**European Cooperation in the field of Scientific and Technical Research - COST -**

**Brussels, 21 November 2012**

**MP1207**

**MEMORANDUM OF UNDERSTANDING**

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| Subject : | Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action MP1207: Enhanced X-ray Tomographic Reconstruction: Experiment, Modeling, and Algorithms |

Delegations will find attached the Memorandum of Understanding for COST Action as approved by the COST Committee of Senior Officials (CSO) at its 186th meeting on 20 - 21 November 2012.

**MEMORANDUM OF UNDERSTANDING**
**For the implementation of a European Concerted Research Action designated as**

**COST Action MP1207**
**ENHANCED X-RAY TOMOGRAPHIC RECONSTRUCTION: EXPERIMENT, MODELING, AND ALGORITHMS**

The Parties to this Memorandum of Understanding, declaring their common intention to participate in the concerted Action referred to above and described in the technical Annex to the Memorandum, have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 4154/11 “Rules and Procedures for Implementing COST Actions”, or in any new document amending or replacing it, the contents of which the Parties are fully aware of.

2. The main objective of the Action is to establish an active, interdisciplinary research network that bridges the gap between the experimental X-ray tomography community and the mathematical image reconstruction community.

3. The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 60 million in 2012 prices.

4. The Memorandum of Understanding will take effect on being accepted by at least five Parties.

5. The Memorandum of Understanding will remain in force for a period of 4 years, calculated from the date of the first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of Chapter V of the document referred to in Point 1 above.

## A. ABSTRACT AND KEYWORDS

The aim of this Action is to establish an active, interdisciplinary research network that bridges the gap between the experimental X-ray tomography community and the mathematical image reconstruction community. While the advanced X-ray imaging community (i.e. synchrotron imaging, advanced lab setups) and the image reconstruction community have each made strong progress in various research projects within Europe, further advances require the combination of efforts and ideas from both fields. A joint network must be established including both communities, where experiences, ideas and computational tools can be exchanged and cross-fertilization can take place in a concerted effort.

The goal is to develop the next generation of X-ray tomography techniques and algorithms for absorption, phase, diffraction, and fluorescence contrast imaging. As a result, both the spatial and temporal resolution of advanced X-ray imaging will be strongly increased, facilitating high-tech research and industrial applications in a wide range of fields (materials science, life sciences, biomedical sciences, etc.).

Working Groups will be formed that deal with quantitative modeling, tailored algorithm development, and practical software development. The resulting ability to disseminate algorithms, knowledge and experimental capabilities throughout the X-ray community in Europe will advance science, as well as industrial R&D.

**A.2 Keywords:** X-ray tomography, image reconstruction, scientific computing

## B. BACKGROUND

### B.1 General background

The ability to inspect the interior of an object in a nondestructive way is of fundamental importance in a wide range of academic and industrial applications, ranging from life science research, to semiconductor quality control, to medical diagnosis. X-ray tomography can provide such a tool by computing a 3D image of the object from a series of X-ray projection images, acquired from a range of viewing angles. Once the data have been obtained, the 3D image is computed by a reconstruction algorithm, which may employ various mathematical techniques to recover the original object.

In recent years, significant advances have been made in the field of advanced X-ray imaging, pushing the limits of spatial resolution, temporal resolution, and image contrast far beyond what can be accomplished by current commercial scanners. By “advanced X-ray imaging”, reference is made to non-clinical imaging setups (i.e. synchrotrons, lab setups) that are, at their present stage of development, mainly targeted at advancing science. Besides absorption contrast, phase contrast is gradually becoming a common complementary imaging modality in such devices, as well as 3D X-ray imaging modes based on collection of fluorescence and diffraction signals emitted from the sample.

To perform 3D imaging at ultra-high resolutions, state-of-the-art X-ray imaging devices must be combined with tomography capabilities. However, many challenges must be dealt with in the reconstruction phase when pushing the capabilities of X-ray tomography setups, for example: (a) mechanical instabilities become a major issue at high resolutions; (b) the imaging process involved in phase, diffraction and fluorescence contrast imaging is highly nonlinear, such that conventional linear reconstruction algorithms can either not be used at all, or lead to images that are plagued by artefacts; (c) Dose constraints and time-resolved imaging require reconstruction algorithms that can compute accurate 3D images from highly limited data.

