collaboration on sensor technologies for a future generation European GW interferometer has been recently manifested by the Birmingham group.
The possible involvement of this group and the synergies with the present project are being defined.

Budget request

The budget request for the NIKHEF contribution is 245 kEuro, divided in the following way (see Addendum):

NIKHEF	
Travel&subsistance	20,000.00
Personel-temporary (Postdoc 3 years)	180,000.00

The budget request for the INFN contribution is 534 kEuro. According to the INFN rules (see Addendum) the portion really available to research is 427.2 kEuro, divided in the following way:

INFN - Napoli	
Consumable (Optics and optomechanics - seismic sensors mechanics and electronics – fibers - electronics for posistion sensors and electrostatic actuators – vacuum components)	94,000.00
Travel&subsistance	40,000.00
Personell-temporary (4years Postdoc)	80,000.00
Available to research	214,000.00

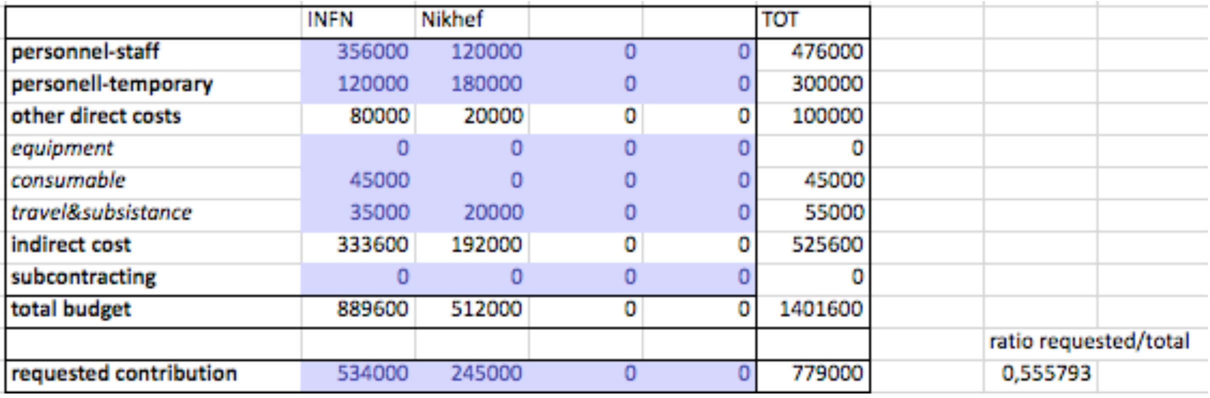
INFN – Tor Vergata	
Consumable (NI PXI DAQ system – electronics – cryogenic liquids – superconducting materials – tiltmeters mechanics and electronics – optics and optomechanics)	53,000.00
Travel&subsistance	30,000.00
Personell-temporary (2years Postdoc+2years contract)	130,000.00
Available to research	213,000.00

Addendum

We report in the following the excel files regarding the budget request.

A.1

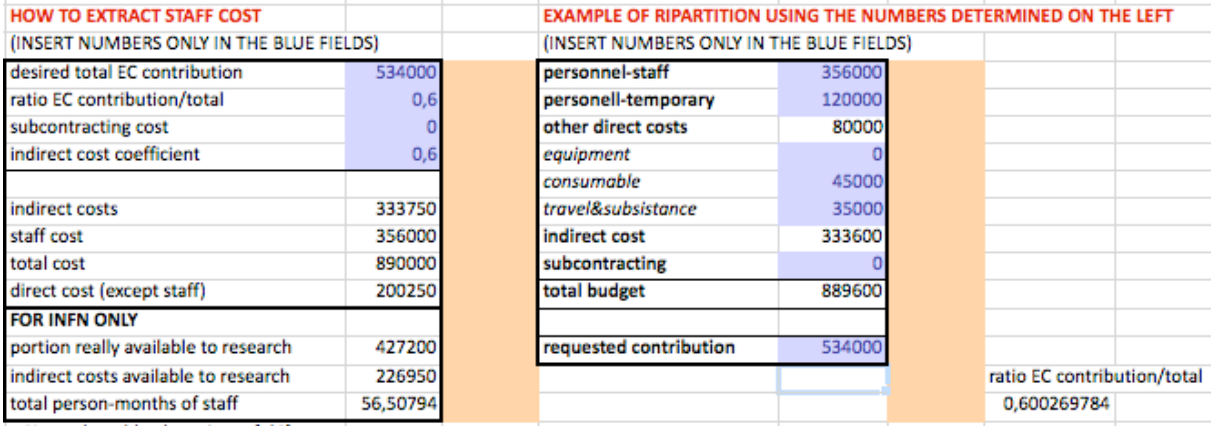
Request



	INFN	Nikhef			TOT	
personnel-staff	356000	120000	0	0	476000	
personell-temporary	120000	180000	0	0	300000	
other direct costs	80000	20000	0	0	100000	
equipment	0	0	0	0	0	
consumable	45000	0	0	0	45000	
travel&subsistance	35000	20000	0	0	55000	
indirect cost	333600	192000	0	0	525600	
subcontracting	0	0	0	0	0	
total budget	889600	512000	0	0	1401600	
						ratio requested/total
requested contribution	534000	245000	0	0	779000	0,555793

