Annex I – JRP protocol

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15SIB03 OC18

Optical clocks with 1E-18 uncertainty

Duration: 36 months

Coordinator
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NPL

Glossary

ACES	Atomic Clock Ensemble in Space
BBR	Blackbody Radiation
BIPM	International Bureau for Weights and Measures
CC	Consultative Committee
CCL	Consultative Committee for Length
CCTF	Consultative Committee for Time and Frequency
CGPM	General Conference on Weights and Measures
CIPM	International Committee for Weights and Measures
CLEO	Conference on Lasers and Electro-Optics
CPEM	Conference on Precision Electromagnetic Measurements
E2	Electric quadrupole
E3	Electric octupole
ECTI	European Conference on Trapped Ions
EFTF	European Frequency and Time Forum
EMRP	European Metrology Research Programme
ESA	European Space Agency
EVN	European VLBI Network
EXL01	EMRP project “Quantum Engineered States for Optical Clocks and Atomic Sensors”
FEM	Finite Element Modelling
FP7-SOC2	EU - FP7 Project “SOC2: Towards Neutral-atom Space Optical Clocks”
GNSS	Global Navigation Satellite Systems
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSA	European GNSS Agency
ICAP	International Conference on Atomic Physics
ICOLS	International Conference on Optics, Lasers and Spectroscopy
IEEE	Institute of Electrical and Electronics Engineers
IEEE-FCS	IEEE Frequency Control Symposium
IND14	EMRP project “New generation of frequency standards for industry”
IOTA	Ion Traps for Tomorrow’s Applications
NMI	National Measurement Institute
OFTEN	EMPIR submitted project “Optical frequency transfer – a European network”
OCS	iMERA-Plus project “Optical clocks for a new definition of the second”
ORCS	Optical Reference Cavities for Space Deployment
QPN	Quantum Projection Noise
rf	Radio frequency
SI	International System of Units
SIB02	EMRP project “Accurate time/frequency comparison and dissemination through optical telecommunication networks”
SIB04	EMRP project “High accuracy optical clocks with trapped ions”
SIB55	EMRP project “International Timescales with Optical Clocks”
STE-QUEST	Space-Time Explorer and Quantum Equivalence Principle Space Test
TAI	International Atomic Time
TWSTFT	Two-Way Satellite Time and Frequency Transfer
ULE	Ultra-low expansivity

UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry
WGATFT	CCTF Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques
WGFS	CCL-CCTF Working Group on Frequency Standards
WGPSFS	CCTF Working Group on Primary and Secondary Frequency Standards
WGSP	CCTF Working Group on Strategic Planning
WGTAI	CCTF Working Group on TAI

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Section A: Key data

A1 Project data summary

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Participant details:

a. Partners (participants who will accede to the Grant Agreement)

no.	Participant Type	Short Name	Organisation legal full name	Country
1	Internal Funded Partner	NPL	NPL Management Limited	United Kingdom
2	Internal Funded Partner	CMI	Cesky Metrologicky Institut	Czech Republic
3	Internal Funded Partner	INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
4	Internal Funded Partner	LNE	Laboratoire national de métrologie et d'essais	France
5	Internal Funded Partner	OBSPARIS	Observatoire de Paris	France
6	Internal Funded Partner	PTB	Physikalisch-Technische Bundesanstalt	Germany
7	Internal Funded Partner	TUBITAK	Turkiye Bilimsel ve Teknolojik Arastirma Kurumu	Turkey
8	Internal Funded Partner	VTT	Teknologian tutkimuskeskus VTT Oy	Finland
9	External Funded Partner	KU	Kobenhavns Universitet	Denmark
10	External Funded Partner	LUH	Gottfried Wilhelm Leibniz Universität Hannover	Germany
11	External Funded Partner	UMK	Uniwersytet Mikolaja Kopernika w Toruniu	Poland

b. Linked Third Parties (participants who will NOT accede to the Grant Agreement)

no.	Participant Type	Short Name	Organisation legal full name	Country
	Linked Third Party (Linked to OBSPARIS)	CNRS	Centre National de la Recherche Scientifique	France

A2 Financial summary

	Internal Funded Partners	External Funded Partners	Unfunded Partners	Total
Labour (€)	1 333 865.42	273 500.00		1 607 365.42
Subcontracts (€)				
T&S (€)	88 804.70	26 400.00		115 204.70
Equipment (€)		3 000.00		3 000.00
Other Goods and Services (€)	112 529.00	29 200.00		141 729.00
Large Research Infrastructure (€)	50 560.00			50 560.00
Indirect (€)	79 287.96	83 025.00		162 312.96
Total eligible costs (€)	1 665 047.08	415 125.00		2 080 172.08
Total eligible costs as % of total costs	80 %	20 %	0 %	
EU contribution (€)	**1 665 047.08**	**415 125.00**		**2 080 172.08**
EU contribution as % of total EU contribution	80 %	20 %	0 %	
Months	221.8	84.6		306.4

A3 Work packages summary

WP No	Work Package Title	Active Partners (WP leader in bold)	Months
WP1	Stable lasers and stability transfer	**LNE**, KU, LUH, NPL, OBSPARIS, PTB, TUBITAK, VTT	64.7
WP2	Probing trapped atoms with sub-Hz resolution	**PTB**, CMI, NPL, UMK, VTT	62.6
WP3	Evaluation of systematic uncertainties	**INRIM**, CMI, LNE, NPL, OBSPARIS, PTB, UMK, VTT	88.6
WP4	Advanced clock operation	**NPL**, INRIM, LUH, OBSPARIS, PTB, UMK	53.2
WP5	Creating impact	**VTT**, all partners	25.4
WP6	Management and coordination	**NPL**, all partners	11.9
		Total months	**306.4**

Some of the staff working on the project at OBSPARIS are employed by the Linked Third Party CNRS. CNRS will provide 6.3 months of labour resource overall to this project in WP1 (2.0 months), WP3 (1.5 months), WP4 (1.0 months), WP5 (1.5 months) and WP6 (0.3 months). This resource is included in the table above.

Section B: Overview of the research

B1 Scientific and/or technical excellence

B1.a Summary of the project

Overview

The main aim of this project is to develop world-leading optical atomic clocks across Europe, which will support a future redefinition of the SI second and underpin international timescales. The target is to be able to determine the rate at which the clocks run to within a systematic uncertainty of 1 part in 10^{18} after just a few hours of statistical averaging.

Need

Optical clocks with 1×10^{-18} uncertainty are needed by a wide range of sectors from basic science and metrology to applications in geodesy, satellite navigation and environmental monitoring.

It is anticipated that there will be an international decision to redefine the SI second in terms of an optical standard, since optical clocks have already been shown to outperform the caesium standards by more than an order of magnitude. Before a redefinition can be made, however, there must be confidence that the optical clocks actually perform at the level they are estimated to achieve. Measurements must therefore be carried out to validate the performance, using the highest accuracy clocks available. Tests of fundamental physics, such as looking for violations of Einstein's Equivalence Principle, also require clocks with 1×10^{-18} accuracy to set an order-of-magnitude tighter constraint on physical theories. Uncertainties in the clock frequency arising from systematic shifts must therefore be evaluated and reduced to the 10^{-18} level.

For statistical uncertainties to reach the same level, the frequency output from optical clocks must be averaged over a period of time. A barrier to using optical clocks 'in the field' can be that the necessary averaging time is of the order of days or weeks. For geodesy applications such as monitoring changes in ocean currents or surveying for gas and oil, much shorter averaging times are required. To reach statistical uncertainties of 10^{-18} after just a few hours, the optical clock must have laser instabilities at or below 10^{-16} at 1 s transferred to the atoms and a coherent probe time of at least 1 s.

The challenges that must be overcome to reach 1×10^{-18} uncertainty are common to the two different types of optical clock being studied: neutral atoms in optical lattice traps and single ions in radio frequency traps. The following objectives will therefore be jointly addressed:

Objectives

1. To achieve instabilities in laser frequencies of 1×10^{-16} or below after 1 s, by investigating: (a) room temperature glass cavities, (b) cryogenic silicon cavities (c) spectral hole burning and (d) active resonators. Guidelines will be written to show how this stability can be transferred from the laser source to the atoms in optical clocks whilst adding no more than 1×10^{-17} to the laser noise after 1 s.
2. To develop traps for single ions and neutral atoms that support > 1 s probe times. Guidelines will be written for an optimised design of ion trap; for neutral atoms a report will be written summarising the effects of collisions, photon scattering and parametric heating on coherence times.
3. To evaluate and reduce systematic uncertainties in optical clocks to the level of 10^{-18}. A report will be written summarising improved control and measurement of the thermal environment in single ion and neutral atom optical clocks, leading to 10^{-18} uncertainties in blackbody radiation shifts for clocks operating at both cryogenic and room temperatures. An uncertainty report for controlling and evaluating lattice light shifts and collisional shifts at the 10^{-18} level in neutral atom optical lattice clocks will also be written.
4. To implement novel interrogation methods in optical clocks that use an optimised sequence of probe pulses to reduce even further the instability and inaccuracy of the clocks. To validate performance with target uncertainty 1×10^{-18}, through direct measurement of the frequency difference between two independent clocks.
5. To facilitate the uptake of the technology by the measurement supply chain and end users by making optical frequency standards more practical and accessible to end users.

Progress beyond the state of the art

The SI second is currently realised with Cs fountain atomic clocks, the best of which have accuracies of $1 - 2 \times 10^{-16}$, which represents the level at which their frequency agrees with the unperturbed atomic transition.

Optical clocks have already been shown to surpass this performance but, to date, only a small number of optical clocks have been evaluated with uncertainty below the level of 1 x 10^{-17}. Furthermore, these evaluations have largely been based on estimates; there has been very little direct experimental verification that the clocks actually operate within the stated uncertainties. This project will develop clocks that go beyond the current state of the art and firmly establish their uncertainty in the 10^{-18} range through direct measurements. This will require advances in all aspects of the optical clocks: laser stabilisation, atomic traps and control of systematic frequency shifts. A combination of iterative advancements and exploration of novel techniques will be employed.

Results

Laser stabilities

Laser noise below 1 x 10^{-16} at 1 s will be achieved through advances in existing optical cavity stabilisation techniques. It is believed that optical cavities will not have much scope for further improvement after this and so novel laser stabilisation techniques are also being explored to assess their suitability to reach towards 10^{-18} at 1 s. In parallel, techniques to transfer the stability to the atoms are also being characterised and improved to ensure they do not add more than 1 x 10^{-17} at 1 s to the laser noise.

Atom traps

To take advantage of the improved laser stabilities, atomic traps for both single ions and neutral atoms will be designed to support > 1 s coherent probe times. New understanding will be gained of the mechanisms inducing heating in the trapped atoms, along with the effects of collisions and photon scattering. Spectroscopic results will demonstrate the coherence times achieved.

Systematic uncertainties

The frequency shifts arising from blackbody radiation, lattice light shifts and collisional shifts will all be controlled to an uncertainty at the 10^{-18} level. New measurements of material properties and temperature sensors will enable vacuum chamber and ion trap designs that suppress uncertainties from blackbody radiation. Collisional and lattice light shifts will be evaluated through a series of auxiliary measurements with carefully controlled external conditions for the atoms.

Novel interrogation methods and validating performance

The statistical and systematic uncertainties in the clocks will be further reduced by applying carefully tailored sequences of probe pulses to the atoms. Operational procedures and supporting experimental control software will also be developed to interleave different operating modes in order to provide real-time monitoring and correction of systematic frequency shifts. For the case of optical lattice clocks, an interleaved probing will be used to approach a zero dead-time interrogation, resulting in stabilities approaching the quantum projection noise limit.

The achieved stabilities and systematic uncertainties will be revealed by direct comparisons of independent clock systems. The target is to demonstrate 10^{-18} level uncertainties. Direct measurements such as these give much greater confidence in the clock performance than estimated uncertainties, which are more commonly evaluated.

Impact

This is an ambitious programme of research, from which many peer-reviewed publications are anticipated. There will also be a strong impact on metrology as the reduction in the optical clock uncertainties will lead to better values for secondary representations of the SI second, and influence the international decision concerning a redefinition of the second.

By taking advantage of the shorter averaging times that will be achieved for the clocks in this project, there will also be large benefits in the longer term for a wide range of end users. The Radio Astronomy community will be able to upgrade to more precise timing signals at each antenna site in Very Long Baseline Interferometry, allowing increased resolution in the observations. For the geodesy community, the use of 1 x 10^{-18} clocks will allow changes in gravity potential to be resolved that are equivalent to 1 cm changes in height, enabling the clocks to be used in applications including alignment of national height systems, oil and gas surveying, and monitoring environmental changes such as melting of the polar ice caps and volcanic processes that take place before an eruption.

Impact on relevant standards

This project will verify the performance of optical clocks at the 1 x 10^{-18} level. The results will be disseminated to a range of standards and technical committees, including the Consultative Committee for Time and Frequency (CCTF) that makes recommendations on updating values for the secondary representations of the

SI second. New values, with smaller uncertainties, could thus be assigned to the following secondary representations of the SI second: ^{87}Sr, ^{171}Yb, $^{88}Sr^{+}$, $^{171}Yb^{+}$(E2) and $^{171}Yb^{+}$(E3).

Impact on industrial and other user communities

The knowledge generated throughout this project will be brought together to produce a set of specifications and recommendations for achieving 1×10^{-18} uncertainty optical clocks. The document will be made publicly available and will be complemented by optimised designs for ion traps, vacuum systems and laser stabilisation reference systems. This information will make it easier for end users to upgrade or build new solutions for their own particular needs. This includes not just industrial end users but also those in the measurement supply chain, such as accredited laboratories contributing to international timescales. With the advent of an optical redefinition of the SI second, there will be demand for local realisations of the new primary frequency standard in these laboratories. Designs and specifications such as proposed here could greatly facilitate this.

Impact on the metrology and scientific communities

The techniques developed within this project for improved laser stabilities and trap coherence times will be shared to enable optical atomic clocks to be operated with up to an order of magnitude better stability. This will reduce the averaging time needed to reach a given statistical uncertainty by up to two orders of magnitude, making optical clocks far more practical for both 'in the field' and laboratory measurements.

For fundamental physics, optical frequency standards at the 1×10^{-18} level can probe for deviations from theoretical predictions with an order of magnitude more precision than currently available. The optical frequency ratio measurements carried out in this project will contribute to the body of data placing limits on the time variation of the fine structure constant. The improved stability of the clocks will also enable more sensitive searches for non-linear time-variations, including dark matter searches. The optical clocks will be an essential part of the ground segments for space-based missions testing General Relativity, such as the Atomic Clock Ensemble in Space (ACES) which is due to be launched in early 2017.

B1.b <u>Overview of the scientific and technical objectives</u>

The overall objective of this project is to develop frequency standards for optical clocks with fractional uncertainties of 1×10^{-18}, and to reduce the instabilities to $10^{-16}/\sqrt{\tau}$, where τ is the averaging time in seconds. This instability will allow the 1×10^{-18} uncertainty to be reached in less than 3 hours of averaging, making the clocks more practical for end user applications. To achieve the overall uncertainty target for the optical clocks, the project plans:

1. To achieve instabilities in laser frequencies of 1×10^{-16} or below after 1 s, by investigating: (a) room temperature glass cavities, (b) cryogenic silicon cavities (c) spectral hole burning and (d) active resonators **(D2)**. Guidelines will be written to show how this stability can be transferred from the laser source to the atoms in optical clocks whilst adding no more than 1×10^{-17} to the laser noise after 1 s **(D1)** (WP1).
2. To develop traps for single ions and neutral atoms that support > 1 s probe times. Guidelines will be written for an optimised design of ion trap **(D3)**; for neutral atom optical lattice traps a report will be written summarising the effects of collisions, photon scattering and parametric heating on coherence times **(D4)** (WP2).
3. To evaluate and reduce systematic uncertainties in optical clocks to the level of 10^{-18}. A report will be written summarising improved control and measurement of the thermal environment in single ion and neutral atom optical clocks, leading to 10^{-18} uncertainties in blackbody radiation shifts for clocks operating at both cryogenic and room temperatures **(D6)**. An uncertainty report for controlling and evaluating lattice light shifts and collisional shifts at the 10^{-18} level in neutral atom optical lattice clocks will also be written **(D5)** (WP3).
4. To implement novel interrogation methods in optical clocks that use an optimised sequence of probe pulses to reduce even further the instability and inaccuracy of the clocks (WP4) **(D7)**. To validate performance with target uncertainty 1×10^{-18}, through direct measurement of the frequency difference between two independent clocks **(D8)** (WP4).
5. To facilitate the uptake of the technology by the measurement supply chain and end users by making optical frequency standards more practical and accessible to end users (WP5).