Custom tailored reconstruction algorithms are needed that are capable of reconstructing images from few, noisy projections acquired in a fast scan. These algorithms should incorporate nonlinear image formation models and be robust with respect to experimental instabilities. Novel reconstruction algorithms that have been developed in the mathematical tomography community are capable of providing these advantages, yet are typically not suited for direct application to complex nonlinear reconstruction problems.

The *key problem* that the experimental X-ray community is facing right now is how to turn these advances in algorithm development into novel computational tools that can be used in the experimental workflow. Until now, elementary algorithms are mostly used, leading to sub-optimal results, regardless of the quality of the experiment. To unleash the full potential of the advances in both communities, a joint network must be established as a COST Action where experiences, ideas and computational tools can be exchanged and cross-fertilization can take place in a concerted effort.

If such an interdisciplinary research network is successfully established, it will

- Act as a catalyst for further advances resulting in further multidisciplinary collaborative projects (e.g. Horizon 2020).

- Enable breakthroughs in research fields that use advanced X-ray tomography, in all of its forms, as a crucial tool for investigating the structure of various objects.

- Enforce European industrial R&D with the ability to develop new techniques and algorithms into commercially viable scanning solutions for applications in medicine, industry and science.

The crucial aspect that motivates this Action is the need for a long-term interdisciplinary research network, that involves a broad research community in Europe. A COST Action is the ideal framework for initiating this network, as it focuses exactly on the networking aspect. Once this network has been established, it can be strengthened and maintained by joint research projects that are formed between the participants of the Action, but acquiring such projects without a coordinating network would lead to scattered efforts throughout Europe, where the wheel is reinvented at various locations. While the ESF Research Networking Programme may also be a suitable instrument for supporting such a network, there are currently no funding calls planned, disqualifying this option entirely.

**B.2 Current state of knowledge**

Since the development of the first CT-scanners in the 1970s, X-ray absorption has been the predominant source of contrast in X-ray tomography setups. Triggered by the advent of third generation synchrotron radiation facilities, more and more research effort has been invested in the development of alternative forms of X-ray imaging that can also be used for tomography, including phase contrast, diffraction contrast and fluorescence contrast. Below, each of these imaging modes and their key challenges will be briefly described.
(a) Absorption contrast, formed by the direction attenuation of the beam. Current challenges, both experimentally and algorithmically, focus on reducing the number of projection images while maintaining reconstruction quality, and on methodologies for dynamic “4D” time-resolved tomography.
(b) Phase contrast. The field of X-ray Phase Contrast Imaging (PCI) has been rapidly growing over the last decade, with many applications in materials science and the life sciences. While

propagation-based phase contrast has been used extensively in synchrotrons since the 1990s, micro-CT scanners are now reaching the market that can perform PCI using diffraction gratings and a portable, poly-chromatic X-ray source. Current challenges center around the accuracy of the retrieved phase signal and the development of algorithms that take the nonlinear character of phase contrast image formation properly into account.

(c) Diffraction contrast. In X-ray Diffraction Contrast Tomography, the diffracted part of the X-ray beam is used for image formation, rather than the transmitted part. This allows grain resolved imaging of 3D microstructures in poly-crystalline materials. In powder like samples (where the crystallite size small compared to the X-ray beam size), the analysis of multiple diffraction patterns (Debye Scherrer rings) allows for reconstruction of the 3D distribution of crystallographic phases. A key problem in this type of imaging is the fact that the detector position of the diffracted signal depends on the local orientation of the crystal lattice. Lattice deformation and strain lead to a highly complex mathematical inverse problem, where the local orientation parameters of the crystal all have to be estimated simultaneously based on the observed diffraction data.

(d) Fluorescence contrast. The principal advantage of X-ray fluorescence (XRF) imaging is the fact that it enables chemical sensitivity in the image acquisition step. XRF utilizes fluorescent X-rays that are emitted from a material that has been excited by means of high energy X-rays. Key challenges for the tomography procedure are the development of reconstruction methods that take the nonlinear image formation model into account, and integration of certain types of prior knowledge that can reduce the number of projection images needed.

