**Table 3.1b: Work package description**

**For each work package:**

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| **Work package number**  | X | **Lead beneficiary** | EGO |
| **Work package title** | EFDAS (Engineered Fiber Distributed Acoustic Sensor) networks for seismic networks and current/next generation GW detectors on earth and future lunar projects  |
| **Participant number** | 1 |  |  |  |  |  |  |
| **Short name of participant** | EGO |  |  |  |  |  |  |
| **Person months per participant:** |  |  |  |  |  |  |  |
| **Start month** | 1 | **End month** | 36 |

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| **Objectives**: Evaluate and upgrade the sensitivities of the current fast growing potential of EFDAS (Engineered Fiber Distributed Acoustic Sensor) networks, in order to a) monitor the seismicity and newtonian noise of the Advanced Virgo detector, compare its sensitivities to a laser strainmeter deployed in the Kamioka mines (Japan) and evaluate the potential of the technology for the next generation Gravitational Wave European detector Einstein Telescope b) increase of the portability and TRL of the technology for use in hostile environments and lunar deployments for both seismic and GW detection issues, in full synergy.c) coordinate the European efforts in the field between industry and research infrastructures and further facilitate the inclusion characteristics of the technology ,by profiting of its assets in the acoustic regime |

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| **Description of work** (where appropriate, broken down into tasks), lead partner and role of participantsWe propose to use the method of phase-Optical-Time Domain Reflectometry (φ-ODTR) based on the phase shift of Rayleigh backscattered laser light in space and time domain of an Engineered Fiber Distributed Acoustic Sensor (EFDAS) to deploy a large multi-sensor network. Using present day technology, one can obtain (sampling every 25 cm over several Km, averaging every 30m, and examining the phase and amplitude of the backscattered light) hundreds of “sensing elements" , with relative strain sensitivity 10-13 /√Hz each. In the low frequency range (mHz to 10Hz) the measured displacement sensitivities are order of magnitude better than current technologies used on earth and at the moon. The work will be organised in the following cross-dependent tasks:**Subtask X.1** We will deploy an EFDAS antenna consisting of two 3 km long EFDAS fiber cables disposed in an L form interrogated by a central interrogator unit, using a narrowband laser light source, illuminating the fibers and taking advantage of the enhanced engineered scatter centers to perform multiple measurements of the displacement strain due to seismic, acoustic or gravitational waves., next to the advVirgo detector in Cascina Pisa. The Virgo EFDAS network (V-EFDAS) will be calibrated again the existing slow sensor network, and also will permit precise localisation studies of the sources  Using present day technology, one can obtain, sampling every 25 cm over 3 Km, averaging every 30m, and examining the phase and amplitude of the backscattered light from the 100“sensing elements" , with relative strain sensitivity 10-13 /√Hz each. An extra factor 10 (=√100) can be obtained by Stacking of the sensors. A laser strainmeter with a 1500-m baseline has been operating since August 2016 in Kamioka/japan (Araya et al. Earth, Planets and Space (2017) 69:77). The laser interferometer measures the change in distance between two retroreflectors housed in two vacuum chambers with a separation of 1500 m. The retroreflectors are fixed to the ground in the tunnel of the KAGRA gravitational wave telescope. Since operations began, ground motions with large amplitude and timescale variations have been detected. The detection limit is estimated as better than 10−12 in the 2–20 mHz range and 10−11 in the 1 mHz–10 Hz range. The direct comparison of the strainmeter with EFDAS, in a quiet environment as is the Kamioka mine, will permit a detailed comparison of resolution, dynamic range, and bandwidth performance, increasing the a available methods for observing low-frequency ground motion on seismic, geodetic, and intermediate timescales. The same system, or a subsystem thereof depending on the infastructure available at the time, will be deployed at the future sites of Einstein Telescope (Sardinia, Meuse-Rhine Euregion, Saxony) for a precise evaluation of earth environmental noise. **Subtask X.2** Increasing the EFDAS portability and space TRL. Among the leading EFDAS systems thSilixa Carina system consists of 2 main components: the Carina Data Interrogator (DI) weighting 25 kg (volume: 52x45x18 cm3), The constellation fiber cable (1 km weighting of the order200 gr) The DI currently uses 245 W but its power consumption will be lower, if one goes to lower frequencies An order of magnitude reduction for the DI power consumption could to be achieved. The DI currently transmits at 100 Gbits/day but here also the data rate needed can be lower, if one goes to lower frequencies, aiming at 1 Gbit/day. The data can be reduced locally. For space applications, the radiation hardness issue has to be studied, but it should not be a major issue given the small dimensions of the data-interrogator. A more important issue is the dependence on temperature since there are e.g. large temperature variations (100 to 400 Kelvin) at the Moon, deployment in permanently shadowed regions and multi-layer insulation (MLI) coverage have to be studied. The extra advantage of a deploying in parallel a DTS (Distributed Temperature Sensor) fiber system will be studied. The above increase the portability of the system for an industrial use but also astrophysics and astroparticle deployments in underground labs, hostile environments and the moon on the context of one of ideas promoted in the ESA L3 lander mission: the Lunar Seismic and Gravitational antenna (LSGA).  The LSGA EFDAS network will satisfy a) a gravitational wave (GW) detection program in synergy with the earth and space GW detectors at a frequency bandwidth between space higher frequency sensitivity limits (LISA, 1 mHz) and earth antenna lower frequency sensitivity limits (10 Hz) in what is called the DeciHertz region b) lunar geoscience goals (mostly the subsurface structure), c) an acoustic follow-up of the lunar surface and subsurface with the potential to address current theoretical and experimental challenges concerning the flux and origin of Ultra-High Energy Cosmic Rays (UHECR), meteoric impact evaluations, and in fine lunar habitability issues.  