B1.c List of deliverables

Relevant objective	Deliverable number	Deliverable description	Deliverable type	Partners (Lead in bold)	Delivery date
1	D1	Guidelines documenting the transfer of stability from the laser source to the atoms whilst adding no more than 1 x 10^{-17} to the laser noise after 1 s	Guidelines	**OBSPARIS**, LNE, LUH, NPL, PTB, TUBITAK	Nov 2018 (M31)
1	D2	Report summarising the achieved laser stabilities with each of the investigated systems: (a) room temperature glass cavity, (b) cryogenic silicon cavity (c) spectral hole burning and (d) active resonators. The target instability is 1 x 10^{-16} or below after 1 s.	Summary report	**PTB,** KU, LNE, LUH, NPL, OBSPARIS, VTT	Dec 2018 (M32)
2	D3	Guidelines for an optimised ion-trap that supports > 1 s probe times	Guidelines	**PTB**, CMI, NPL, VTT	Jun 2018 (M26)
2	D4	Report summarising the effects of collisions, photon scattering and parametric heating on coherence times in neutral atom optical lattice traps	Summary report	**UMK**, NPL, PTB	Aug 2018 (M28)
3	D5	Uncertainty report on controlling and evaluating lattice light shifts and collisional shifts at the 10^{-18} level in neutral atom optical lattice clocks	Uncertainty report	**LNE,** INRIM, OBSPARIS, UMK	Aug 2018 (M28)
3	D6	Summary report on improved control and measurement of the thermal environment in single ion and neutral atom optical clocks, leading to 10^{-18} uncertainties in blackbody radiation shifts for clocks operating at both cryogenic and room temperatures	Summary report	**INRIM**, CMI, NPL, PTB, UMK, VTT	Jan 2019 (M33)
4	D7	Guidelines on optimised interrogation methods that minimise optical clock instability and inaccuracy	Guidelines	**NPL,** INRIM, LUH, OBSPARIS, PTB	Dec 2017 (M20)
4	D8	Report on validation of clock performance through direct comparison of two independent clocks, targeting uncertainty at the 10^{-18} level	Validation report	**NPL,** INRIM, OBSPARIS, PTB, UMK	Apr 2019 (M36)
5	D9	Evidence of contributions to or influence on the top-level realisation of the SI second, with specific focus on recommendations to the Consultative Committee for Time and Frequency (CCTF) and its associated working groups. These documents will also include a specifications document suitable for end users building optical clocks.	Reporting documents	**VTT**, all partners	Apr 2019 (M36)
n/a	D10	Delivery of all technical and financial reporting documents as required by EURAMET	Reporting documents	**NPL**, all partners	Apr 2019 (M36) + 60 days

B1.d Need for the project

The EURAMET Time and Frequency roadmap [13], identifies optical clocks with 1 x 10^{-18} uncertainty as a target, triggered by needs across a wide range of sectors from basic science and metrology to applications in geodesy, satellite navigation and environmental monitoring. This project addresses challenging scientific research to take Europe to a world-leading position in the field of atomic clocks and frequency standards, and to make these advances accessible to the wider community.

Validating clock performance

A particular need for improved optical clocks is in the metrology community. The second is the SI unit that can presently be realised the most accurately and this superiority will allow it to play a central role in the "new SI" proposed for 2018 in which the realisation of six of the seven base units will depend on the second. It is further anticipated that there will be an international decision to redefine the SI second in terms of an optical standard, since optical clocks have already been shown to outperform the caesium standards by more than an order of magnitude. Before a redefinition can be made, however, there must be confidence that the optical clocks actually perform at the level they are estimated to achieve. Measurements must therefore be carried out to validate the performance. There must also be a clear understanding of which of the candidate species has the best performance (both current and projected). Developing high performance optical clocks in this project, across a range of species including neutral atoms of Sr and Yb, and single ions of Sr^+ and Yb^+, will build up a broad knowledge base and strengthen Europe's influence in the international decision. Furthermore, it will provide Europe with the required infrastructure to realise the new definition rapidly when it comes into force.

Laser instabilities of 1 x 10^{-16} or below after 1 s

To reach uncertainty levels of 1 x 10^{-18}, the frequency output from optical clocks needs to be averaged over a period of time, τ, to reduce the statistical uncertainty to this level. A barrier to using optical clocks 'in the field' can be that the necessary averaging time in typical optical clocks is of the order of days or weeks. For geodesy applications such as monitoring changes in ocean currents or surveying for gas and oil, much shorter averaging times are required. With a laser instability of 10^{-16} or below at 1 s, the statistical averaging could reduce as $10^{-16}/\sqrt{\tau}$, reaching 10^{-18} after 10,000 s, which is less than 3 hours, making optical clocks far more practical. Similarly, applications relying only on the stability of optical clocks (and not their absolute accuracy) will benefit from laser stabilities of 10^{-16} at 1 s. A good example is the Radio Astronomy community for whom better stability clocks at each antenna site in Very Long Baseline Interferometry will enable increased resolution in the observations.

Traps that support > 1 s probe times

In order to realise the optimum clock stability for a given laser, sources of noise and decoherence at the atom must be minimised. To benefit from laser instabilities of 10^{-16} or below at 1 s, probe times of at least 1 s should be used. Traps for single ions and neutral atoms are therefore needed that minimise heating effects, collisions and photon scattering in order to avoid decoherence on 1 s timescales.

Systematic uncertainties at the 10^{-18} level

Testing the theories of fundamental physics and searching for deviations from the Standard Model requires measurements to be made at unprecedented levels of accuracy. With the ability of optical atomic clocks to measure frequencies more accurately than any other measureable quantity, new knowledge can be acquired. For example, optical clocks with 1 x 10^{-18} uncertainty could make laboratory-based tests for time-variation of fundamental constants with an order of magnitude more precision than has currently been demonstrated, along with searches for dark matter and tests of Lorentz Invariance. Beyond the laboratory, space-based experiments have also been proposed, such as ACES and STE-QUEST, each requiring high performance atomic clocks to test Einstein's Equivalence Principle. To ensure the clock accuracy is at the 10^{-18} level for all these applications, the uncertainties in systematic frequency shifts must be reduced to at least this level. Following the successful characterisation of blackbody radiation and light shifts for single ion clocks in the EMRP project SIB04, the need is now to focus more on reducing the corresponding uncertainties in the neutral atom clock systems.

Facilitating industry uptake

Besides the needs identified above that require 1 x 10^{-18} uncertainty clocks to achieve their immediate goals, there is an even larger end user community with a fast growing need for precise timing and frequency measurements. Examples include the telecommunications industry (where better timing resolution enables high-speed network synchronisation and coherence multiplexing schemes for high-speed optical communications) and global navigation satellite systems (where optical clocks on-board the satellites would improve autonomy and simplify the ground segments). As industries such as these progress, they need to assess the feasibility and cost of upgrading their timing systems. There is thus a need to share knowledge well beyond the research community and to facilitate the uptake by a broad range of industry.

B1.e Progress beyond the state of the art

Validating clock performance [WP4]

To date, only a few optical clock systems have been evaluated as frequency standards with systematic uncertainties below 1 x 10^{-17}: Sr [31, 44], Al^+ [7] and Yb^+ [21]. Most of these evaluations have been based on estimates; there has been very little direct experimental evidence that the clocks actually operate with the stated uncertainties. One of the objectives of this project is therefore to establish the 10^{-18} range more firmly through direct measurements made with independent clocks and with sufficient averaging time to reduce the statistical uncertainty in order to verify the accuracy. This builds upon the successes of EMRP project SIB55 in which a framework was established for comparing clocks via optical frequency ratios and gaining confidence in the stated uncertainties. This project will concentrate on pushing the performance of the clocks to have an order of magnitude better accuracy, and demonstrating this by measuring clock frequency ratios within *individual* institutions. The related project 15SIB05 (OFTEN) is focussed on developing a network of optical fibre links to enable high accuracy comparisons between optical clocks in *different* institutions. The combined results from the two projects will thus allow a comprehensive validation of optical clock uncertainties across Europe at an unprecedented level.

The overall 1 x 10^{-18} uncertainty target will be achieved by building upon the attainments of previous European collaborative projects and by developing new concepts and techniques to push the performance for each of the clock's subsystems:

Laser instabilities of 1 x 10^{-16} or below after 1 s [WP1]

Most clocks require more than a day of statistical averaging to reach the 10^{-18} uncertainty level, and the best reported clock stability to date has been with Sr [31, 44] at 2 x $10^{-16}/\sqrt{\tau}$. This project aims to achieve 1 x $10^{-16}/\sqrt{\tau}$ in order to reach 10^{-18} after 3 hours of averaging. Laser instabilities are thus needed at or below the 10^{-16} level at 1 s. The best laser instability demonstrated so far is 8 x 10^{-17} over 1 s – 1000 s [17]. This relies on a long (48 cm) Fabry-Pérot cavity to reduce the fractional contribution from the thermal noise of the mirror surfaces, but progress towards longer cavities is made difficult by their increased sensitivity to vibrations.

In this project alternative techniques will be explored based on cryogenic silicon cavities, spectral hole burning and active resonators in order to establish which of these emerging technologies is best suited for clock laser sources with instabilities capable of going low into the 10^{-17} range at 1 s. The project will also implement the low thermal noise cavity mirrors that were developed in the EMRP project EXL01 by the REG "Crystalline Mirror Solutions". Further ideas for low noise cavities, including methods to evaluate vibration sensitivity, were generated in EMRP project IND14, which can be transferred to the larger systems envisioned in this project. Innovative techniques will also be applied to predict and remove frequency drift in cavities, using a collection of environmental sensors and a feedforward algorithm so as to maintain long term drifts close to 10^{-16} at 1000 s.

Traps that support > 1 s probe times [WP2]

Combined with the stable lasers from above, the activities in work package WP2 should enable fully coherent probe interrogation times exceeding 1 s, going beyond what is currently achieved in either single ion or neutral atom optical clocks.

From the collaborative research carried out under EMRP project SIB04, new endcap traps for single ions were developed and built at NPL and PTB that had considerably better thermal properties than previous designs due to the thermal analysis and FEM modelling carried out by CMI and VTT. This has greatly reduced the uncertainty due to blackbody radiation in ion traps. The limitation of these traps is now their anomalous motional heating rates that limit the interaction time for uncooled ions and may lead to Doppler shifts. The programme of research proposed here will address this by investigating electrode materials, surface preparations and geometries. This will provide much needed information to inform a next-generation design of trap.

For neutral atom optical clocks, many of which were developed under the iMERA-Plus "OCS" project, long coherence times are equally important and hence better understanding is required of the collisional, scattering and heating effects that occur in optical lattices. To date, studies on the effects of background gas collisions with cold atoms in a lattice have been purely theoretical, but in this project an experimental study will be undertaken. Measurements will also be carried out to characterise photon scattering and parametric heating to understand the lattice parameters required for attaining optimum coherence times.

Systematic uncertainties at the 10^{-18} level [WP3]

<u>Blackbody radiation shift uncertainty</u>

For the commonly used ^{87}Sr clock system, temperature homogeneity must be maintained to within about 10 mK to achieve a 1 x 10^{-18} uncertainty when working at room temperature. This is currently achieved in just two systems [2, 31], and this project will further enhance the design with extended characterisation of materials to attain the very best temperature homogeneities. An alternative strategy is to have the atoms in a cryogenic environment, where the temperature uncertainty can be more relaxed. The current state of the art in a cryogenic ^{87}Sr system [44] has already achieved 1×10^{-18} uncertainty for the BBR shift, but the atoms underwent transport from the loading region to the science region, which reduces the clock cycle time and hence stability. This project will therefore design and build a cryogenic system that does not have this limitation and so will achieve 1×10^{-18} systematic uncertainty without compromising the stability.

Improved values of atomic parameters

More accurate measurements of the frequency shifts in Sr and Yb, arising from the optical lattice potential that traps the atoms, will provide improved values of non-linear polarisability coefficients. New results are also expected regarding the parameters governing collisional shifts between the atoms within the lattice potentials, as well as collisions with background gases. In addition to improving the evaluation of frequency shifts and uncertainties for the optical clocks, these parameters will also be of wider interest to the atomic physics community.

Novel interrogation methods [WP4]

Most optical clocks use a simple implementation of Rabi spectroscopy, yet it is now apparent that more sophisticated probing sequences can reduce both inaccuracy and instability allowing systems to achieve the highest performance. A prominent example of this was a suppression of the ac Stark shift in $^{171}Yb^{+}$ from the probe field by four orders of magnitude when using a hyper-Ramsey probing sequence [20]. Control of the shift, however, comes at a cost of reduced short-term stability and introduces a sensitivity to cycle-synchronous phase fluctuations. Further development of such sequences in this project will address these issues. It should reduce light shifts below 1×10^{-18} and will also be applied for the first time to cancel Zeeman shifts that arise in magnetically induced spectroscopy of ^{88}Sr.

Neutral atom optical clocks will also be demonstrated to operate with close to zero dead-time interrogation by interleaving the probing in two identical systems, each with a 50 % duty cycle. With zero dead-time, noise due to stroboscopic sampling effects of the local oscillator noise (Dick effect) would be eliminated. The Dick effect currently limits the instability of optical lattice clocks to around ten times the quantum projection noise (QPN) limit and its removal would enable an unprecedented optical clock instability approaching $1 \times 10^{-17}/\sqrt{\tau}$.

B2 Potential outputs and impact from the project results

B2.a Projected early impact on industrial and other user communities

A specifications document for developing 10^{-18} optical clocks

One of the objectives of this project is to make high performance optical clocks more accessible to a wider community The knowledge generated throughout this project will be brought together in WP5, deliverable D9, to produce a set of specifications and recommendations for achieving 1×10^{-18} uncertainty optical clocks. This document will be made publicly available to enable end users and those in the measurement supply chain to budget for and construct new or upgraded clock systems that address their own particular frequency and timing needs. The target end user community includes groups developing optical clocks for ESA missions (both ground-based and space borne), and operators of telecommunications and energy networks, requiring the very best synchronisation. Those in the measurement supply chain that could benefit from this type of ‘instruction manual’ for building optical clocks includes smaller NMIs and other accredited laboratories that contribute to international time scales. With the advent of an optical redefinition of the SI second, there will be demand for local realisations of the new primary frequency standard in these laboratories. Documented guidelines and procedures such as proposed here could greatly facilitate this.

Optimised designs for clock subsystems

This project will develop designs for laser stabilisation (WP1), ion traps enabling long coherence times (WP2) and vacuum chambers with good temperature homogeneity (WP3). These designs will be evaluated for commercial exploitation. It is envisaged that if such designs translate into off-the-shelf components, the uptake will go beyond just those wanting to build atomic clocks. For example, traps for the atomic reference that allow long interrogation times without loss of coherence (WP2) are necessary in the rapidly multiplying applications of quantum information processing. Ultrastable lasers (WP1) are in wide demand for applications such as precision spectroscopy.

B2.b Projected early impact on the metrological and scientific communities

Knowledge transfer and collaborations

This consortium will create impact through publications in peer-reviewed journals, presentations at conferences, and updates on the project website. There will also be a one-week summer school aimed at PhD students. Opportunities for secondments and research visits will also be available throughout the duration of the project and many of the laboratories within the consortium will have students participating in this research as part of their PhD studies.

Inputs to secondary representations of the SI second

This project will verify the performance of optical clocks at the 1×10^{-18} level. The results will be disseminated to a range of standards and technical committees, as listed in Section B2.c, including the Consultative Committee for Time and Frequency that makes recommendations on updating values for the secondary representations of the SI second. New values, with smaller uncertainties, could thus be assigned to the following secondary representations of the SI second: ^{87}Sr, ^{171}Yb, $^{88}Sr^{+}$, $^{171}Yb^{+}$(E2) and $^{171}Yb^{+}$(E3).

Optical clocks with shorter averaging times

The techniques for improved laser stabilities (WP1) and trap coherence times (WP2) will be shared, initially within the consortium and subsequently through scientific publications, to enable optical atomic clocks to be operated with up to an order of magnitude better stability. This will reduce the averaging time needed to reach a given statistical uncertainty by up to two orders of magnitude. Optical clocks will thus become far more practical because precise measurements can be made in hours rather than days or weeks.

Advanced knowledge in fundamental physics

Measurements in optical frequency standards can probe for deviations from fundamental physical theories at a very sensitive level. The optical clock frequency ratios carried out in WP4 of this project will contribute to the body of data placing limits on the time variation of the fine structure constant. The improved stability of the clocks (arising from WP1 and WP2) will also enable more sensitive searches for non-linear time-variations, including dark matter searches. The optical clocks will also be an essential part of the ground segments for space-based missions testing General Relativity, such as ACES which is due to be launched in early 2017.

B2.c Projected early impact on relevant standards

The most direct impact of this project will be on the top-level realisation of the SI second. The systems under study in this project include five of the seven standards that are currently accepted as optical secondary representations of the SI second. Reduced uncertainties in these standards will therefore bring not only immediate benefits to the measurement supply chain, but also pave the way towards a future choice of primary frequency standard and a redefinition of the SI second.

Definitions and changes in the definitions of the SI units are made by the General Conference on Weights and Measures (CGPM) on the advice of the International Committee for Weights and Measures (CIPM). The CIPM itself takes advice on scientific and technical matters from a number of Consultative Committees (CCs), which prepare recommendations for discussion at the CIPM. For matters related to time and frequency this advice comes from the Consultative Committee for Time and Frequency (CCTF).