A number of new X-ray imaging endstations have recently been built in Europe or are currently under construction in order to satisfy the requests from an ever increasing user community using tomographic imaging in the life sciences, cultural heritage (i.e. paleontology), materials science, geology, environmental sciences, food research, chemistry, and other fields. Large European initiatives and research projects can be found in many of these fields that either advance the *hardware* of these facilities (e.g., the LACX FP7 project) or aim to be *users* of these new techniques (e.g., INSIDEFOOD/FP7, BioStruct-X/FP7). Having pushed the technique to the limits of existing technology, the X-ray tomography community has to face a variety of algorithmic challenges that can only be solved by combining state-of-the-art experimental facilities with advanced algorithms for image reconstruction.

At the same time, the *mathematical community* involved in the development of advanced reconstruction algorithms has made significant progress in its own right. Reconstruction problems from highly limited data can now be solved effectively (e.g. Compressive Sensing, Discrete Tomography), which was not possible just a few years ago. At several European institutes,

pioneering research is performed on the development of new algorithms that allow the improvement of image quality even much further.
A collaborative research network where experimental X-ray physicists jointly work with mathematicians and computer science experts to develop the next generation of tomography algorithms currently does not exist anywhere in the world. Although several local collaborations currently exist between members of the two communities, *coordination* of the networking activities is needed to bring the two communities together in such a way that effective, fruitful joint research is made possible. The Action will use the powerful networking instruments of the COST framework to achieve this goal, providing the European research community with a strong competitive advantage, and enforcing industrial R&D in Europe.

**B.3 Reasons for the Action**

Algorithmic challenges currently form a major obstacle for further improving the spatial and time resolution as well as the information content, accuracy and sensitivity in advanced X-ray tomography. A combination of high quality experimental facilities, accurate modeling of the underlying physics, and custom-tailored reconstruction algorithms forms the key to the next generation of tomographic imaging. Independent efforts have been made in the various imaging facilities to develop software and algorithms for a variety of tomography problems, leading to duplication of efforts. Moreover, the required expertise on novel reconstruction techniques is often lacking, motivating the need for a concerted effort that involves the image reconstruction community. More specifically, the following reasons for the Action can be identified:
(a) In both the X-ray community and the reconstruction community, there is a widespread desire to benefit from the strong expertise of the “other side”, while at the same time there is reluctance to enter a new field, caused by unfamiliarity and lack of common terminology. A well-coordinated COST Action, guided by leading experts from both fields, can pave the way for broad collaboration between these two powerful communities in Europe.
(b) Researchers from the experimental and algorithmic fields usually do not interact and visit separate conferences. Bringing these two groups together by the instruments of a COST Action (focused Workshops, Short Term Scientific Missions, etc.) will allow collaborations to be formed that will serve as a foundation for future joint research and activities.
(c) The experimental and algorithmic communities have an entirely different focus. Coordination and identification of the relevant questions in both fields is needed to align the interests of both communities in solving urgent experimental problems with the best available algorithmic

techniques.

The Action is mainly aimed at the advancement of science and technology in developing the next generation of X-ray tomography techniques and algorithms for absorption, phase, diffraction, and fluorescence contrast imaging. As a result of these advances, both the spatial and temporal resolution of advanced X-ray imaging will be strongly increased, facilitating high-tech research and industrial applications in a wide range of fields (materials science, life sciences, biomedical sciences, etc.). Specific scientific, social and industrial benefits of the Action are outlined in Section C.4, whereas the means for reaching these goals are described in Section D.

**B.4 Complementarity with other research programmes**

Within the individual countries of the participants, several active research projects are currently running that fit directly in the scope of the Action, funded by national sources. However, there is little coordination between these national projects. There are several European research projects and networks which are related to this Action, for example:

- COST Action MP1203 (advanced X-ray metrology)
- TECHNOTUBES (nanotube applications for advanced X-ray sources, FP7)
- INSIDEFOOD (X-ray imaging of foods, FP7)
- LACX (large X-ray detectors for coloured imaging, FP7-PEOPLE)
- BioStruct-X (infrastructure access for structural biology, FP7).