The detection of the gravitational waves at the moon has two possible strategies: a) use the moon as a spherical detector and detect its vibrations caused by GW (e.g. using an EFDAS as in LSGA) or detect directly the space-time distortions caused by GW (Lunar Ranging Strainmeter method). An EFDAS antenna deployed at the Moon thus , beyond the strong interdisciplinarity aspect with Geoscience gives access to the Decihertz bandwidth (1 mHz-10Hz) complementary to earth (LIGO, Virgo, KAGRA, ET , CE) and space (LISA) GW sensitivities and permits the study of : a) Intermediate-Mass Black Holes (IMBH), including the impact of the stellar/galactic environment and the eventual evolutionary paths to the formation of supermassive BHs; b) Double White Dwarfs (DWD) eventual progenitors of Supernovae Ia; c) Stellar and galaxy evolution through the multiband and/or multi-messenger study of the stellar-mass binaries, Binary Neutron Stars (BNS) and Binary Black Holes BBH, in coordination with earth detectors; d) Isolated supernovae bursts (CCSNae) e) Cosmology through measurements of the Hubble constant and Dark Energy equation of state and dark matter searches f) Stochastic Gravitational Wave Background (SGWB) of cosmological origin, e.g. primordial phase transitions, topological defects and other transitions; g) Fundamental theory; through multiband analyses enabling tests of fundamental physics (General Relativity and Standard model of Particle Physics) There are three obvious structural advantages of deploying a GW network at the Moon: a) **S*eismic background*.**  The moon has 3 orders of magnitude less seismicity than the Earth, no atmospheric effects and variations of pressure and no need to sustain an artificial vacuum. b) ***Localisation precision*,** for early warning of multi-messenger events and/or population studies independent from an electromagnetic counterpart, given the large earth-moon distance and parallax type studies. c) ***Multi-band analysis*** when associating earth and moon detections of an inspiral/merger event will permit a much better precision of the inspiral/merger parameters. The increase of the portability, cited above will thus permit in the not so distant future (next decade) the deployment of an antenna consisting of two 10 km long EFDAS consisting of fiber cables disposed in an L form interrogated by a central interrogator unit, using a narrowband laser light source, illuminating the fibers and taking advantage of the enhanced engineered scatter centres to perform multiple measurements of the *horizontal displacement strain* due to seismic or gravitational waves (e.g. 1000 sensors for a gauge length of 10m). The network will be complemented with distributed a temperature sensing (DTS) fiber implementation.this deployment can be accompanied by the deployment of Lunar Ranging Strainmeter (LRS) along the same L form, that will profit from the new generation of ranging reflecting mirrors and high TRL lasers from the developments of LISA. The second deployment will greatly profit from the beam-forming capabilities of phase 1, giving a detailed description of the surface seismic noises and the LISA Pathfinder and LISA pre-flight experience. The first phase of the project consists of the deployment of an antenna consisting of two 10 km long Engineered Fiber optic Distributed Acoustic Sensors consisting of fiber cables disposed in an L form interrogated by a central interrogator unit, using a narrowband laser light source, illuminating the fibers and taking advantage of the enhanced engineered scatter centres to perform multiple measurements of the *horizontal displacement strain* due to seismic or gravitational waves (e.g. 1000 sensors for a gauge length of 10m). The network will be complemented with distributed a temperature sensing (DTS) fiber implementation. Synergy with the project LGWA deploying seismometers sensitive to horizontal accelerations for GW detection can and will be exploited.  The second phase of the project consists of a the deployment of Lunar Ranging Strainmeter (LRS) along the same L form, that will profit from the new generation of ranging reflecting mirrors and high TRL lasers from the developments of LISA. The second phase will greatly profit from the beam-forming capabilities of phase 1, giving a detailed description of the surface seismic noises and the LISA Pathfinder and LISA pre-flight experience. The other very important issue of LSGA is the deployment issue. A small rover could be the optimal solution, but the largest challenge remaining is the optimal contact with the ground.  LSGA will also satisfy a series of ambitious geoscience goals: a) Study the lunar interior in a way complementary to the Farside Seismic Suite to be deployed in 2024-2025 (horizontal versus vertical displacement and localising multi-sensor versus isolated measurements) using Deep Moon Quakes (DMQ) to study the nature of the crust/mantle boundary and improve the understanding of crustal thickness and composition; b) Study the lunar subsurfaceand in particular the lunar background hum (LBH). The increased localisation potential of LSGA, due to its mutli-sensor structure will certainly be a big asset of characterisation of each component of LBH. LSGA can be used to further investigate the presence of the water in the subsurface of the Moon. The natural activities on the Moon, such as Thermal Quakes and Moonquakes, as well as Meteorite Impact (MI) vibration can be used as ambient seismic sources. The low-frequency response of EFDAS is of particular importance for quantitatively precise estimation of elastic reservoir properties and estimating the extent of any water reservoir existing in the subsurface of the Moon; c) Study of the mineralogy of the mantle and also how do crustal and mantle structures vary from one region to another.  In summary, current fiber optics technologies permit, provided their TRL is augmented, an order of magnitude better individual sensor displacement sensitivity w.r.t. Apollo, while one can obtain acceleration and displacement sensitivities close to the ones of VBB seismometers @ 1Hz which therefore can be used for calibration purposes and an order of magnitude better sensitivities at the mHz range. Their networking capacity brings another factor circa 20 by stacking. The current sensitivities of LSGA-EFDAS, seem to be sufficient to address some major seismic measurement challenges. Stacking and template matching will increase further the sensitivity, in cases where this is applicable. The LSGA-EFDAS phase 1 network complies to the demands of a Geoscience oriented study, and can also identify properly the seismic activity as a background to GW studies. **Subtask X.3 Fiber network coordination, data availability, engagement and inclusion issues.** There a few European companies working on parts or the totality of fiber networks: laser issues, timing, fiber development, deployment of full systems. This sub-workpackage will attempt, based on the previous experience of the coordinators to organize technical meetings and workshops (one per year for each category), between the RI and industrial part, so that innovative solutions emerge. (We need to work on the list of companied here)The data that will be produced, will be open to the public and furthermore will be the source of a citien-science project, where citizens are invited to contribute to classifications and other issues. This last activity will be based on the experience of EGO on citizen science issues, after the coordination and production of demonstrators of the very succesfull EU funded citizen's science project REINFORCE (https://www.reinforceeu.eu/).Last but not least, since most of the data are in subsonic or sonic frequencies, the sonification of data according again to the long experience of EGO on these matters, will increase the inclusion aspects of the citizen's science activity, at the same time increasing the perceptual capabilities of the group. |