The consortium is well represented on the CCTF and its associated working groups, which in several cases are chaired by members of the consortium. Information on the progress and results of this project will be disseminated to the groups listed below through attendance at the meetings and, where appropriate, a written report will be submitted for consideration by the committee.

Standards Committee / Technical Committee / Working Group	Partners involved	Likely area of impact / activities undertaken by partners related to standard / committee
Consultative Committee for Time and Frequency (CCTF)	INRIM, NPL, OBSPARIS, PTB, TUBITAK	INRIM together with NPL, OBSPARIS, PTB, and TUBITAK will write reports on the scientific progress and frequency measurements at each institute and submit them to CCTF allowing them to make recommendations to CIPM on updating values for the secondary representations of the SI second.

CCL-CCTF Frequency Standards Working Group (WGFS)	NPL (co-chair), PTB (co-chair), INRIM, OBSPARIS, KU, VTT	NPL, PTB, INRIM, OBSPARIS, KU and VTT will give summaries at working group meetings on the progress in accuracy of the different standards being made throughout the project as this underpins the recommendations made by this committee for new/improved values of optical frequencies for secondary representations of the second.
CCTF Working Group on Primary and Secondary Frequency Standards (WGPSFS)	INRIM, NPL, OBSPARIS, PTB	INRIM, NPL, OBSPARIS and PTB will give summaries at working group meetings on the progress made in frequency ratio measurements during the project. This working group discusses the measurements and procedures for the introduction of data from secondary representations for the calibration of TAI.
EURAMET Technical Committee on Time and Frequency (TC-TF)	INRIM, NPL, OBSPARIS, PTB, TUBITAK, VTT	INRIM, NPL, OBSPARIS, PTB, TUBITAK and VTT will present summaries of the results of this project annually at the meetings held by this committee. These presentations will also provide an opportunity to engage with smaller NMIs and understand their needs. The outputs from the project will have the potential to influence future roadmaps.
ACES Investigator Working Group	NPL, OBSPARIS, PTB	NPL together with OBSPARIS and PTB will provide updates on the performance and availability of the optical clocks at meetings of this working group. This will assist with the scheduling of the measurement campaigns for the ACES mission, due to begin in 2017.
Working group of German UTC laboratories	PTB	PTB will liaise with this working group and participate in technical discussions on the realisation of frequency references and time scales and applications in geodesy, navigation, astronomy and telecommunication.

B2.d Projected wider impact of the project

Environmental impact

Optical clocks with 1 x 10^{-18} uncertainty will be able to measure gravity potential differences arising from just 1 cm changes in height at well-defined locations. This will complement the data obtained from satellite missions such as GOCE or GRACE, which provide global coverage but give values that are spatially averaged over length scales of about 100 km. Adoption of optical clocks by the geodesy community could enable a consistent alignment of national height systems within Europe as well as important checks of global geoid models established by alternative means. It will also be possible to measure variations in local gravity potentials over longer timescales, allowing monitoring of seasonal and long-term trends in ice sheet masses, ocean current transport and overall ocean mass changes. Such data provides critical input to the models which are used to study and forecast the effects of climate change.

Financial and social impact

The most immediate impact of improving atomic clocks within this project will be on the European time and frequency infrastructure. Currently, the European NMIs disseminate time as a free-of-charge service so it is difficult to quantify the financial impact of this. There are, however, more than 100 million receivers across Europe of the radio timing signals from NMIs, demonstrating the widespread impact on daily lives. Improved atomic clocks at the NMIs are however also critical for high-profile science, such as the European VLBI Service, for whom the availability of precise frequency standards across Europe enables a synchronised array of radio telescopes across a very large baseline to give astronomy images with unprecedented resolution. Better stability timing signals will also enable radio astronomy to acquire images at lower wavelengths, possibly revealing new physical phenomena.

Precision frequency and timing information is also at the core of many technologies upon which society increasingly relies. The most notable is probably global navigation satellite systems (GNSS), which depend on a constellation of highly precise atomic clocks on board satellites, and a further network of ground based clocks to provide accurate position and timing information. With location devices now included in most mobile phones, there has been a rapid explosion in the number of users of this service. It is estimated that there are now 4 billion GNSS devices in use worldwide, with Europe accounting for nearly a quarter of this market, and the anticipated sales growth through until 2019 is 8 % per annum [14]. Other widely used technologies that rely on precision frequency and timing include telecommunications (where better timing signals could result in increased network resilience and lower operating costs) and energy networks (where synchronised monitoring of weaknesses in the grid can enable power to be transferred more efficiently). Improved atomic clocks can bring significant benefits to the level of these services and stimulate growth in new applications across a broad range of industries.

B3 The quality and efficiency of the implementation

B3.a Overview of the consortium

The consortium brings together all the European NMIs active in the field of optical atomic clocks, combining the expertise in both neutral atom and single ion optical clocks as well as the leaders in the development of stable lasers. The external partners will bring in additional expertise, such as theoretical modelling and novel techniques that will enhance the clock capabilities across the whole consortium. Many of the scientists involved in this project have previously collaborated in the past, and have established working relations that will facilitate the efficient management of this project.

CMI brings expertise in temperature modelling and materials analysis. CMI will assist the design and fabrication of advanced ion traps whilst developing their own Yb^+ system (WP2, WP3).

INRIM brings expertise in neutral atom optical clocks. A clock system based on Yb will be operated (WP3, WP4), along with development of a new design of vacuum chamber to reduce uncertainties from the blackbody radiation shift (WP3).

LNE and OBSPARIS both bring expertise in neutral atom optical clocks and laser stabilisation. The clocks are already operating at internationally competitive levels. Two clock systems based on Sr will be operated (WP3, WP4), along with development work on spectral hole burning and transfer of laser stability (WP1).

NPL brings expertise in neutral atom and single ion clocks, and laser stabilisation. The clocks are already operating at internationally competitive levels. Clock systems based on Sr, Yb^+ and Sr^+ will be operated (WP3, WP4), along with development of traps (WP2) and stable lasers & stability transfer (WP1).

PTB brings expertise in neutral atom and single ion clocks, and laser stabilisation. The clocks are already operating at internationally competitive levels. Clock systems based on Sr and Yb^+ will be operated (WP3, WP4), along with development of traps (WP2) and cryogenic oscillators & stability transfer (WP1).

TUBITAK brings expertise in femtosecond optical frequency combs. As the only partner in the consortium with a comb based on an Yb-fibre laser (as opposed to Er-fibre lasers which are used by the other partners), TUBITAK will evaluate the suitability of Yb-fibre frequency combs for use in future optical clocks (WP1).

VTT brings expertise in ion traps and laser stabilisation. VTT will participate in temperature characterisation and improved electronics for ion trap design (WP2, WP3) as well as investigating non-linear cavity drift correction for laser stabilisation (WP1).

KU brings expertise in the emerging field of combining neutral atoms with optical cavities to reduce the frequency noise of the laser. The focus of KU's activities in this project will be in the exploration of novel techniques for generating stable laser light (WP1) in collaboration with LNE, NPL, OBSPARIS and PTB.

LUH brings expertise in optical cavities and laser noise characterisation. LUH will design new optical cavity systems that operate more simply (WP1) and undertake a theoretical analysis of laser noise to provide guidelines on optimal pulse interrogation methods (WP4).

UMK brings expertise in neutral atom optical clocks and atomic physics theory. Two clock systems based on Sr will be operated (WP3, WP4), along with an investigation of the effects of collisions from both background gases and other atoms in the lattice trap (WP2, WP3).

CNRS is a Linked Third Party (LTP) in this project and is linked to OBSPARIS. OBSPARIS and CNRS have a strong collaboration over many years. CNRS as an LTP to OBSPARIS will contribute to WP1, WP3-WP4 and WP5-6.

Section C: Detailed project plans by work package

C1 WP1: Stable lasers and stability transfer

The aim of this work package is to develop a new generation of stable lasers and strategies to transfer their stability either directly to the atoms or to wavelengths necessary for clock operation. The spectral purity of the ultrastable clock laser probing the narrow atomic transition is a key factor in the performance of the clock: firstly it dictates the Fourier width of the resonance, and secondly the sampling of the residual frequency noise (Dick effect) adds noise to the measurements.

Presently, state-of-the-art laser technology limits optical clock stability to 2 - 4 x $10^{-16}/\sqrt{\tau}$ for neutral atom systems (more than one order of magnitude above the anticipated quantum limit) and 1 x $10^{-15}/\sqrt{\tau}$ for single ion systems. With the overall targeted uncertainty being 1 x 10^{-18}, clock frequency stabilities of 1 x $10^{-16}/\sqrt{\tau}$ are necessary in order to reach this level after only a few hours of averaging. This requires laser sources to have noise that is at most at the 1 x 10^{-16} level, but preferably at the 1 x 10^{-17} level, after one second, before the lasers are steered by the clock atoms.

In the first task, advanced techniques will be developed to tackle the factors presently limiting ultrastable cavities: the thermal noise and the vibration noise. The second task will be dedicated to the transfer of spectral purity, in order to demonstrate that a stability level of 10^{-17} after one second can be transferred to metrologically relevant target wavelengths and be brought to the atoms. Finally, exploratory novel techniques will be studied in the third task in order to assess their reliability and potentials for use in optical clocks.

C1.a <u>Task 1.1: Advanced techniques for ultrastable Fabry-Pérot cavities</u>

The aim of the first task is to progress towards lower stability floors for ultrastable reference cavities. This will be achieved by dedicating complementary efforts to the control of thermal noise and of the vibration noise. These two limiting factors are closely linked: extending the length of cavities is the simplest way to reduce the fractional contribution of thermal Brownian noise, but it has proved to be very challenging to support long cavities while preserving a low sensitivity to vibrations. Pioneering work performed at PTB demonstrated the suppression of thermal noise down to 1 x 10^{-16} in a 210 mm long silicon cavity cooled down to 124 K [25]. Going to even lower temperatures will be one of the objectives in this task, thus raising the prospect of a thermal noise floor of 1 x 10^{-17} after 1 s at 1542 nm.

Controlling the frequency instability resulting from the vibration noise at the same level has never been demonstrated so far with laboratory-based systems. It requires the study of new strategies that must be accessible not only to Time and Frequency specialists, but also to institutions outside the community. First, a simple way to passively control vibrations at the 1 x 10^{-16} level will be developed together with a simplified design for a 30 cm long cavity at room temperature. To go further, another activity will focus on providing cavities with sensors recording tilts, temperature and pressure fluctuations. Together with numerical modelling, this will allow an improved prediction of the cavity frequency, even when the atomic signal is not available to correct drifts. The last axis of development will be the sensing of vibrations very close to the cavity and the implementation of active feedforward corrections. These studies will progressively open the road towards a control of vibrations at the level of 1 x 10^{-17} after 1 s.

Activity number	Activity description	Partners (Lead in bold)
A1.1.1	PTB, LNE and OBSPARIS will collaborate to investigate three methods (Gifford-McMahon cryostats, pulsed-tube cryostats and bellows and copper braids) to reduce vibration noise induced by cryogenic environments on the silicon cavity (A1.1.2) and the crystal of the spectral hole burning activity (A1.3.4). The requirements are very similar for the two approaches. LNE and OBSPARIS will compare the performances of Gifford-McMahon cryostats and pulsed-tube cryostats. PTB will investigate means to mechanically decouple the cold head from the cavity by using bellows and copper braids. The two groups will exchange information on the progress and the capabilities of the different approaches, and decide the best optimised design suitable for the two setups.	**PTB**, LNE, OBSPARIS

A1.1.2	PTB will set up and investigate a 210 mm long silicon cryogenic cavity, cooled down below 20 K (17 K, possibly 4 K). The cavity will be operated at 1542 nm and the frequency transfer to metrological wavelengths will be addressed by task 1.2. With input from A1.1.1, PTB will devise techniques to reduce the influence of vibrations, locking errors, and temperature fluctuations, targeting the expected thermal noise limit of 1×10^{-17} for averaging times longer than 1 s. The performance will be evaluated by comparing the silicon cavity against other systems (available at PTB) at the same wavelength and at a different wavelength via a frequency comb. Results will be prepared for submission to a peer-review journal.	**PTB**
A1.1.3	LUH will demonstrate a simplified 30-cm-long room temperature glass cavity design at 946 nm to achieve a targeted stability floor of 1×10^{-16} after 1 s. Classical dielectric coatings will be contacted to a light-weight spacer made of bulk ULE (Ultra-Low Expansion) glass, which will be supported using a simplified vibration-insensitive mount that has already been characterised outside of this project. LUH will measure the temperature of the zero-crossing of the coefficient of thermal expansion (expected to be around 30 °C), and the sensitivity around this point. LUH will demonstrate the stabilisation of a laser at 946 nm to this cavity via a compact and fully digital locking electronics, which replaces analogue mixer, phase-shifter and PID controller. The frequency noise floor will be characterised by comparisons with other cavities via a frequency comb. LNE and OBSPARIS will assist LUH by providing a set of technical drawings of a simple temperature regulation system. Initially designed for a light-weight transportable ultrastable cavity, this system will be adapted to the horizontal cuboid geometry of LUH.	**LUH**, LNE, OBSPARIS
A1.1.4	VTT will measure the correlations between the drift of an optical cavity and external sensors recording temperature, vacuum pressure, and tilts, enabling the cavity drift to be predicted. A feedforward correction can then be used to improve the stability of the cavity over long timescales, with a target stability at the low 10^{-16} level at 1000 s. NPL will use numerical modelling techniques in order to characterise the mechanisms behind the correlations between environmental perturbations and cavity drift. These results will be fed into the work at VTT, and together a better understanding of cavities' residual dependence on environmental parameters will be achieved, enabling improved future cavity designs. PTB will investigate the use of acceleration sensors as close as possible to their cavities in order to have a direct access to the forces leading to deformations of the resonator. This approach will allow an online compensation of these effects.	**VTT**, NPL, PTB
A1.1.5	Using inputs from activities A1.1.1 to A1.1.4, LNE, LUH, NPL, OBSPARIS, PTB, and VTT will document the specifications and recommendations relating to optical cavities. The objective is to describe the requirements on all parameters of cavities (e.g. ULE glass or Si for the cavity material, necessary degree of control on the temperature of operation, and residual sensitivity to vibrations) depending on the targeted stability, thus making ultrastable lasers accessible to non-specialists. These guidelines will be sent to VTT for compilation into the specifications document as part of deliverable D9.	**LNE**, LUH, NPL, OBSPARIS, PTB, VTT
A1.1.6	Based on the outcomes of A1.1.1 to A1.1.5 and using input from A1.3.6 PTB, with assistance from KU, LNE, LUH, NPL, OBSPARIS and VTT, will write a report summarising the achieved laser stabilities with each of the investigated systems: (a) room temperature glass cavity (A1.1.3), (b) cryogenic silicon cavity (A1.1.2) (c) spectral hole burning (A1.3.4) and (d) active resonators (A1.3.1 – A1.3.3). The target instability is 1×10^{-16} or below after 1 s.	**PTB**, KU, LNE, LUH, NPL, OBSPARIS, VTT
A1.1.7	Once the report has been agreed by the consortium, PTB on behalf of KU, LNE, LUH, NPL and OBSPARIS and VTT will send the coordinator D2 "Report summarising the achieved laser stabilities with each of the investigated systems: (a) room temperature glass cavity, (b) cryogenic silicon cavity (c) spectral hole burning and (d) active resonators. The target instability is 1×10^{-16} or below after 1 s". The coordinator will then submit deliverable D2 to EURAMET.	**PTB**, KU, LNE, LUH, NPL, OBSPARIS, VTT

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C1.b Task 1.2: Metrological dissemination of ultrastable carriers

The aim of this task is to demonstrate that stabilities in the 10^{-17} range after 1 s can be delivered to the atoms with a negligible technical degradation. State-of-the-art ultrastable lasers are often operated at specific wavelengths (e.g. 1542 nm or 1160 nm), and their spectral purity must then be transferred to the target metrological wavelengths. This can be achieved via a frequency comb, able to coherently link a "master" ultrastable laser and a target "slave" laser used to probe the atoms, with negligible added noise [32]. Another challenge is the control of frequency noise during propagation of the laser from the ultrastable point (e.g. cavity or slave laser) to the atoms. Below an instability of 1×10^{-16}, propagation in optical fibres and even in free space adds frequency noise (due to acoustic and mechanical perturbations) and frequency bias (slow temperature drifts with the optical path length), which must be compensated.

Building on techniques pioneered by PTB, LNE and OBSPARIS, the activities of this task will study different configurations (single-branch or multi-branch combs) and different comb technologies (erbium-doped fibre lasers and ytterbium-doped fibre lasers) with the goal of extending the range of accessible metrological targets with negligible added noise. Additionally, new compensation techniques will be developed to entirely stabilise the optical propagation of the optical carrier at the 10^{-17} level at 1 s between the ultrastable reference and the atoms. These activities aim specifically at reducing the noise of the transfer and the dissemination of spectral purity, they can be carried out completely independently of the activities in Task 1.1.