Some participants of the Action are involved in one or more of these projects. The projects that are related to X-ray imaging, but not tomography, are highly complementary to the Action as the image quality that can be reached in tomography depends on *both* the X-ray imaging technology and the algorithms used to reconstruct the object from the image data. Projects that use X-ray tomography as a tool (INSIDEFOOD, BioStruct-X) are also complimentary, and will benefit from the advances made in the Action.

The standardization of data formats is currently actively discussed in the synchrotron X-ray tomography community, and recently there has been a preliminary agreement between three large

facilities in moving to HDF5 as common data format.
Concerning laboratory X-ray tomography equipment and data analysis strategies, a series of projects exist on the national scale. At the same time, there are currently no joint research projects at a European scale where the experimental community and algorithmic community are both well represented. This clearly identifies the need for this COST Action, as an enabling instrument from which all of the aforementioned projects, and many others, will benefit.

## C. OBJECTIVES AND BENEFITS

### C.1 Aim

The main objective of the Action is to establish an active, interdisciplinary research network that bridges the gap between the experimental X-ray tomography community and the mathematical image reconstruction community, which will enable the development of next generation X-ray tomography techniques and algorithms for absorption, phase, diffraction, and fluorescence contrast imaging.

### C.2 Objectives

The Action will establish an interdisciplinary network of experts covering the full domain of advanced X-ray tomography, including image acquisition, physics modeling, and reconstruction algorithms. Crossing the boundaries between these fields will lead to high impact contributions of the European research community to the field of X-ray tomography and will open up this field to new groups getting into the field.
Specifically, the objectives of the Action are:
(a) To organize a series of European workshops, where experts from the advanced X-ray imaging field and experts on the mathematics and algorithms of tomographic reconstruction are both represented. The Action will entail a large annual workshop where all Working Groups are represented, and smaller workshops where the individual Working Groups focus on specific problems.
(b) To setup and run a wiki-style website containing a public overview of the Action, as well as a more technical description of the various experimental X-ray tomography techniques, the underlying physics models, and available algorithms. This website will be developed by representative members from both communities, to ensure that the content will be accessible for researchers with all relevant backgrounds.

(c) To compile an inventory of available software for image acquisition, processing of raw projection data, alignment, tomographic reconstruction and postprocessing, which avoids re-inventing the wheel when good tools are already available within the community.
(d) To construct a software platform, possibly formed by aggregation of several existing packages, which is capable of dealing with the most important tasks considered by each of the Working Groups (WG) in a standardized way and contains a set of benchmark problems and datasets for comparing algorithms.
(f) To organize Training Schools aimed specifically at familiarizing young experimentalists with the advanced reconstruction concepts and tools of the mathematical community, and similarly, training events aimed at familiarizing young algorithm researchers with the actual experiments.
(g) To have a substantial number of joint journal and conference publications co-authored between members of the Action.
(h) To encourage applications for interdisciplinary research funding by participants of the Action.
(i) To ensure the active dissemination of the Action's results and initiate new collaborations between academic and industrial partners.
(i) To ensure continuous attention for Gender Balance aspects within the network.
These objectives will facilitate the development of advanced tomography algorithms in a collaborative effort between the experimental community and the image reconstruction community. The network formed by the Action will play a leading role in guiding and coordinating the academic and industrial X-ray tomography research in Europe, not only during the time period of the Action, but also afterwards. The COST Action will be clearly acknowledged in all deliverables and publications that result from the Action.
The following quantitative metrics will be documented to measure how well the Action achieves its goals:
(a) The number of events organized as part of the Action including Workshops, Training Schools, Short Term Scientific Missions (STSM), etc., as well as the number of participants in these activities.
(b) The number of joint publications (and publication types) that have resulted from the Action.
(c) The amount of research funding that has been acquired as a result of the Action.
(d) The number of female researchers involved in the Action, and the number of Early Stage Researchers (ESR).