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| **Deliverables** (brief description and month of delivery)**Subtask X.1** Month 6: A fully functioning system of EFDAS at VirgoMonth 12: 2 scientific papers on the seismic and acoustic environmental noise of Virgo (Milestone 1)Month 18: A fully functioning system of EFDAS at KAGRAMonth 24: 1 scientific paper on comparison of sensitivities of Laser Strainmeters and EFDAs networks (Milestone 2)Month 30: Deployments at future Einstein Telescope sites Month 36: 1 scientific paper on the environmental comparison of candidate ET sites. (Milestone 3)**SubTask X.2**Month 12: A detailed study of power and data transfer issues of the Data Interrogator unit in view of hostile and/or lunar environments (Milestone 4)Month 24: 3 Scientific papers on deployment, temperature and radiation variation issues (Milestone 5)Month 36: A new generation DI prototype (Milestone 6)**SubTask X.3**Month 12: A report on the 1st coordination workshop and the technical meetingMonth 18: An open access database for the V-EFDAS network (Milestone 7) Month 24: A report on the 2nd coordination workshop and the technical meetingMonth 24: A citizen's science demonstrator, including sonification (Milestone 8)Month 36 A report on the 3rd coordination workshop and the technical meeting**Global Task** Month36: A detailed report on the 3 subtask activities. |