Activity number	**Activity description**	**Partners (Lead in bold)**
A1.2.1	NPL and PTB will explore multi-branch transfer of spectral purity with frequency combs. NPL will study the transfer of spectral purity from a 1064 nm master oscillator to selected clock laser wavelengths (e.g. 934 nm, 871 nm, 698 nm, 674 nm) using a multi-branch erbium-doped fibre comb that includes frequency doubling stages to reach the clock laser wavelengths. As a first step, the limits to the transfer stability of the existing frequency comb setup will be explored. In the second step, methods for improving the stability beyond the limits established in the first step will be investigated. This is likely to include some or all of the following (depending on the findings in 'step 1'): tighter locking of the frequency comb, reduction of the coupling between the repetition rate and the carrier-envelope offset frequency of the comb, and improvements in the signal to noise ratio of the beat signals. The aim is to transfer the stability of the master oscillator to all wavelengths without degrading its stability. PTB will, in a similar fashion, study the transfer of stability floors of 1×10^{-17} with an erbium-doped fibre comb, also in a multi-branch configuration. The two groups will collaborate to further their understanding on the capabilities and the limits of the multi-branch method with erbium-doped fibre combs.	**NPL**, PTB
A1.2.2	LNE, OBSPARIS and TUBITAK will explore single-branch configurations. LNE and OBSPARIS will transfer the spectral purity of the 1160 nm laser used for the spectral hole burning activity (A1.3.4) onto lasers of metrological interest (698 nm for the strontium lattice clocks, 1062 nm for the mercury lattice clock). This activity will be carried out with an erbium-doped fibre comb. TUBITAK will explore the capabilities of ytterbium-doped-fibre combs. This technology, very little studied for the moment, has a strong potential: the optical power delivered by the laser is very large and the output spectrum ranges from 700 nm to 1400 nm, which is ideal for most optical clocks. TUBITAK will study the potential of having very large signal-to-noise ratios in bands of typically 100 kHz or 1 MHz, and test the principle of the transfer between a master laser at 1064 nm and a slave laser within reach of the ytterbium comb.	**OBSPARIS**, LNE, TUBITAK
A1.2.3	LNE, LUH and OBSPARIS will address the frequency noise that arises during propagation of the laser to the atoms. LUH will implement an ion trap with a metal-coated reflecting surface next to the ions in its second generation Al^+ optical clock. This surface will be used as a reference plane to close an interferometer and phase-stabilise the ultrastable light probing the clock transition. LNE and OBSPARIS will implement a similar approach in one of the strontium optical lattice clocks. The reference plane will be one of the mirrors of the cavity forming the magic lattice. Tests of reliability will be performed by probing the atoms alternately from both directions and checking the agreement of the measurements. Both groups will work in parallel in their own systems and demonstrate the cancellation of the propagation noise and the control of the drifts of the optical path length at the 1×10^{-17} level beyond 1 s of integration time. Results will be prepared for submission to a peer-review journal.	**LUH**, LNE, OBSPARIS
A1.2.4	As a first stage towards enabling an ytterbium-doped fibre comb to be tested on an optical clock at a remote site, TUBITAK will develop a transportable ytterbium-doped fibre comb. Currently, the ytterbium-doped fibre comb is built on an optical table. All of the optical system will be reassembled in a temperature stabilised box (with temperature set point in the region of 20 – 25 degrees Celsius) to reduce the effects of thermal drifts and air flow. Optomechanical components will be replaced by higher temperature and mechanical stability counterparts. The current Mach-Zehnder f:2f interferometer will be replaced by a single arm interferometer for robustness and better noise immunity. NPL will provide support and guidance on how to develop a common-path f:2f interferometer for a Ti:sapphire comb.	**TUBITAK**, NPL

A1.2.5	Using input from A1.2.1 to A1.2.4, LNE, LUH, NPL, OBSPARIS, PTB and TUBITAK will write guidelines and recommendations documenting the transfer of stability from the laser source to the atoms whilst adding no more than 1 x 10^{-17} to the laser noise after 1 s. The document will cover the transfer of spectral purity to another wavelength (including choice of frequency comb technology and configuration) and dissemination of spectral purity up to the atoms (both neutrals and ions). Input will also be provided to VTT for compilation into the specifications document as part of deliverable D9.	**OBSPARIS**, LNE, LUH, NPL, PTB, TUBITAK
A1.2.6	Once the guidelines from A1.2.5 have been agreed by the consortium OBSPARIS on behalf of LNE, LUH, NPL, PTB and TUBITAK will send the coordinator D1 “Guidelines documenting the transfer of stability from the laser source to the atoms whilst adding no more than 1 x 10^{-17} to the laser noise after 1 s”. The coordinator will then submit deliverable D1 to EURAMET.	**OBSPARIS**, LNE, LUH, NPL, PTB, TUBITAK

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C1.c Task 1.3: Exploratory techniques for ultimate frequency stabilities

The aim of this task is to assess the capability of several new approaches to provide spectral features enabling the stabilisation of lasers down to a frequency floor in the 10^{-18} range after 1 s. This level would drastically improve the stability of all optical clocks, and would even allow the Quantum Projection Noise limit to be reached with neutral atom clocks, and therefore reap the full benefit of their potential. The exploratory nature of this work is most efficiently tackled by different institutes implementing different techniques to avoid duplication of efforts, and communicating closely on the relative advantages discovered in each approach.

In the first approach, the pioneering experiments performed at KU on atomic frequency discriminators inserted in an optical cavity [47] will be developed. Contrary to conventional high finesse resonators, this alternative approach is based on a low finesse (100-1000) cavity, such that the system is operated in the so-called bad cavity regime where the cavity linewidth is significantly larger than the narrow atomic transition width. This reduces the system’s sensitivity to thermal noise and cavity pulling effects. Introducing narrow linewidth atoms brings non-linear effects into the dynamics that considerably enhance the spectral sensitivity of the system and at the same time provide an absolute reference for the laser. The second approach will explore spectral hole burning, in which going to a temperature of 4 K allows the persistence over several days of very narrow spectral features imprinted at 1160 nm to a rare-earth-doped crystal [42]. In the last few years, proof-of-principle experiments indicated that noise floors below 10^{-17} seem possible, associated with drifts lower than 1 mHz/s. OBSPARIS has recently demonstrated spectral holes with a width of 2.5 kHz, thus competing with state-of-the-art ultrastable cavities, and progress towards a laser based on this technique will be carried out in this task. Finally, mirrors equipped with crystalline coatings have already been demonstrated to have a very promising potential in terms of control of the thermal noise at room temperature [8]. In this task the ability of these coatings to withstand cryogenic temperatures (17 K, possibly 4 K) will be studied.

Activity number	Activity description	Partners (Lead in bold)
A1.3.1	KU will develop an active resonator, consisting of a simple cavity setup loaded with a MOT (Magneto-Optical Trap), and lock a laser at 689 nm to the narrow atomic feature provided by the atoms. KU will characterise the locking in terms of atom number and probe laser power. PTB will assist by providing advice on locking techniques and electronics. KU will measure the time scales of the system, i.e., time necessary to lock efficiently, delay before regenerating the MOT becomes necessary. Results will be prepared for submission to a peer-review journal.	**KU**, PTB
A1.3.2	KU will implement an improved two-mirror cavity design with a finesse above 1000 based on a zerodur/ULE spacer. One of the mirrors will be attached to a piezoelectric transducer (PZT). The cavity mirrors will also allow for an optical lattice at 914 nm to be added in order to extend the atoms’ interaction time with the probe light. The loading into the lattice will be performed using the drain technique invented at OBSPARIS. LNE, OBSPARIS and PTB will select one transportable cavity to take to KU. This will allow KU to assess the stability that can be achieved by their laser when locked to the narrow spectral feature studied in this activity.	**KU**, LNE, OBSPARIS, PTB

A1.3.3	KU will design a slow bright beam line that will allow continuous laser stabilisation, using a cavity based on a similar design to the NPL compact cubic design. Atom induced phase response of the system will be characterised in terms of probe power, beam flux and finesse of the cavity. KU will also investigate the conditions for continuous super-radiant laser operation in a cavity setup by investigating threshold atom number, threshold power and spectral purity of the generated output. NPL will assist KU to design a compact cubic cavity and to adapt it to the transverse spectroscopy of the slow atomic beam.	**KU**, NPL
A1.3.4	OBSPARIS and LNE will stabilise an 1160 nm laser using the spectral hole burning technique demonstrated recently in Eu^{3+}-doped crystalline matrix, and characterise its metrological performance (suitability to be used as a clock laser) by comparing with other ultrastable lasers via a frequency comb. With input from A1.1.1, the cryogenic environment will be optimised to minimise the impact of vibrations. The servo-locking optimisation will be carried out to improve the experimental performance, notably by studying the optimal number of holes to lock to. The transfer of the spectral purity of this laser to wavelengths of metrological interest is dealt with independently in task 1.2.	**OBSPARIS**, LNE
A1.3.5	PTB will test a pair of mirrors equipped with crystalline coatings at 17 K, possibly 4 K, and assess their ability to survive at low temperatures. If the outcome is positive, these mirrors will be contacted to a silicon spacer and a 1542 nm laser will be locked to this cavity.	**PTB**
A1.3.6	Using input from A1.3.1 to A1.3.5, LNE, NPL, OBSPARIS, PTB and KU will write a summary of the results obtained with these exploratory techniques. It will detail the capabilities of each approach to be implemented on optical clocks. PTB will include the summary in the report for activity A1.1.6.	**PTB**, KU, LNE, NPL, OBSPARIS

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C2 WP2: Probing trapped atoms with sub-Hz resolution

The aim of this work package is to demonstrate sub-Hz resolution in the optical reference line of the clock, accessible in the Fourier limit with probe times approaching and exceeding 1 s. A narrow linewidth in general facilitates the detection and analysis of perturbations that could lead to broadening or a systematic shift of the line. For the single-ion optical clocks, the linewidth is the most important parameter that can be used to improve the stability. In most of the advanced optical clocks the linewidth is limited either by the laser or by decoherence in the atoms. While the first issue will be addressed in WP1, this work package will investigate the limitations imposed to coherent trapping times in optical lattices and ion traps and will strive to reduce them to the level that sub-Hz resolution with full contrast (100 % excitation probability on resonance) becomes possible. This combination has so far not been obtained with any optical clock.

Atoms in an optical lattice and ions in a radiofrequency trap are exposed to different types of perturbations that limit the coherent interaction time: in the case of atoms one needs to consider collisions, parametric heating through the lattice potential and the scattering of photons from the lattice light. For the single trapped ion, the main concern is heating from fluctuating electric fields. In both cases, decoherence of the internal state due to coupling to electric and magnetic field noise needs to be avoided.

In response to this situation, it is planned to build new trap systems for optical clocks that incorporate a number of measures to reduce heating rates and minimise other possible sources of decoherence. The knowledge and techniques acquired during these studies will be shared as part of the 'Specifications Document' being compiled in WP5. The developed trap designs will be made available to others – both within the consortium and to a wider end user community.

C2.a Task 2.1: Ion traps with reduced motional heating rates

The aim of this task is to characterise and understand the motional heating rates suffered by ions in rf traps, and to produce a new ion trap design that minimises the heating rates. The maximum probe time interval is usually determined by the rate at which the ion's oscillation amplitude from secular motion increases in the absence of laser cooling: the coherent interaction terminates when the oscillation amplitude approaches $\lambda/4$ (λ: probe light wavelength). The presence of motional heating also compromises the benefits of multi-pulse excitation schemes like the hyper-Ramsey scheme, investigated in WP4 [20, 40]. Finally, motional heating leads to an increased interaction of the trapped ion with the confining electric field so that Doppler and Stark shifts can be significantly increased. So far, motional heating has been investigated mainly for traps designed for quantum information processing experiments [6]. Here, usually planar electrode structures are used whose characteristic dimensions are smaller than those of typical optical-clock traps. It is commonly observed that the spectral density of the electric field noise produced by the trap electrodes is much larger than the thermal

(Johnson and blackbody) noise level expected from an ideal electrode surface. In a number of cases strong improvements due to cryogenic operation or cleaning of the electrodes by solvents or ion impact were reported. The dominant sources of anomalous heating in ion traps and the physical mechanisms behind them are still not fully understood [6]. An investigation carried out in the frame of EMRP project SIB04 showed that heating rates in the traps of PTB (Yb^+ clock) and NPL (Sr^+ clock) are in the range of 500 to 1000 motional quanta per second, exceeding the thermal noise level by several orders of magnitude. This prevents further progress in exploiting the potential of the Yb^+ E3 transition to realise a single-ion clock with particularly high stability and accuracy.

PTB and NPL plan to build new trap systems for their single-ion optical clocks that incorporate a number of measures to reduce motional heating rates to less than 10 quanta s^{-1}. This would enable a coherent probe time of up to 10 s for the Yb^+ E3 transition. To our knowledge, up to now heating rates in this range have been reported for only 5 trap systems, all with rather diverse construction features [3, 11, 24, 33, 43]. The construction of the new traps will also take into account the improved knowledge of how to avoid sources of excessive blackbody radiation.

Activity number	Activity description	Partners (Lead in bold)
A2.1.1	PTB and CMI will build at least three traps to investigate the influence of electrode materials and surface preparations on the motional heating rate. At PTB, trap electrodes will be machined from Cu or a UHV-compatible Cu-base alloy, as an alternative to the presently employed Mo electrodes. CMI will measure the difference in ion heating rate for the bare molybdenum electrodes (as a reference) and gold plated molybdenum electrodes that provide a chemically more inert surface. Measurements of heating rates will be performed with Yb+, targeting 10 quanta s^{-1} in at least one system. The following measures for reducing anomalous heating will be investigated by PTB: (i) Extensive cleaning of trap electrodes after assembly through selective etching, electropolishing, CO_2 snow, and flushing with highly purified solvents and water. (ii) Selective in-situ baking of the trap electrode system up to 300 ^{0}C under UHV conditions. This will require a new design of the electrical feedthroughs of the UHV chamber. (iii) In-situ plasma cleaning of the trap electrodes through a low-pressure rf discharge. This cleaning technique is known to be efficient at removing hydrocarbons from surfaces. Compared to cleaning by high-power laser light or ion bombardment, surface erosion and sputtering of material are strongly suppressed. Implementation will require extension of the UHV system in order to admit and pump discharge gases.	**PTB**, CMI
A2.1.2	NPL and VTT will characterise the motional heating rate in endcap traps in relation to the geometric and electrical design. The electrode material used will be molybdenum and the tests will be carried out with Sr^+ at VTT and with Sr^+ or Yb^+ at NPL. The trap designs at NPL and VTT are very similar, with the main geometric difference being the separation between the rf electrodes and the main electrical difference being the choice of rf feedthrough.	**NPL**, VTT
A2.1.3	Using input from A2.1.1 and A2.1.2, PTB, with CMI, NPL and VTT will combine the results of the investigations of trap geometry, electrical properties, material selection and surface quality characteristics in an optimised single-ion trap design for the application in optical clocks, suitable for production in a small series for distribution among research institutes (for example within the European COST network IOTA) or eventually via a commercial supplier that is active in the fields of optical or mass spectroscopy. This would comprise the trap structure mounted on a vacuum flange with the rf feedthrough, for easy integration into different systems.	**PTB**, CMI, NPL, VTT
A2.1.4	NPL and VTT will design and develop new filtering electronics for both the rf trap drive and dc compensation voltages in order to reduce the electrical noise from external sources and rf crosstalk and interference seen by the ion. A programmable stable low-noise constant-voltage source for DC compensation voltages and a constant-current source for control of the B-field seen by the ion will be developed. The stability and noise of the sources will be characterised at both NPL and VTT.	**VTT**, NPL
A2.1.5	Using input from A2.1.1 to A2.1.4, PTB and NPL will investigate the achievable improvement in resonance linewidth with the improved traps in their single-ion clocks (PTB: Yb^+, NPL: Yb^+ or Sr^+). Guidelines will be written by CMI, NPL, PTB and VTT summarising the improved design of the trap and electronics, the results on the obtained heating rates, and the spectroscopic results. Input will be provided to VTT for inclusion in the specifications document being compiled as part of deliverable D9.	**PTB**, CMI, NPL, VTT

A2.1.6	Once the guidelines from A2.1.5 have been agreed by the consortium PTB on behalf of CMI, NPL and VTT will send the coordinator D3 “Guidelines for an optimised ion-trap that supports > 1 s probe times”. The coordinator will then submit deliverable D3 to EURAMET.	**PTB**, CMI, NPL, VTT

C2.b Task 2.2: Understanding processes that limit coherence times in optical lattice clocks

The aim of this task is to investigate the scattering and heating processes that limit the coherence times for neutral atoms in one-dimensional optical lattices. Collisions with background gas atoms and scattering with photons from the optical lattice will cause the transition frequency to be broadened and the coherence time to be reduced. With a better understanding of these effects, optical lattice traps can be designed to minimise the decoherence rate and enable probe interrogation times > 1 s with full contrast. The study of collisions will focus on the specific case of atoms, trapped and cooled to ultra-low temperature, affected by collisions with perturbers at room temperature. Though not yet studied experimentally, the effects of background-gas collisions can be one of the leading uncertainties in optical lattice clocks operating at the 10^{-18} level. The best existing measurements are from room-temperature spectroscopy (e.g. [19, 36] for the case of neutral Sr atoms). Theoretical calculations [15], however, show that these measurements cannot be directly transferred to the cold-atom regime, since it is argued that nearly all collisions with room-temperature background atoms that transfer momentum will eject the cold atoms from the trap and the frequency shift is therefore dominated by the interference between the scattered and un-scattered waves in the forward direction. With this assumption, the calculated uncertainty of the frequency shift is of the order of 0.6×10^{-18} [31]. Nevertheless, the shift and broadening from weak background gas collisions with atoms remaining in the trap cannot be totally neglected. In particular, part of the procedure needed to establish an accuracy budget of the clock requires a relatively deep trap potential [46, 35] and in this case weak collisions, which do not result in atom loss from the trap, can be much more numerous and also responsible for collisional shift and broadening [4].