**C.3 How networking within the Action will yield the objectives?**

The scientific objectives within the Action will be achieved by linking various research projects that are being carried out among the participants with the unique networking and coordinating capabilities provided by COST. Participation by leading European research groups from both the experimental X-ray tomography and the mathematical image reconstruction community will ensure a high quality level of the collaborative research. Throughout Europe, several collaborations between individual groups from both communities already exist. By the use of the networking instruments (Workshops, Training Events, STSMs), these collaborations will be made more effective, and their scope will expand as many new groups are included.
The concrete objectives of the Action, such as setting up the website, compiling the software repository, and initiating joint research projects, will be facilitated by physical meetings of the Action participants at the networking events, but also by frequent communication through email and videoconferencing. The Action website will serve as a central hub for providing the necessary contact information and agenda.
To coordinate the joint research efforts, two types of Working Groups (WGs) will be established, focused on the different stages of the tomography process (W1-W3) and the different imaging modalities (T1-T3), respectively, which will be outlined in detail in Section D.2. The activities within these WGs will be coordinated by the Management Committee (MC) members and WG leaders through online communication, as well as physical meetings in a series of joint Workshops. STSMs, in particular between groups from the different fields, will strengthen collaborations. Biannual Training Schools will be organized to familiarize young researchers with the interdisciplinary aspects of the field.
Active networking with industrial partners will be achieved by involving these partners in the networking activities (Workshops, Training Schools, etc.) and also as lecturers and instructors. In particular, a Workshop is planned that is dedicated specifically to X-ray imaging in industry, where industrial partners can present their case studies and possibilities for collaborative research can be explored. An Exploitation Manager will be appointed among the MC members to act as a liaison between the academic and industrial partners, and to settle Intellectual Property (IP) issues.

**C.4 Potential impact of the Action**

The Action will act as a catalyst for interdisciplinary innovations in X-ray tomography. As a result, a wide range of users of these techniques will benefit. In particular, the following fields of impact can be identified:

(a) Impact for the participants from the experimental community. The collaborative efforts in the Action will result in the availability of advanced, problem-specific algorithms which will lead to sharper images, containing fewer artefacts compared to those produced by the classical methods.

(b) Impact for the mathematical image reconstruction community. Access to challenging, practical, and mathematically intricate problems is crucial to guide the community towards research that is both fundamental and practically useful. The interdisciplinary nature of the Action will enable mathematicians to apply their skills and tools to high impact research fields.

(c) Impact for scientific and industrial users of X-ray tomography. Users in various application fields (e.g. materials science, life sciences, geosciences) will all benefit from the enhancements in image quality and resolution that result from the Action and will advance their respective fields as a result.

(d) Economic impact. The imaging advances developed in the Action will be adopted by European industrial parties for applications in medical imaging, quality control, security, etc., leading to a competitive advantage for European industry and job creation.

(e) Benefits for Early Stage Researchers. The interdisciplinary background that young researchers can gain by participating in the Action and its Training Events will be of major benefit throughout their careers.

(f) Long-term benefits for society. Once laboratory technologies developed through the networking activities of the Action find their ways into commercial scanners, industrial advances in medicine, materials science and biotechnology are made possible by the new imaging methods, with impact on clinical scanning, solar cell research, medicine research, and many other fields.

**C.5 Target groups/end users**

Several target groups and categories of end users can be identified for this Action:

(a) Advanced X-ray tomography labs, including synchrotrons, will utilize the exchange of research ideas and software for direct improvements in their imaging systems.

(b) Applied researchers in materials science and the life sciences will exploit the key advances in spatial and time resolution that arise from this project for advanced structure imaging in their respective fields.

(c) Researchers in image reconstruction will be able to focus on cutting-edge experimental problems and datasets, and will obtain relevant imaging models, so that their new algorithms can

find their way to high-impact application fields (e.g. life sciences).
(d) High-tech industrial users will pick up the most successful techniques for 3D structure characterization in their efforts to produce high-tech materials and measurement devices.
(e) Early Stage Researchers (ESRs) will use the Training Events and Workshops to increase their ability to perform high-impact interdisciplinary research throughout their careers.
Established Researchers and ESRs from the advanced X-ray imaging community, the image reconstruction community, and application areas of X-ray tomography were jointly involved in preparing the Action.