**Table 3.1c: List of Deliverables**

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| --- | --- | --- | --- | --- | --- | --- |
| **Deliverable (number)** | **Deliverable name** | **Work package number**  | **Short name of lead participant**  | **Type** | **Dissemination level** | **Delivery date****(in months)** |
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**Table 3.1d: List of milestones**

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| --- | --- | --- | --- | --- |
| **Milestone number** | **Milestone name** | **Related work package(s)** | **Due date (in month)** | **Means of verification** |
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**Table 3.1e: Critical risks for implementation**

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| **Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)** | **Work package(s) involved** | **Proposed risk-mitigation measures** |
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**Table 3.1f: Summary of staff effort**

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|  | **WPn** | **WPn+1** | **WPn+2** | **Total Person-****Months per Participant** |
| **Participant Number/Short Name**  |  |  |  |  |
| **Participant Number/****Short Name**  |  |  |  |  |
| **Participant Number/****Short Name**  |  |  |  |  |
| **Total Person Months** |  |  |  |  |

**Table 3.1g: ‘Subcontracting costs’ items**

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| **Participant Number/Short Name** |
|  | **Cost (€)** | **Description of tasks and justification** |
| **Subcontracting**  |  |  |

**Table 3.1h: ‘Purchase costs’ items (travel and subsistence, equipment and other goods, works and services)**

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| **Participant Number/Short Name** |
|  | **Cost (€)** | **Justification** |
| **Travel and subsistence**  |  |  |
| **Equipment**  |  |  |
| **Other goods, works and services** |  |  |
| **Remaining purchase costs (<15% of pers. Costs)** |  |  |
| **Total** |  |  |

**Table 3.1i: ‘Other costs categories’ items (e.g. internally invoiced goods and services)**

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| **Participant Number/Short Name** |
|  | **Cost (€)** | **Justification** |
| **Internally invoiced goods and services** |  |  |
| **…** |  |  |

**Table 3.1j: ‘In-kind contributions’ provided by third parties**

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| **Participant Number/Short Name** |
| **Third party name** | **Category** | **Cost (€)** | **Justification** |
|  | **Select between**Seconded personnelTravel and subsistenceEquipmentOther goods, works and servicesInternally invoiced goods and services  |  |  |
|  |  |  |  |