In addition, decoherence from photon scattering will be considered. Although the optical lattices that trap the atoms are far detuned from resonances, even photon scattering rates of about one hertz lead to a considerable decoherence when interrogation is performed with state-of-the-art clock lasers that allow for coherent probing of longer than 0.5 s. Since the scattering rate is expected to be larger in the $^3P_0$ state than in the $^1S_0$ level, excited state atoms must also be considered in the theories. The effect will be investigated both theoretically and experimentally with Sr atoms that are trapped in a magic wavelength lattice of variable depth. Experimental studies will also be carried out in Sr to determine the parametric heating rates at different lattice depths. The results will all be combined together to develop a set of guidelines for the maximum acceptable trap depth for a required coherence time.

Activity number	Activity description	Partners (Lead in bold)
A2.2.1	UMK will perform a theoretical and experimental study on background collisions in optical lattice clocks, applicable also to the systems at NPL and PTB. The theory will treat the straight line trajectory approximation and numerically calculated real classical trajectories. If the characteristic trap energy is much smaller than the perturber kinetic energy, weak collisions do not significantly change the perturber trajectory and the straight line trajectory approximation can be used. The experimental study of background collisions in optical lattice clocks will be carried out at UMK with different lattice trap depths and for different partial pressures (10^{-7} Torr and below) of different absorbers commonly present in ultra-high vacuum environments due to outgassing, such as He, H_2, N_2, CO_2 and CO. NPL and PTB will provide parameters of their existing systems to UMK, which will evaluate the atom losses, broadening, decoherence and frequency shifts of the clock transition, for each of the three clock systems.	**UMK**, NPL, PTB
A2.2.2	PTB will investigate the loss rates of Sr atoms by lattice photon scattering. Guidelines for the maximum trap depth that allows a coherence time of 1 s will be developed by PTB. UMK will provide advice, with input from A2.2.1, to distinguish atom loss due to photon scattering from the influence of collisions.	**PTB**, UMK
A2.2.3	NPL will design and construct an in-vacuum optical cavity to form a lattice trap with low parametric heating rate, compatible with the other limiting effects on coherence (photon scattering and background gas collisions). The properties of the cavity must be stable over several months, and not degrade significantly in vacuum. PTB will provide advice from A2.2.2 on acceptable lattice depths and UMK will use their theoretical and experimental results from A2.2.1 to assess the decoherence rate due to background collisions. NPL will then carry out spectroscopy measurements to characterise the heating rate and demonstrate laser limited coherence.	**NPL**, PTB, UMK

A2.2.4	Using input from A2.1.1 to A2.2.3, UMK with NPL and PTB will write a report summarising the results on background collisions, photon scattering and parametric heating rates and the ensuing influences on the resonance lineshape. Input will be provided to VTT for the specifications document being compiled as part of deliverable D9.	**UMK**, NPL, PTB
A2.2.5	Once the report from A2.2.4 has been agreed by the consortium UMK on behalf of NPL and PTB will send the coordinator D4 “Report summarising the results on collisions, photon scattering and parametric heating in optical lattice traps (targeting coherence times > 1 s in neutral atom optical clocks)”. The coordinator will then submit deliverable D4 to EURAMET.	**UMK**, NPL, PTB

C3 WP3: Evaluation of systematic uncertainties

The aim of this work package is to reduce systematic uncertainties through improved understanding and control of dominant frequency shifts. Clock accuracies of 1 x 10^{-18} are targeted through control of blackbody radiation (BBR) shifts from the atoms’ thermal environment, light shifts from the optical lattice, and collisions within lattices. The two tasks in this work package will carry out detailed studies of these shifts and will provide designs, guidelines and measurements useful for future optical clocks. Following the successful characterisation of BBR and light shifts for single ion clocks in the EMRP project SIB04, this work package will be more focussed on the neutral atom clock systems.

Task 3.1 will focus on BBR shifts, which are a leading term in the uncertainty budget for many optical clock systems. Contributions to the BBR shift uncertainty arise from both the uncertainty in the atomic response to the radiation (differential polarisability coefficient) and uncertainty in the thermal field at the position of the atoms. Highly precise measurements have made the contribution from uncertainties in polarisabilities [1, 12, 30, 34] very small and it therefore remains to reduce temperature uncertainties. An alternative approach to reducing the shift and the uncertainty is to interrogate the atoms inside a cryogenically cooled enclosure which may also open the pathway to the 10^{-19} uncertainty range [29].

Recent studies have demonstrated the feasibility of evaluating BBR shifts with uncertainty at the 10^{-18} level in neutral atom systems for both room temperature [2, 5] and cryogenic [44] environments. However, in the cryogenic environment, atoms were transported from a loading region to a science region for interrogation and this could limit the duty cycle, and hence stability, of the clock. The project plans to overcome this limitation by loading atoms directly into the science region. For the room temperature system, the project plan to make the characterisation of the thermal environment more practical. For neutral atom systems this will involve careful design of the vacuum chamber to make it as close to a blackbody as possible and then sensors can be placed around the chamber to determine the temperature. For single ion clock systems, there is an additional problem: the temperature sensors can be perturbed by the high rf voltages used to trap the ion. Whilst the EMRP project SIB04 demonstrated that it is possible to use a combination of thermal imaging and modelling to characterise the temperature environment, a more direct approach will be pursued here that can determine the thermal field at the position of the ion in real time during clock operation.

Other important terms in the uncertainty budget of optical lattice clocks are (higher order) light and collision induced shifts; these will be studied in Task 3.2. Theoretical proposals have been made for possible strategies for Sr, Yb, and Hg clocks to achieve lattice-induced systematic uncertainty below 1 x 10^{-18} [22] and these will now be investigated experimentally. Collisional shift cancellation has already been demonstrated (outside of Europe) below 1x10^{-18} for Sr and at the 5x10^{-18} level for Yb [27, 31] and the project will now target achieving 1 x 10^{-18} uncertainties in European clocks for both Sr and Yb systems.

C3.a <u>Task 3.1: Understanding and controlling BBR shifts</u>

The aim of this task is to reduce the uncertainty from BBR shifts in both neutral atom and single ion optical clocks to the level of 1 x 10^{-18}. For ^{87}Sr, studied at LNE, NPL, OBSPARIS, PTB and UMK, the fractional frequency uncertainty from the BBR shift at room temperature is 8 x 10^{-17} for every kelvin of temperature uncertainty [30]. For ^{171}Yb, studied at INRIM, the corresponding figure is 3 x 10^{-17} [1], and for $^{88}Sr^+$, studied at VTT and NPL, the figure is 7x10^{-18} for every kelvin of temperature uncertainty [12]. When working at room temperature, it is thus necessary to determine the temperature seen by the atoms to within about 10 mK for ^{87}Sr, 30 mK for ^{171}Yb and 200 mK for $^{88}Sr^+$ to ensure uncertainties at the 1 x 10^{-18} level. Cryogenic environments at around 77 K, however, greatly reduce the shift and thus lead to relaxed requirements of about 1 K temperature uncertainty for the ^{87}Sr system.

In this task, for the single ion optical clocks, the project will study the feasibility of real-time thermometry using optical sensors, which are immune to rf interference from the ion’s trapping field. The project will test different sensors and investigate ways to apply them to the trap structures to reach temperature uncertainties below

200 mK. For neutral atoms, two different vacuum chambers with BBR control will be realised: one for operating with Yb at room temperature, and one for operating with Sr in a cryogenic environment. The thermal properties and emissivity of various materials used in the vacuum chambers will be studied, including metals, viewports, optical coatings and black thermal coatings. By designing the room temperature system with better thermal homogeneity, temperature uncertainties below 30 mK will be more easily achieved. Numerical simulations will be run to predict the best strategies to be used at both room and cryogenic temperatures. By comparing the complementary approaches of better BBR control at room temperature or direct BBR reduction in cryogenic environments, the project will consolidate the understanding of BBR shifts. The project will find optimised strategies for operating lattice clocks with strongly reduced BBR uncertainty without compromising the clock stability, and for operating ion clocks with real time thermometry of the trap.

Activity number	Activity description	Partners (Lead in bold)
A3.1.1	NPL and VTT will study the feasibility of real-time thermometry of ion traps. NPL will investigate fibre-based temperature measurement using either commercial GaAs bandgap-based or fluorescence detection technology with an existing test trap. VTT will investigate at least two temperature sensor types (for example, fibre Bragg grating, fibre-coupled bandgap sensor, band-gap sensor with free-space readout) using a test trap of (at least) one of their trap designs. The temperature of the sensors will first be compared to thermistors or platinum resistance thermometers (PRTs) in air, in the absence of an rf field. Then the self-heating of the sensors in an rf field will be investigated.	**VTT**, NPL
A3.1.2	NPL and VTT will carry out a comparison between the alternative temperature sensor techniques developed in A3.1.1. Different ways of applying these to the trap structures (for example, application to insulators vs conductors, surface mounting vs embedding, consideration of local RF field strength) will be studied in order to assess the feasibility of integrating temperature sensors into the next generation of operational ion traps.	**VTT,** NPL
A3.1.3	VTT, with support from CMI, will measure the temperature distribution of a new VTT trap (developed within EMRP SIB55) using thermal imaging. CMI using also thermal imaging will measure the temperature distribution of a new CMI trap (developed in A2.1.1). CMI will carry out the corresponding FEM simulations for both traps. The results will be compared to the traps studied in EMRP SIB04 and the most critical positions to place sensors in A3.1.1 will be determined. CMI will optimise the design of the CMI trap so that the BBR temperature rise seen by the ion is lower than 0.5 K. The blackbody radiation shifts for ^{171}Yb+ in the CMI trap and ^{88}Sr+ in the VTT trap will be evaluated.	**VTT**, CMI
A3.1.4	UMK will investigate the thermal properties of materials which are used in neutral atom vacuum systems and the transmission of the viewports. UMK will measure the emissivity of various materials such as fortal, titanium and stainless steel, with different surface quality, by direct measurement of the clock frequency on the temperature of a sample, using a second clock as a stable reference. Ray tracing simulations carried out at UMK will be compared to experimental data. The results will be used to inform the design in A3.1.6 and A3.1.7 of new vacuum chambers with very well controlled blackbody radiation emission.	**UMK**
A3.1.5	INRIM, using their initial system design for A3.1.7, and PTB using their initial system design for A3.1.6 will provide UMK their parameters: temperature of vacuum chamber parts, ambient temperature in laboratory, geometry of vacuum viewports etc. UMK will use these parameters with the materials knowledge acquired in A3.1.4 to run numerical simulations of the temperature of radiation seen by the atoms in each of the INRIM and PTB systems. The temperature of crucial points of the vacuum systems will be monitored during the experiment cycle by calibrated thermistors. A finite element method and a parallel computing or a look-up table will allow the BBR frequency shift to be computed in real time.	**UMK,** INRIM PTB
A3.1.6	From A3.1.4 and A3.1.5, UMK will provide PTB with advice on materials and results from numerical modelling. PTB will use this information to develop a cryogenic clock without atom translation, resulting in a reduction of the BBR shift by a factor of 100 without reduction of clock duty cycle.	**PTB**, UMK
A3.1.7	From A3.1.4 and A3.1.5, UMK will provide INRIM with advice on materials and results from numerical modelling. INRIM will design and build a new vacuum chamber for an Yb optical lattice clock to be operated at room temperature. The target temperature homogeneity is 30 mK, allowing a BBR uncertainty of about 1×10^{-18}. INRIM will also investigate a possibility to convert the chamber for use at cryogenic temperatures, with advice from PTB following their experience in A3.1.6.	**INRIM**, PTB, UMK

A3.1.8	Using input from A3.1.1-3.1.3, a report will be written, led by NPL with contribution from VTT and CMI, on documented guidelines for the control and evaluation of the BBR shifts and their uncertainty in ion clocks at the 10^{-18} level. This report will be sent to VTT and used in the specifications document to form part of deliverable D9.	**NPL,** CMI,VTT
A3.1.9	Using input from A3.1.4-3.1.7, a report will be written, led by INRIM with contribution from PTB and UMK, on documented guidelines for the control and evaluation of the BBR shifts and their uncertainty in optical lattice clocks at the 10^{-18} level. This report will be sent to VTT and used in the specifications document to form part of deliverable D9.	**INRIM,** PTB, UMK
A3.1.10	INRIM on behalf of CMI, NPL, PTB, UMK and VTT will write a report summarising A3.1.8 and A3.1.9	**INRIM**, CMI, NPL, PTB, UMK, VTT
A3.1.11	Once the report from A3.1.10 has been agreed by the consortium INRIM on behalf of CMI, NPL, PTB, UMK and VTT will send the coordinator D6 “Summary report on improved control and measurement of the thermal environment in single ion and neutral atom optical clocks, leading to 10^{-18} uncertainties in blackbody radiation shifts for clocks operating at both cryogenic and room temperatures”. The coordinator will then submit deliverable D6 to EURAMET.	**INRIM**, CMI, NPL, PTB, UMK, VTT

C3.b Task 3.2: Understanding and controlling light and collisional shifts in optical lattice clocks

The aim of this task is to achieve a frequency shift uncertainty at the level of 1 x 10^{-18} by investigation and control of higher-order lattice light shifts and collisions in 1D optical lattice potentials. Lattice light shifts are the biggest contributions to the uncertainty after BBR shifts in Sr and Yb clocks. They can be investigated directly by observing the frequency shift in different depths of the lattice potential, created by different intensity lasers. Large trap depths are required to reveal the frequency shifts, and can be enabled by enhancement cavities and high power laser sources. Theoretical proposals have been made for possible strategies for Sr and Yb clocks to achieve lattice-induced systematic uncertainty below 1 x 10^{-18} and they will be investigated.

The contribution from collisional shifts between atoms trapped within the lattice potential will also be examined, both experimentally and theoretically, to establish shift uncertainties at the 10^{-18} level. The experimental studies will involve photo-association measurements to establish the molecular energy levels and collisional cross-sections of the atoms. The theoretical studies will take into account the experimentally determined parameters, and will also include models that allow the collisional shifts to be predicted in the other neutral atom optical clocks.

Activity number	Activity description	Partners (Lead in bold)
A3.2.1	INRIM, LNE and OBSPARIS will together determine the best techniques to study higher order shifts in optical lattice clocks coming from high lattice depths and the ellipticity of the light. Two experimental setups will be designed (one in LNE-OBSPARIS and one in INRIM), based either on enhancement cavities or high power laser sources. The experiments will be designed to provide direct measurement of the hyperpolarisability at high lattice power and also the dependence on the lattice ellipticity, targeting a frequency uncertainty from hyperpolarisability at the 10^{-18} level. The experimental design will be used in A3.2.2 and A3.2.3.	**LNE,** INRIM, OBSPARIS
A3.2.2	LNE and OBSPARIS will implement the design of A3.2.1 to study the hyperpolarisability and multipolar (E2/M1) effects in a ^{87}Sr optical lattice clock. In particular LNE and OBSPARIS will study the hyperpolarisability with a large lever arm from high lattice depth, explore its dependence on the polarisation of the trapping light, and check its consistency when using different laser sources (semi-conductor or titanium-sapphire laser). INRIM will review the results and compare with those of the Yb study in A3.2.3. UMK will compare the results with the photo-association measurements of A3.2.4.	**LNE,** INRIM, OBSPARIS, UMK
A3.2.3	INRIM will implement the design of A3.2.1 in its lattice clock to investigate hyperpolarisability and multipolar (E2/M1) effects at high lattice depth in ^{171}Yb. LNE and OBSPARIS will review the results and compare with the data from A3.2.2. Moreover INRIM will also investigate two-photon resonances in ^{171}Yb near the magic wavelength, including the dependence on different lattice polarisations, to provide data for theoretical models. Results will be prepared for submission to a peer-review journal.	**INRIM**, LNE, OBSPARIS

A3.2.4	UMK will perform photo-association measurements to evaluate the collisional shift in Sr optical lattice clocks. Optical transitions in various strontium isotopes will be studied in one of the UMK clock systems, while the second optical lattice clock operating in parallel will provide a stable frequency reference. UMK will measure the energies of molecular states close to the $^1S_0$ – $^3P_0$ clock line asymptote, either directly, or by multi-colour photo-association with allowed atomic transitions. -	**UMK**
A3.2.5	UMK will perform theoretical studies of collisional shifts in Sr and Yb lattices, using the atomic parameters determined in A3.2.4. LNE, OBSPARIS and INRIM will provide UMK with experimental details relevant to their respective optical clock systems. The theoretical evaluation will then be used to constrain the collisional shift in the low 10^{-18} range for the Sr systems at UMK, LNE and OBSPARIS, and for the Yb system at INRIM. Results will be prepared for submission to a peer-review journal.	**UMK**, INRIM, LNE, OBSPARIS
A3.2.6	Using input from A3.2.1-3.2.5, an uncertainty report will be written, led by LNE with contributions from INRIM, OBSPARIS and UMK, on documented guidelines for the control and evaluation of the light and collisional shifts and their uncertainty in optical lattice clocks. This report will be sent to VTT and used in the specifications document (A5.3.1) as part of deliverable D9.	**LNE,** INRIM, OBSPARIS, UMK
A3.2.7	Once the uncertainty report from A3.2.6 has been agreed by the consortium LNE, on behalf of INRIM, OBSPARIS and UMK will send the coordinator D5 “Uncertainty report on controlling and evaluating lattice light shifts and collisional shifts at the 10^{-18} level in neutral atom optical lattice clocks”. The coordinator will then submit deliverable D5 to EURAMET.	**LNE,** INRIM, OBSPARIS, UMK

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C4 WP4: Advanced clock operation

WP4 aims to develop and apply interrogation methods that boost clock accuracy and stability, and, together with the advancements made throughout the technical work packages, firmly establish the operation of optical clocks at the 10^{-18} level by direct comparison of co-located clock systems.