## D. SCIENTIFIC PROGRAMME

### D.1 Scientific focus

The research tasks of the Action are focused on the development of state-of-the-art software and algorithms for the various types of experimental X-ray tomography, including absorption, phase, diffraction and fluorescence contrast. To this end, all stages of algorithm development, must be carried out in a collaborative effort between experimentalists and algorithm experts.
The Action addresses a range of X-ray imaging modalities, each leading to different mathematical models and reconstruction methods. At the same time, there are also similarities in the different components of the tomography workflow between these modalities.
To effectively coordinate research that takes the specific problems into account yet also benefits from their similarities, two types of Working Groups will be formed, focused on specific parts of software and algorithm development (W1-W3) and on specific imaging techniques (T1-T3), respectively. These two types of workgroups are orthogonal, in the sense that each algorithmic/software aspect considered in W1-W3 has problem-specific details for each of the imaging techniques considered in T1-T3.
The algorithm and software Working Groups are defined as follows:

- W1 - Software and data exchange; focused on establishing a common software suite that facilitates the exchange of datasets and experiments with different types of algorithms.

- W2 - Quantitative modeling; focused on the development of quantitative (approximate) models of X-ray image formation that facilitate efficient computation while also accurately modeling the underlying physics.

- W3 - Algorithm development; focused on the development and implementation of novel reconstruction algorithms that can deal with the specific (often non-linear) problems of various X-ray imaging techniques.

The imaging technique Working Groups T1-T3 interact with the three groups W1-W3, while focusing on the specific details of a particular imaging technique:

- T1 - Absorption and phase contrast; focused on optimizing X-ray tomography for transmission imaging based on the direct attenuation and phase changes of the beam, which allows to reconstruct the attenuation coefficients and refractive index of the object.

- T2 - Diffraction contrast; focused on optimizing X-ray tomography for 2D and 3D diffraction contrast imaging, which allows to reconstruct shape, orientation and strain for individual grains in poly-crystalline samples.

- T3 - Fluorescence contrast; focused on optimizing fluorescence tomography, which allows to perform X-ray imaging with chemical sensitivity.

*Flexibility of the workplan for the Action*

Although the general coordination of the research in the Action will follow the Working Group structure outlined above, the actual implementation and scope of each component is flexible and liable to alterations, depending on the contributions of new participants and developments in the research field.

The research underlying the Action will be carried out within national and international research projects. Once the Action has started, the MC will actively advertise participation in the Action through its network of current participants in order to include a broad consortium of researchers from both the experimental X-ray community and the mathematical community.

*Human and technical means to achieve the objectives*

The research groups that have already expressed the intent to participate in the Action cover a broad range of expertise in all relevant fields, and ensure the availability of state-of-the-art experimental facilities. The following skills, technologies, and facilities are available from the start to carry out the research relevant to the Action:

(a) State-of-the-art experimental facilities, including a number of European synchrotrons and

advanced X-ray labs for each of the four imaging modalities.
(b) Expertise and experience in experimental design and X-ray physics modeling.
(c) Expertise and experience in algorithm development, where participants have made major contributions to the state-of-the-art in recent years.
(d) Expertise and experience in software development and high performance implementation of tomographic reconstruction algorithms.

**D.2 Scientific work plan - methods and means**

As outlined in Section D.1, the activities of the Action will be coordinated by establishing six Working Groups. Each of these groups will work on specific aspects of X-ray tomography. Most participants will be a member of at least two WGs, one of the groups W1-W3 and one of the groups T1-T3. These cross-links will facilitate the exchange of knowledge between the WGs.
Below, the work plan and methods for each of the Working Groups will be outlined.