A.2

Cost Determination_INFN

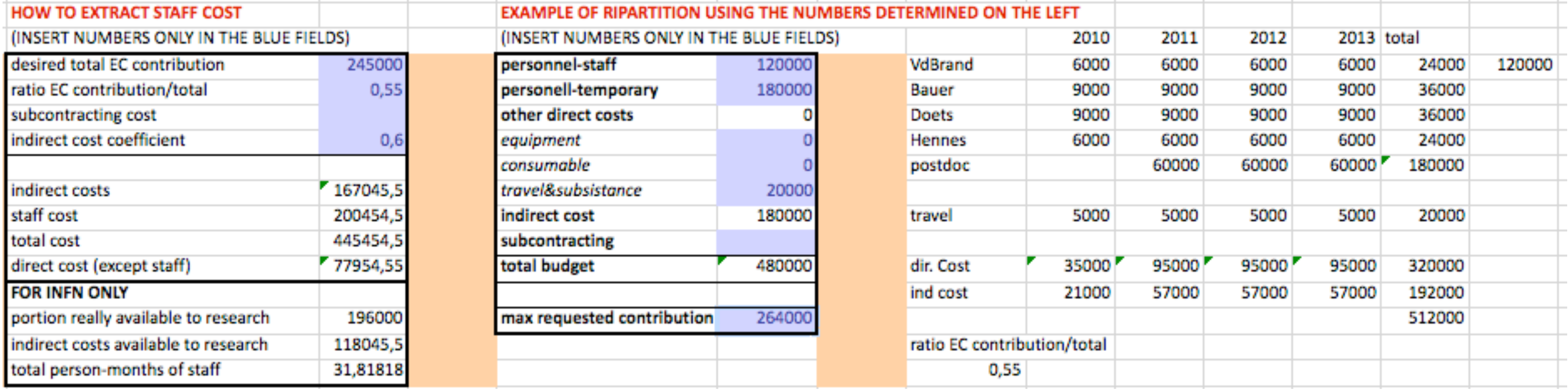


HOW TO EXTRACT STAFF COST	
(INSERT NUMBERS ONLY IN THE BLUE FIELDS)	
desired total EC contribution	534000
ratio EC contribution/total	0,6
subcontracting cost	0
indirect cost coefficient	0,6
indirect costs	333750
staff cost	356000
total cost	890000
direct cost (except staff)	200250
FOR INFN ONLY	
portion really available to research	427200
indirect costs available to research	226950
total person-months of staff	56,50794

EXAMPLE OF RIPARTITION USING THE NUMBERS DETERMINED ON THE LEFT		
(INSERT NUMBERS ONLY IN THE BLUE FIELDS)		
personnel-staff	356000	
personell-temporary	120000	
other direct costs	80000	
equipment	0	
consumable	45000	
travel&subsistance	35000	
indirect cost	333600	
subcontracting	0	
total budget	889600	
requested contribution	534000	
		ratio EC contribution/total
		0,600269784

A.3

Cost Determination_NIKHEF



HOW TO EXTRACT STAFF COST		EXAMPLE OF RIPARTITION USING THE NUMBERS DETERMINED ON THE LEFT								
(INSERT NUMBERS ONLY IN THE BLUE FIELDS)		(INSERT NUMBERS ONLY IN THE BLUE FIELDS)			2010	2011	2012	2013	total	
desired total EC contribution	245000	**personnel-staff**	120000	VdBrand	6000	6000	6000	6000	24000	120000
ratio EC contribution/total	0,55	**personell-temporary**	180000	Bauer	9000	9000	9000	9000	36000	
subcontracting cost		**other direct costs**	0	Doets	9000	9000	9000	9000	36000	
indirect cost coefficient	0,6	*equipment*	0	Hennes	6000	6000	6000	6000	24000	
		consumable	0	postdoc		60000	60000	60000	180000	
indirect costs	167045,5	*travel&subsistance*	20000							
staff cost	200454,5	**indirect cost**	180000	travel	5000	5000	5000	5000	20000	
total cost	445454,5	**subcontracting**								
direct cost (except staff)	77954,55	**total budget**	480000	dir. Cost	35000	95000	95000	95000	320000	
FOR INFN ONLY				ind cost	21000	57000	57000	57000	192000	
portion really available to research	196000	**max requested contribution**	264000						512000	
indirect costs available to research	118045,5			ratio EC contribution/total						
total person-months of staff	31,81818			0,55						