Presently, optical clocks generally use a simple implementation of Rabi spectroscopy, with a single extended coherent excitation of the clock transition optimised to remain robust to perturbations of the clock laser frequency. Many more sophisticated interrogation schemes have been proposed, but their potential has yet to be explored in operational optical clocks.

For systems with extremely narrow clock transitions, engineering a sufficient excitation within the coherence time of the interrogation necessitates high probe intensities or additional fields that result in problematic probe-related shifts, e.g. in Yb^+ (E3) and neutral atom bosons Sr/Yb/Hg/Mg (E1-M1). Despite this, these systems remain attractive and techniques have been proposed that go some way towards tackling these shifts. The most promising is an engineered pulse sequence known as hyper-Ramsey [48] which recently achieved a probe-induced Stark shift suppression on the order of 10^4 in a Yb^+ E3 system at PTB [20] and with further development will be able to control probe shifts below 1 x 10^{-18}. The technique offers to minimise sensitivity to all probe-synchronous perturbations and therefore can be applied to cancel the Zeeman shift that arises in magnetically induced spectroscopy of bosonic lattice clock systems, clearing a path for future bosonic clock development.

Using conventional interrogation techniques, a 10^{-17} laser instability range (WP1) will enable optical clock instabilities at an impressive 1 x $10^{-16}/\sqrt{\tau}$ level. By exploring interrogation methods that deal better with local oscillator noise, clock instability can be lowered even further. In particular, optical lattice clocks can benefit greatly from a reduced dead-time interrogation, which in the limit of uninterrupted operation would eliminate noise due to stroboscopic sampling effects of the local oscillator noise (Dick effect). The Dick effect currently restricts the instability of optical lattice clocks to ~10 times the QPN limit. Its removal would immediately yield an unprecedented optical clock instability ~1 x $10^{-17}/\sqrt{\tau}$ and enable future quantum enhancements that exploit many-body collective effects (such as spin-squeezed states). To reach this regime two identical lattice clocks with 50 % duty cycle can be combined by an alternate interrogation of each clock.

To verify the performance of optical clocks at a level of 10^{-18} the project must go beyond estimated systematic uncertainties and make direct measurements of the clock output. This requires two clocks to be built at this level and then compared.

The activity is separated into two tasks: The first addresses probe pulse sequences and interrogation schemes that suppress probe related shifts and enhance clock stability. The second implements and verifies the achieved optical clock performance.

C4.a Task 4.1: Interrogation methods for reduced clock inaccuracy and instability

The aim of this task is to develop interrogation methods and operation protocols that reduce both clock inaccuracy and instability. Probe sequences based on hyper-Ramsey spectroscopy will be implemented to eliminate problematic probe related Stark shifts present in systems with extremely forbidden clock transitions (e.g. Yb^+ E3, and ^{88}Sr) to a level below 1×10^{-18}. The technique will also be applied to address the quadratic Zeeman shift present in magnetically induced spectroscopy of bosonic optical lattice clock species. In a separate scheme, by interleaving interrogations of the reference transition with interrogations of other transitions more sensitive to perturbing effects, it is possible to leverage the measurement of environmental shifts to ensure prolonged clock operation with low inaccuracy. This will be explored, for example, using Yb^+ E2 transition to determine magnetic field and electric quadrupole shifts for Yb^+ E3.

With particular relevance to ion clocks, software-only improvements to clock instability will be studied in a theoretical treatment of Rabi and Ramsey interrogation sequences exploiting the presence of non-Markovian clock laser frequency noise. To circumvent the Dick effect in optical lattice clocks, a dead-time-free interleaved clock array will be pursued which combines two Sr lattice clocks, each with duty cycle approaching 50 %, and the achieved instability for Rabi and Ramsey interrogations compared.

Activity number	Activity description	Partners (Lead in bold)
A4.1.1	NPL and PTB will each develop and demonstrate complementary interrogation methods that minimise the influence of probe related Stark shifts to < 1×10^{-18} in clock systems with extremely forbidden clock transitions (here Yb^+ and ^{88}Sr). Results from NPL and PTB will be compared and an optimised method established. NPL will investigate extension of the method to probe related Zeeman shifts resulting from magnetically induced spectroscopy in bosonic optical lattice clocks. Results will be prepared for submission to peer-review journal.	**NPL**, PTB
A4.1.2	LUH will provide a theoretical analysis of optimal interrogation pulse parameters in the presence of non-Markovian clock laser frequency noise. A basic analytical and numerical toolbox will be developed by LUH along with guidelines for optimised Rabi and Ramsey interrogation schemes. Results will be prepared for submission to peer-review-journal.	**LUH**
A4.1.3	OBSPARIS will investigate the stability of its optical lattice clocks in the limit approaching zero dead-time interrogation by realising experimentally the interleaved interrogation of two Sr clock systems. In this limit, engineered Ramsey pulse sequences that minimise the aliasing of clock laser frequency fluctuations will be implemented to provide a lower clock instability through better knowledge of the required frequency corrections. Results will be prepared for submission to peer-review journal.	**OBSPARIS**
A4.1.4	PTB and NPL will each develop and demonstrate operational procedures and a supporting experimental control software to provide real-time monitoring and correction of systematic frequency shifts in trapped ion optical clocks. Interleaved interrogation of sensitive electronic transitions or operating modes will be used to achieve this (e.g. using Yb^+ E2 transition to determine magnetic field and electric quadrupole shifts in Yb^+ E3). INRIM and NPL will investigate similar schemes to provide real time monitoring and correction for application to optical lattice clocks.	**PTB**, INRIM, NPL
A4.1.5	NPL, INRIM, LUH, OBSPARIS and PTB based on A4.1.1 to A4.1.4 will write guidelines describing the interrogation techniques and operational best practices for optical clocks targeting 1×10^{-18} inaccuracy and instability. NPL will send this document to VTT for inclusion in the specifications document as part of deliverable D9.	**NPL**, INRIM, LUH, OBSPARIS, PTB
A4.1.6	Once the guidelines from A4.1.5 have been agreed by the consortium NPL, on behalf of INRIM, LUH, OBSPARIS and PTB will submit deliverable D7 to EURAMET send the coordinator D7 “Guidelines on optimised interrogation methods that minimise optical clock instability and inaccuracy”. The coordinator will then submit deliverable D7 to EURAMET.	**NPL**, INRIM, LUH, OBSPARIS, PTB

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C4.b Task 4.2: Performance validation at 10^{-18} level

The aim of this task is to advance towards the firm establishment of optical clock performance at the 10^{-18} level by direct comparison of independently evaluated co-located clocks. Each clock will be engineered to have a total estimated systematic frequency uncertainty targeting 1×10^{-18} and an instability compatible with reaching this uncertainty in a realistic averaging time. The comparison will draw on work developed throughout WP1 to WP4 and will go beyond estimated performance to validate the operation of optical clocks at the 10^{-18} level.

Same-species local comparisons will provide the first stage validation of clock performance beyond estimated uncertainty but may hide common frequency biases. To further scrutinise clock performance there is the opportunity within this consortium to compare local optical frequency ratios between fully independent systems Sr/Yb^+(E3) measured at NPL and PTB. The results of these frequency ratios can also contribute to improved values of the corresponding secondary representations of the SI second. This builds upon the framework established in EMRP project SIB55, in which frequency ratio measurements can be gathered into a matrix, from which a least squares analysis can obtain optimised values for the frequency of each standard.

Activity number	Activity description	Partners (Lead in bold)
A4.2.1	PTB (Yb^+, Sr), NPL (Sr^+, Yb^+, Sr), OBSPARIS (Sr) and UMK (Sr) will each carry out a direct comparison of independent clocks in their institutions to demonstrate the attainable instability, making use of the extended coherence times achieved in WP1 and WP2.	**PTB**, NPL, OBSPARIS, UMK
A4.2.2	NPL, INRIM, OBSPARIS and PTB will each estimate the systematic uncertainty of one or more of their optical clock systems, targeting 1 x 10^{-18} for at least one of the clock species Yb^+, Sr^+, Yb and Sr.	**NPL**, INRIM OBSPARIS, PTB
A4.2.3	PTB and NPL will measure the frequency ratio of two independent, co-located optical clocks, evaluated in A4.2.2. The target is for the ratios to agree to within the uncertainty expected from the combined uncertainties of the individual clocks.	**PTB**, NPL
A4.2.4	NPL together with INRIM, OBSPARIS, PTB and UMK will write up the results from the experiments carried out in A4.2.1 - A4.2.3 to validate the performance level of the optical clocks.	**NPL**, INRIM, OBSPARIS, PTB, UMK
A4.2.5	Once the validation report from A4.2.4 has been agreed by the consortium NPL on behalf of INRIM, OBSPARIS, PTB and UMK will send the coordinator D8 “Report on validation of clock performance through direct comparison of two independent clocks, targeting uncertainty at the 10^{-18} level”. The coordinator will then submit deliverable D8 to EURAMET.	**NPL**, INRIM, OBSPARIS, PTB, UMK

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C5 WP5: Creating impact

The aim of this work package is to ensure that the knowledge generated within this project is disseminated efficiently to a wide range of stakeholders and end users as well as to gain feedback from this community. The project anticipates that the most immediate uptake of the knowledge will be by smaller NMIs and other accredited laboratories in the measurement supply chain wanting to begin building optical clocks. Since the clocks are large and complicated devices, only the larger NMIs so far have had the resources to implement the necessary research programme in this area. Key aspects of this knowledge will be transferred through a comprehensive specifications document (A5.3.1), which will be an invaluable guide for those designing and building new systems. When the SI second is redefined in terms of an optical frequency, it is likely that the demand for optical clocks will rise even further, as many institutions will want to have a local realisation of the new definition.

C5.a Task 5.1 Knowledge transfer

Activity number	Activity description	Partners (Lead in bold)
A5.1.1	**Project webpage** NPL will set up, host and maintain a project website. The project website will be launched within the first 2 months and will be updated at least every 3 months. The public level of the site will present the project and make the reports, scientific papers, and theses produced in the project available. A copy of the specifications document (A5.3.1) will also be placed here. The level restricted to partners will be used to exchange data and technical information in order to allow efficient collaboration between partners.	**NPL**, all partners

A5.1.2	**Peer reviewed publications** At least 14 scientific papers will be submitted to peer-reviewed journals; 7 of these have been identified in activities within the technical work packages. Target journals include Science, Nature, Physical Review Letters, Physical Review A, New Journal of Physics, Optics Letters, Optics Express, Metrologia, Measurement Science and Technology, Review for Scientific Instruments. The authors of the peer reviewed papers will clearly acknowledge the financial support provided through EMPIR as required by EURAMET. At least 3 of these papers will be of collaborative nature and involve authors from at least two partners.	**VTT**, all partners
A5.1.3	**Conference contributions** At least 6 presentations will be given at leading international conferences such as • EFTF (annual conference, to be held in Besançon in July 2017 and in Turin in 2018) • IEEE-FCS (annual conference, will be held jointly with EFTF in 2017) • ICAP (biennial conference, to be held in Seoul in July 2016) • CPEM (biennial conference, to be held in Ottawa in July 2016) • CLEO (annual conference, to be held in San Jose in June 2016) • ICOLS (biennial conference, to be held in Bordeaux in July 2017) • ECTI (to be held in Arosa in August-September 2016)	**VTT**, all partners
A5.1.4	**Stakeholder List** A list of interested and relevant stakeholders and end users will be compiled by NPL with input from all other partners. The initial list will be agreed at the kick-off meeting and it will be reviewed for completeness at each subsequent project meeting. The list will be used to enable the consortium to identify and prioritise who to disseminate project results to.	**NPL**, all partners
A5.1.5	**Liaison with standardisation bodies** Information on progress and results of the project will be disseminated to a range of standards and technical committees (see table in Section B2.c). Annual committee meetings such as EURAMET TC-TF provide a good forum to publicise the project's research progress and engage with smaller NMIs to understand their needs. The partners representing the consortium on each committee will ask the chairperson to include a point in the agenda to briefly present the outputs of the project that are relevant to that committee's work and comments and feedback will be sought from the other committee members. Where appropriate a written report will be submitted for consideration by the committee. The following input will be given to the targeted standardisation bodies: CCTF: reports on the scientific progress and frequency measurements will be submitted to this consultative committee CCL-CCTF WGFS: update on the progress in accuracy of the different standards CCTF WGPSFS: update on frequency ratio measurements EURAMET TC-TF: annual presentation of the project results ACES Investigator Working Group: update on the performance and availability of the optical clocks Working group of German UTC laboratories: participation in technical discussions on the realisation of frequency references and time scales and applications in geodesy, navigation, astronomy and telecommunication	**NPL**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C5.b Task 5.2 Training

Activity number	Activity description	Partners (Lead in bold)
A5.2.1	**Summer School** INRIM, with assistance from all other partners, will organise a one-week summer school on optical clocks. This will be aimed at a level suitable for PhD students, and the topics will include an introductory part as well as all aspects of the subject addressed within the project. The target number of participants will be 30–50. The summer school will be advertised on the project website, through the partners' existing networks and in conferences related to the field. The lecturers will be selected mainly from among the partners, but several leading experts from outside Europe will also be invited. The school could for example be arranged in conjunction with EFTF 2018 in Turin.	**INRIM**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C5.c Task 5.3 Uptake and exploitation

Activity number	Activity description	Partners (Lead in bold)
A5.3.1	**Specifications document** A specifications document describing the requirements for a 1×10^{-18} clock will be prepared. Its purpose is to transfer knowledge to end users and those in the measurement supply chain to build new or upgraded systems that address their own particular timing and frequency needs. It may be that details are required for building complete optical clocks, or it may simply be individual subsystems that are needed, such as lasers, cavities, traps etc. Within each technical work package, chapters covering each of these subsystems will be prepared for the specifications document. Here, these will be collated into the final document and submitted by the coordinator to EURAMET as part of deliverable D9. The document will also be sent out to stakeholders and made more widely available through the project website (A5.1.1) and uploaded to the arXiv server, providing high visibility through web searches.	**VTT**, all partners
A5.3.2	**Exploitation plan** In the technical work packages WP1, WP2 and WP3 research will be carried out that leads to optimised designs for laser stabilisation, ion traps enabling long coherence times and vacuum chambers with good temperature homogeneity. These designs will be evaluated for commercial exploitation beyond the application in primary frequency standards and will be assessed for the potential to license, patent or otherwise protect the IP that has been created. Such an assessment will be carried out at each of the project meetings and an exploitation plan will be prepared.	**NPL**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

All IP and potential licencing/exploitation will be handled in accordance with the Grant Agreement and the Consortium Agreement.

C6 WP6: Management and coordination

C6.a Task 6.1: Project management

Activity number	Activity description	Partners (Lead in bold)
A6.1.1	**Project management** The project will be managed by the coordinator from NPL, who will be supported by a team consisting of at least one representative from each institute, including the work package leaders. This project management team will attend all progress meetings and will take it in turns to organise and host project meetings at their local institute.	**NPL**, all partners
A6.1.2	**Interaction between the WP leaders and the coordinator** The work package leaders will report on the on-going progress to the coordinator by email, telephone or Skype conferences.	**NPL**, all partners

A6.1.3	**Risk management** The coordinator, with support from the partners, will manage the project's risks to ensure timely and effective delivery of the scientific and technical objectives and deliverables.	**NPL**, all partners
A6.1.4	**Ethics** The consortium will ensure that any ethics issues identified (see Section D.3) are addressed.	**NPL**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C6.b Task 6.2: Project meetings

Activity number	Activity description	Partners (Lead in bold)
A6.2.1	**Kick-off meeting** The kick-off meeting involving all of the partners will be held approximately one month after the start of the project, at NPL.	**NPL**, all partners
A6.2.2	**Project meetings** In addition to the kick-off meeting, there will be four more formal meetings held prior to reporting around M9 (January 2017), M18 (October 2017), M27 (July 2018) and M36 (April 2019). The meetings will be used to present progress-to-date, organise the next steps and discuss any issues arising. The locations of the meetings will be chosen to rotate around the partners' institutions, or else may be held as a satellite meeting attached to a conference or other meeting taking place.	**NPL**, all partners
A6.2.3	**Technical meetings** Technical meetings may additionally be held, most likely as Skype conferences, between the reporting periods, dependent on the need.	**NPL**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

C6.c Task 6.3: Project reporting

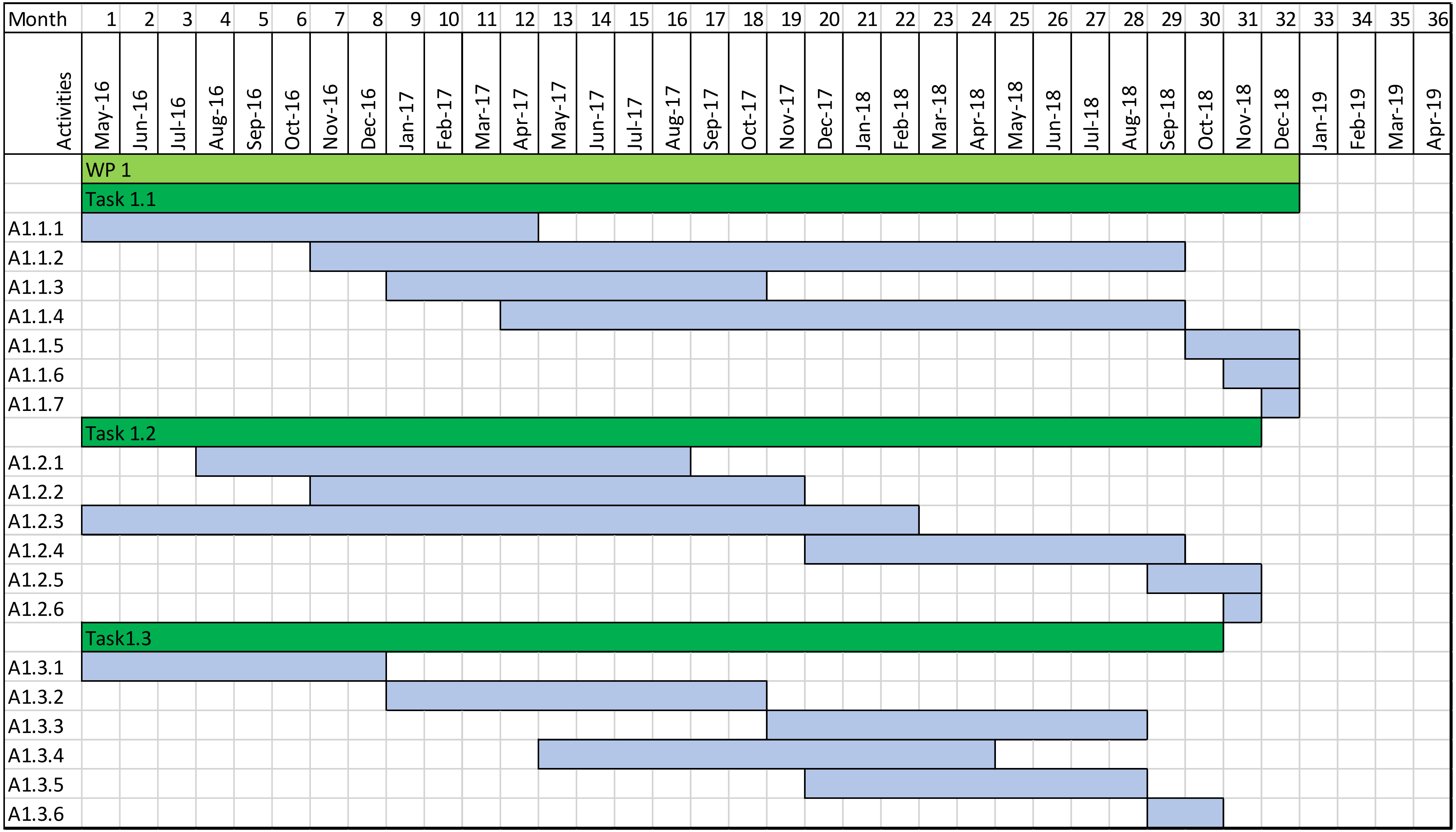
Activity number	Activity description	Partners (Lead in bold)
A6.3.1	**Publishable summary** One month after the signature of the grant agreement a publishable summary will be produced and submitted to EURAMET.	**NPL**, all partners
A6.3.2	**Progress reporting** Following Articles 17 and 20 of the grant agreement, information will be submitted to EURAMET, in accordance with the procedures issued by them to enable EURAMET to comply with its obligations to report on the programme to the European Commission. • Progress reports will be submitted at months M9 (January 2017 + 45 days), M27 (July 2018 + 45 days), M18 (October 2017 + 60 days), M36 (April 2019 + 60 days). • Impact/Output reports will be submitted at the same times. All partners will provide input to these reports and the coordinator will provide these and updated publishable summaries to EURAMET. A report on the assessment of the potential for dual use applications of the results and outcomes of the project and where applicable how dual use risks can be mitigated will be written and submitted to EURAMET M36 (April 2019 + 60 days) (see section D3).	**NPL**, all partners
A6.3.3	**Periodic reporting** Periodic Reports (including financial reports and questionnaires) will be delivered on M18 (October 2017 + 60 days) and M36 (April 2019 + 60 days) in accordance with Article 20 of the grant agreement. All partners will provide input to these reports and the coordinator will provide these to EURAMET.	**NPL**, all partners

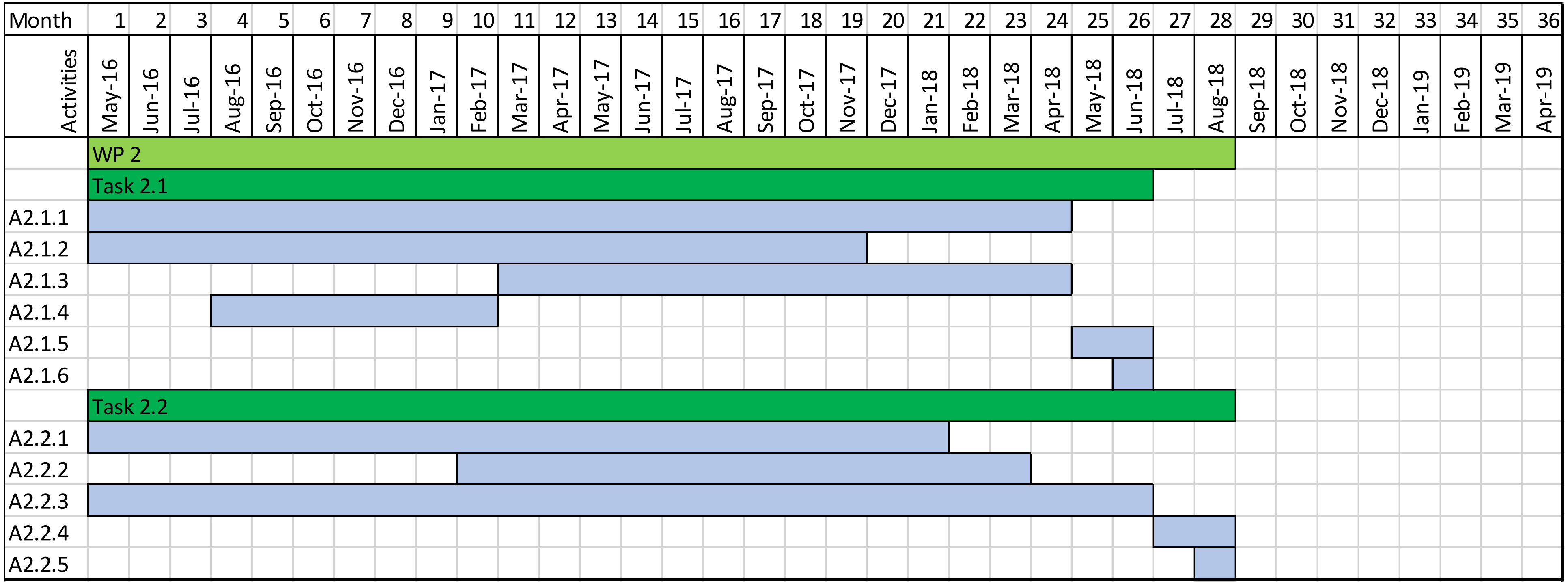
A6.3.4	**Final reporting** Final Reports will be delivered on M36 (April 2019 + 60 days) in accordance with Article 20 of the grant agreement. All partners will provide input to these reports and the coordinator will provide these to EURAMET.	**NPL**, all partners

The Linked Third Party CNRS will work with partner OBSPARIS on this task.

Formal reporting will be in line with EURAMET's requirements and will be submitted in accordance with the Reporting Guidelines.

C7 Gantt chart

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Activities
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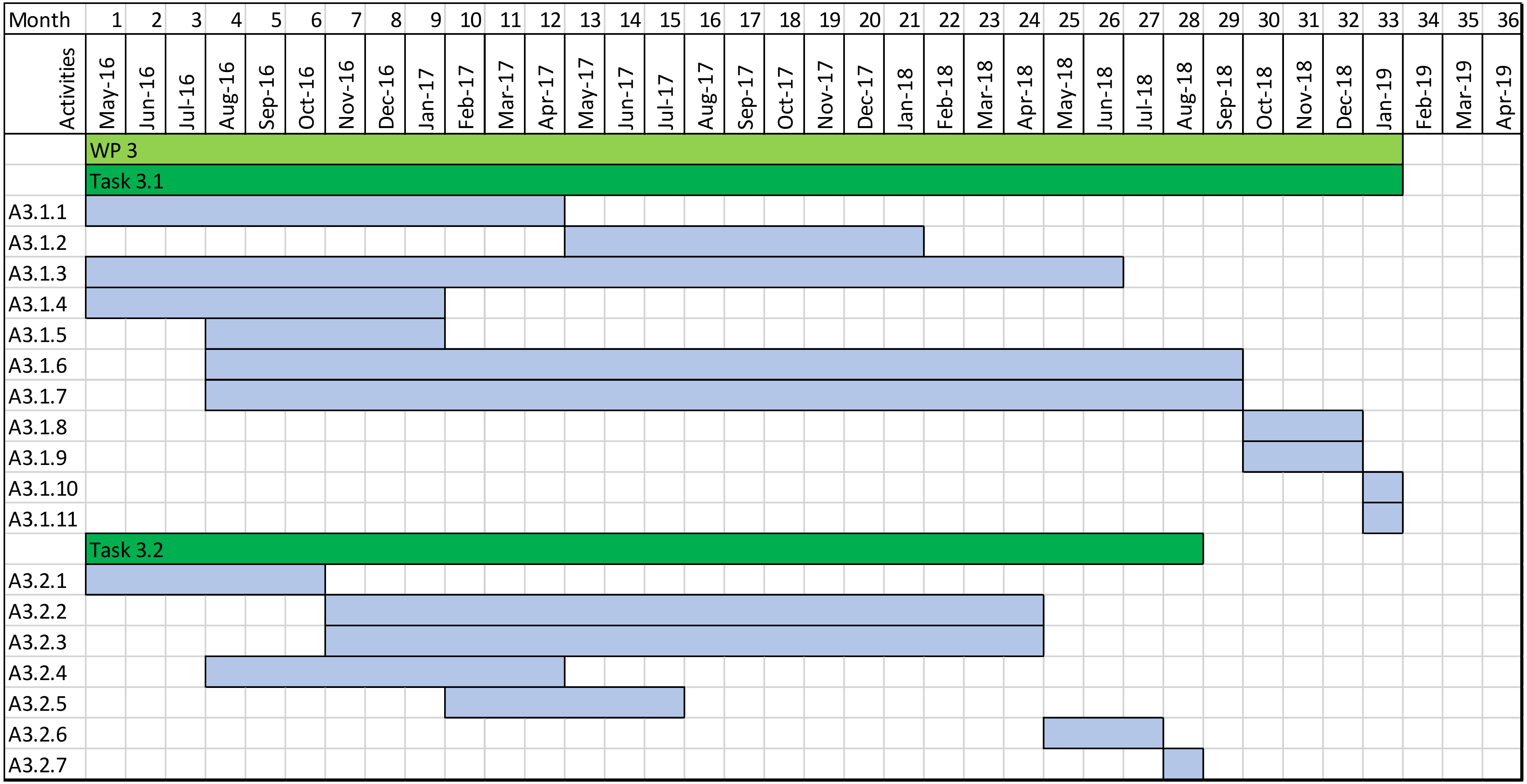
WP 2
Task 2.1
A2.1.1
A2.1.2
A2.1.3
A2.1.4
A2.1.5
A2.1.6
Task 2.2
A2.2.1
A2.2.2
A2.2.3
A2.2.4
A2.2.5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WP 3
Task 3.1
A3.1.1
A3.1.2
A3.1.3
A3.1.4
A3.1.5
A3.1.6
A3.1.7
A3.1.8
A3.1.9
A3.1.10
A3.1.11
Task 3.2
A3.2.1
A3.2.2
A3.2.3
A3.2.4
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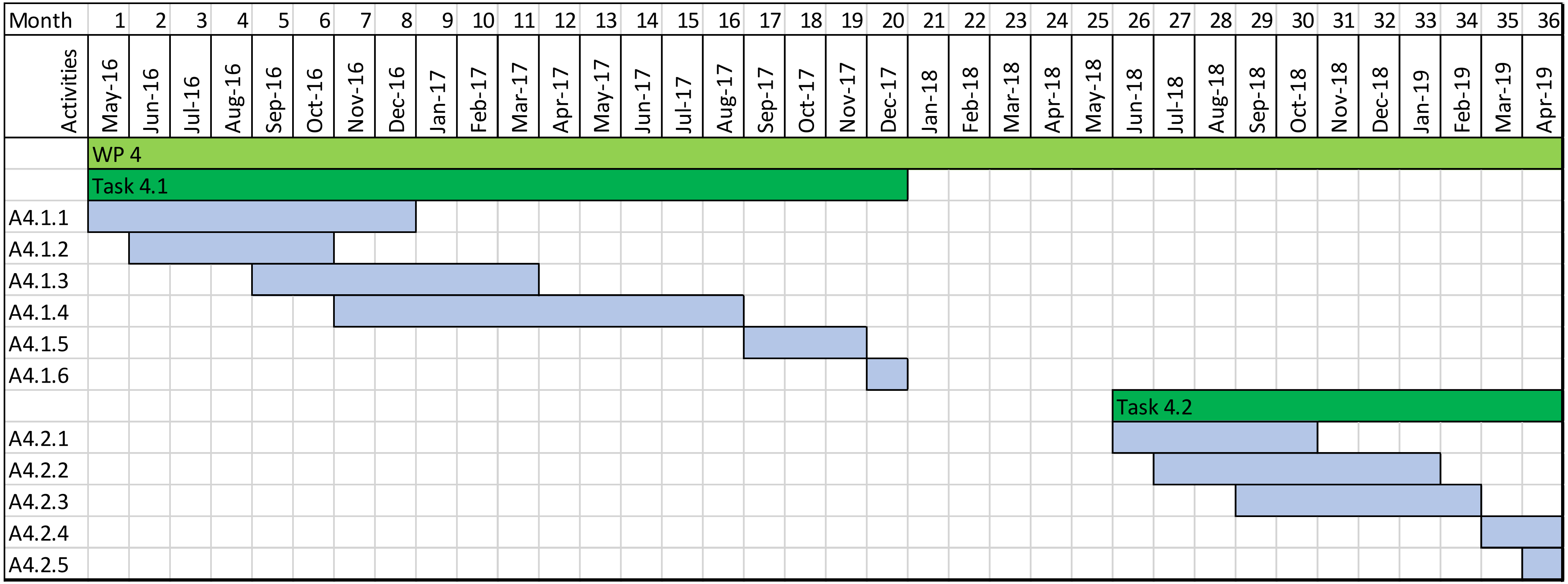
A3.2.6
A3.2.7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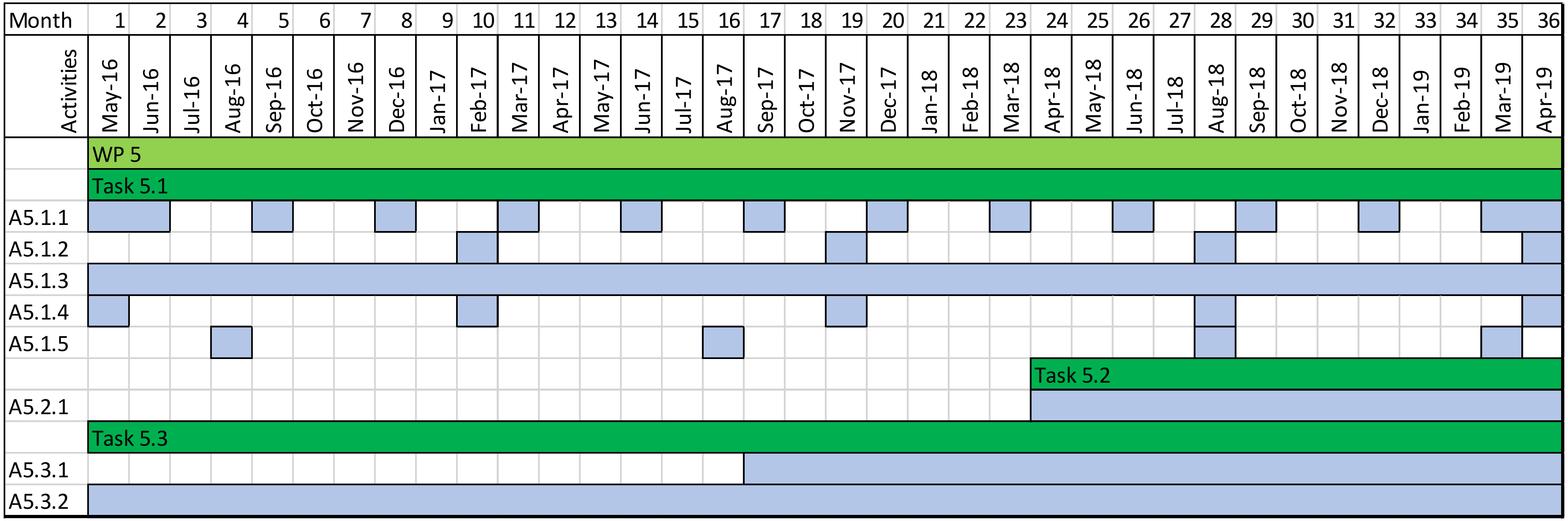
WP 4
Task 4.1
A4.1.1
A4.1.2
A4.1.3
A4.1.4
A4.1.5
A4.1.6
Task 4.2
A4.2.1
A4.2.2
A4.2.3
A4.2.4
A4.2.5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WP 5
Task 5.1
A5.1.1
A5.1.2
A5.1.3
A5.1.4
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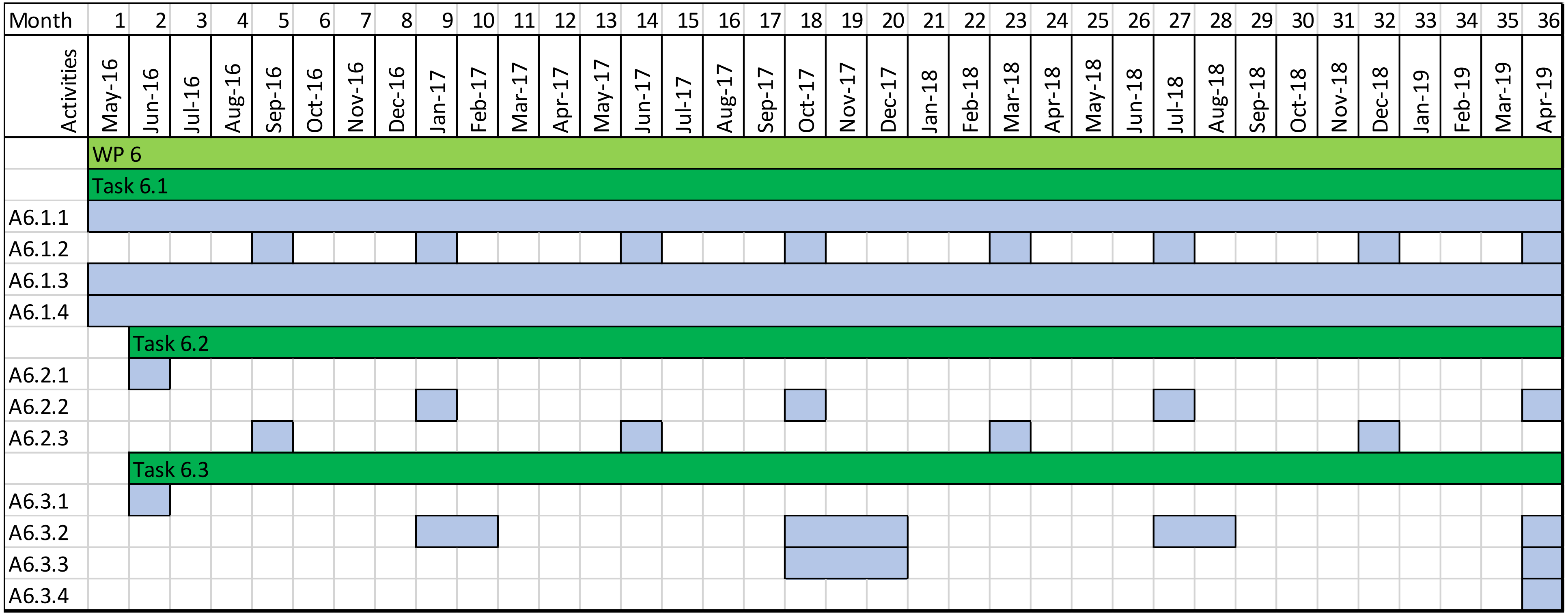
Task 5.2
A5.2.1
Task 5.3
A5.3.1
A5.3.2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WP 6
Task 6.1
A6.1.1
A6.1.2
A6.1.3
A6.1.4
Task 6.2
A6.2.1
A6.2.2
A6.2.3
Task 6.3
A6.3.1
A6.3.2
A6.3.3
A6.3.4

Section D: Risk and risk mitigation

D1 Scientific/technical risks

Risk (description)	**Likelihood and impact of occurrence**	**Mitigation** i.e. what the consortium will do to decrease the likelihood of the risk occurring	**Contingency** i.e. what the consortium will do if despite the mitigation the risk still occurs
A1.1.2/A1.3.4: Vibrations on the cryogenic cavity and the crystal of spectral hole burning cannot be sufficiently suppressed	Likelihood without mitigation: Medium Impact: limit to the stability of the laser locked to the cryogenic cavity/spectral holes. Likelihood after mitigation: Low	Independent studies of vibrations induced by different types of cryogenic environments will be carried out in A1.1.1.	Reduce interrogation time, employ correlated interrogation sequences to reduce influence of laser noise. In parallel, A1.1.4 will aim at sensing vibrations as close as possible to the frequency reference.
A1.1.4: Correlations are too weak or too complex to allow for significant improvement	Likelihood without mitigation: Medium Impact: Limits the predictability and real-time correction. Likelihood after mitigation: Low	Numerical modelling of full setup will provide good guidelines for efficient placement of sensors.	With the other cavities available within the consortium, and using atomic signals for prediction of the drift, good clock stability can still be reached.
A1.2.1: The multi-branch approach of the transfer of spectral purity by a frequency comb shows large uncorrelated noise	Likelihood without mitigation: Medium Impact: Limitation of the transfer of spectral purity to the level of a few 10^{-16} after 1 s. Likelihood after mitigation: Low	Additional shielding of the outputs of the comb's amplifiers (acoustic noise, temperature fluctuations).	The single amplifier approach is still possible, the noise of the amplifier is eliminated in this case, at the expense of flexibility. If ytterbium combs perform well in terms of power, it will offer a single-amplifier alternative.
A1.3.5: The bond of crystalline coatings to silicon mirror substrates cannot withstand temperatures below 20 K	Likelihood without mitigation: Low Impact: impossible to build a cavity at 4 K with these coatings. Likelihood after mitigation: Very Low	Crystalline coatings on Si substrates will be tested in collaboration with the manufacturer to optimise the bonding process. Additional tests can be carried out with mirrors contacted to a Si spacer at 124 K (temperature of the first cancellation point of the CTE).	If the crystalline coatings cannot withstand 4 K, the silicon cavity with classical dielectric coatings has a projected thermal noise floor at $1x10^{-17}$, therefore already fulfilling the needs of the project. Dielectric coatings can withstand temperatures below 20 K.
A2.1.1: Copper surfaces of trap electrodes deteriorate during assembly in air	Likelihood without mitigation: Medium Impact: Efficiency of in-situ cleaning procedures reduced or poorly reproducible. Likelihood after mitigation: Low	Work in a clean flow box environment and minimise exposure time to air from surface preparation to vacuum integration.	Relocate the assembly work towards a clean room area and work within a protective gas atmosphere.
A2.1.4: Endcap traps of present design do not reach <10/s heating rates	Likelihood without mitigation: Low Impact: Interrogation times of > 1 s will not be achievable. Likelihood after mitigation: Very Low	Optimise all accessible parameters of electrical and geometric characteristics of the trap.	Scale-up the design to benefit from the nonlinear dependence of heating rate on trap size, at the expense of higher trapping voltages.
A2.2:1: Composition and pressure of residual gases in lattice clock system not controllable at the required precision	Likelihood without mitigation: Medium Impact: Results may not be transferrable from one clock vacuum system to another. Likelihood after mitigation: Low	Employ different methods and sensors for pressure measurement and residual gas diagnostics.	Combine the clock vacuum system with a dedicated gas handling system designed for the control of low partial pressures.

A2.2:3: Quality of in-vacuum cavity mirrors not stable over a period of months	Likelihood without mitigation: Medium Impact: Instable lattice intensity and trap depth. Likelihood after mitigation: Low	Consult with research groups and manufacturers of optical coatings that have investigated systems for cavity QED experiments under comparable conditions.	Relocate the mirrors outside the vacuum system. This will compromise the mechanical rigidity, but may still allow low parametric heating rates to be achieved.
Task 3.1: Temperature sensors in A3.1.1 and A3.1.2 are not suitable for real time thermometry of ion traps due to technical reasons	Likelihood without mitigation: Medium Impact: Real time thermometry in ion traps is not feasible. Likelihood after mitigation: Low	Different kinds of sensors (e.g. fibre Bragg grating temperature sensors and/or bandgap sensors) will be considered, and extra time is allocated to test more than one type.	Instead of real time thermometry in ion traps the BBR shifts in ion clocks will be monitored by thermal imaging and finite element analysis.
Task 3.1: Measurement of material properties and emissivity not available due to technical problems	Likelihood without mitigation: Medium Impact: A higher uncertainty in the material properties affects the design of the chamber for control of BBR. Likelihood after mitigation: Low	Design of chamber for BBR control should be made as robust as possible with respect to unknown material parameters.	Design of vacuum chamber and simulation of BBR shifts still possible but with higher uncertainty.
Task 3.1: Target BBR shift uncertainties in optical lattice clocks in A3.1.6 and A3.1.7 not achieved due to technical problems	Likelihood without mitigation: Low Impact: The level of precision in the control and measurement of BBR shift is degraded. Likelihood after mitigation: Very Low	Recent progress on a similar optical lattice clock at NIST and RIKEN suggests that the target accuracy should be attainable, so discuss with these research groups to establish which details have been overlooked.	Operate with the best temperature stability that can be attained. An improved BBR control can still be achieved, even if the target uncertainty is not fully reached.
Task 3.2: Target uncertainties for lattice light shifts and collisional uncertainty in optical lattice clocks not achieved due to technical problems	Likelihood without mitigation: Medium Impact: The evaluation of these shifts is degraded. Likelihood after mitigation: Low	Independent measurements are being made in different clocks (Sr, Yb) by different partners. Recent progress at NIST and JILA suggests that the target accuracy should be attainable.	Evaluation of light and collisional shifts will still be made, but may not reach the target uncertainty.
Task 4.1: Minimisation of Zeeman shift by Hyper-Ramsey spectroscopy in A4.1.1 may be technically unfeasible due to required switching of magnetic fields	Likelihood without mitigation: Medium Impact: Zeeman shift limits the advancement of bosonic optical lattice clocks towards 10^{-18} level. Likelihood after mitigation: Low	Develop and implement modified pulse sequences with magnetic field switching character that minimises the impact on the shift cancellation technique.	Demonstrate the technique with a reduced cancellation of the Zeeman shift and inform the design specifications of future systems required to achieve the desired performance.
Task 4.1: Achieving the required duty cycle to reach zero dead-time interrogation in A4.1.3 may be technically unfeasible at time of project	Likelihood without mitigation: Medium Impact: Projected clock instability will not be reached. Likelihood after mitigation: Low	Effort will be applied to both reduce the atom preparation time and to increase the coherence time of the interrogation.	Benefits of near-zero dead-time interrogation will be investigated although with a reduced possible enhancement.
Task 4.2: Validation of co-located clocks at 1 x 10^{-18} in A4.2.3 may fail to reach target uncertainty	Likelihood without mitigation: High Impact: A failure of the project to validate the desired clock performance. Likelihood after mitigation: Medium	Technical work packages are designed to address the key barriers to achieving the target uncertainty. The consortium will focus on the integration of techniques at two NMIs to maximise likelihood of success.	The clocks can still be operated at an improved level, even if the target uncertainty is not fully reached.

D2 Management risks

Risk (description)	**Likelihood and impact of occurrence**	**Mitigation** i.e. what the consortium will do to decrease the likelihood of the risk occurring	**Contingency** i.e. what the consortium will do if despite the mitigation the risk still occurs
Key scientific personnel are lost to the project during the duration of the project.	Likelihood without mitigation: Medium. Impact: The loss of key team members would create difficulties in delivering the project, or specific tasks or deliverables within the project. Likelihood after mitigation: Low	All the partners are experienced in running large research projects and they are familiar with the associated staffing risks; they will identify backups for key workers wherever possible to reduce the overall risk to the project. Project plans will be shared within the consortium and results and methodology will be documented in laboratory notebooks as work on the project progresses.	If a key team member leaves the project, then the partner concerned will be responsible for appointing a replacement. However this may still lead to some delay in project delivery.
Intellectual property (IP) rights could be a source of potential conflict between partners.	Likelihood without mitigation: Low. This project is oriented towards developing methods and procedures to be used as widely as possible within the international metrology community, rather than new or patentable products. Impact: Any disagreements could delay the progress of technical work or the publication of scientific results. Likelihood after mitigation: Low	All partners will sign the consortium agreement, which includes IP clauses, prior to the start of the project. Any disagreements arising will be referred in the first instance to the Project Steering Group, who will attempt to resolve the conflict in accordance with the terms of the consortium agreement.	Independent arbitrators will be used in the unlikely event of any disagreements that prove impossible for the Project Steering Group to resolve.
Managing a large consortium of 12 participants is too complex.	Likelihood without mitigation: Medium Impact: Failure to fully cooperate or communicate effectively within the consortium could endanger efficient delivery of the project. Likelihood after mitigation: Low	The partners are all experienced in cooperating in multinational projects. Many have previously developed close relationships through collaborating within other European consortia. Regular communication and feedback, both in the project meetings and in between, will ensure that potential problems are identified at an early stage and that all partners are clear on their roles.	WP leaders will play an important role in flagging up potential problems to the coordinator and the project management board, who will then decide on the best course of action to take. If necessary, work will be reassigned to an alternative partner, or parts of the work re-scoped in agreement with EURAMET.
Inter-dependencies between technical activities and tasks are too complex	Likelihood without mitigation: Medium Impact: Tasks could be impossible to carry out if a related task has not been completed first. Likelihood after mitigation: Low	Timelines are planned carefully and, where tasks follow on from one another, allowance is made in the schedule for potential slippage of the first task.	If an earlier task still overruns, then an attempt will be made to catch up the lost time on subsequent tasks so as to get back on schedule. If it is not possible to recover the lost time before the end of the project, parts of the work may need to be re-scoped in agreement with EURAMET.
Linked third-party CNRS does not deliver key parts of the work.	Likelihood without mitigation: Low. Impact: Parts of the project would not be delivered effectively. Likelihood after mitigation: Low	Under the terms of the grant agreement OBSPARIS would be liable for the relevant parts of the project if CNRS defaults.	If OBSPARIS also defaults on their obligations then the other members of the consortium become liable. The tasks affected would have to be reassigned or re-scoped in full consultation with EURAMET.

D3 Ethics

The EMPIR Ethics Review 2015 has given JRP 15SIB03 OC18 “Conditional ethics clearance”.

Third countries

The consortium will ensure that any partners or collaborators from Third Countries fully adhere to H2020 ethics standards, no matter where the research or activities are carried out and that research or activities performed outside the EU are compatible with European Union, national and international legislation and can be legally conducted in one of the EU Member States. The consortium will also, in the case of dual use applications, clarify whether any export licence is required for the transfer of knowledge or material.

Data protection

The consortium will ensure that all participants in training activities and meetings give a valid informed consent for the processing of personal data.

Dual use

The ethics reviewers identified that there is potential application of the project outcomes in spatial positioning for military purposes, in particular to its usage in navigation of offensive weapons and military satellite technology. The consortium will assess and report on the potential of dual use applications and how dual use risks will be mitigated. The report will be submitted after the grant signature, with the last technical report. As the dual use issue is an ongoing issue it will be continuously assessed during the entire course of the project.

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