***Software and Algorithms Working Groups: W1-W3***

*W1: Software and data exchange*

This Working Group is focused on establishing the definitions and documentation of common, open data formats, datasets and software that can be used throughout the Action, and also beyond the boundaries of the Action. The core of this Working Group is formed by representative members from each of the other Working Groups, who will ensure that these common software and data formats are disseminated throughout the Working Groups of the Action. Rather than building "production software", the main focus is on a clear and flexible platform for algorithm development and benchmarking.
The tasks for this WG will include:
(a) Creating an inventory of tomographic software that is already available. Whenever possible, good existing solutions will be preferred over re-inventing the wheel. Open source for the program code as well as the benchmark data will be a primary requirement for all software adopted in this Working Group.
(b) Creating an inventory of data formats that are currently used throughout the X-ray community. Depending on the input of expert members, a choice will be made for working with existing data formats or developing a new format.
(c) Developing flexible, high-performance implementations of building blocks for tomography

algorithms (e.g. projection and backprojection) and basic benchmark implementations of common reconstruction algorithms.

(d) Assembling a collection of benchmark datasets for the key reconstruction problems in all X-ray imaging modalities.

*W2: Quantitative modeling*

This Working Group is focused on the development, documentation, simulation, and validation of quantitative models of the X-ray image formation process for the various modalities. Even though X-ray optics has been described extensively in the literature, many choices have to be made when using such models in algorithm implementations. For effective collaboration between the experimental experts and mathematical algorithm developers, it is imperative to have a clear overview of these models, their underlying assumptions, possible simplifications, etc.

The tasks for this WG will include:

(a) Creating an inventory of the analytical models available for the various X-ray imaging modalities, including the regime where they are valid and the underlying assumptions.

(b) Establishing a simulation platform for testing the influence of using approximation models in algorithms.

(c) Validating the imaging models and the reconstructed 3D images by reference experiments, using known benchmark objects as well as alternative scanning and sectioning techniques.

*W3: Algorithm development*

This Working Group deals with the development of advanced tomographic reconstruction algorithms, as well as algorithms for other stages of the tomography pipeline (alignment, dynamic angle selection, etc.). As the specific details of the algorithms depend on the particular imaging technique (covered in the WGs T1-T3), the research in this WG focuses on generic algorithmic techniques that can be tailored for more specific applications in the other WGs.

The tasks for this Working Group include:

(a) Developing highly flexible and efficient implementations of iterative methods for linear inverse problems, such as the Algebraic Reconstruction Technique (ART) and Conjugate Gradient Least Squares (CGLS).

(b) Developing and implementing flexible numerical schemes for nonlinear inverse problems (Gauss-Newton types methods, Levenberg-Marquardt, stochastic methods).

(c) Developing and implementing flexible algorithms for image reconstruction from highly limited data (Compressive sensing, Discrete tomography).

(d) Developing and implementing algorithms for real-time tomography (hybrid Filtered Backprojection methods, neural networks).

(e) Developing and implementing algorithms for parameter optimization and estimation (alignment parameters, estimation of motion parameters, etc.).

***Imaging Techniques Working Groups: T1-T3***

*T1: Absorption contrast and phase contrast tomography*

This Working Group focuses specifically on the reconstruction challenges in tomographic imaging based on detection of the phase and amplitude of the transmitted X-ray signal, leading to absorption and phase contrast. Both modalities can be reconstructed separately, but can also be used together in a single reconstruction procedure. Research tasks for this Working Group include:

(a) Developing a procedure for fast imaging from limited data, based on incorporating sample-specific prior knowledge in the reconstruction method.

(b) Developing algorithmic techniques for accurate phase retrieval from single and from multiple projection images, which requires suppressing artefacts that currently limit the accuracy.

(c) Developing algorithmic techniques for combined absorption and phase contrast tomography.

*T2: Diffraction contrast tomography*

This Working Group is focused on the specific and highly nonlinear reconstruction problems in diffraction contrast tomography. As the direction of the diffracted beam depends on only on the direction of the incoming beam, but also on the crystal orientation of the sample itself, the geometrical parameters of the imaging formation must be determined as part of the reconstruction. Research tasks for this Working Group include:

(a) Developing algorithms for accurate sorting of (possibly overlapping) diffraction spots to link them to individual grains.

(b) Developing algorithms for fast reconstruction of grain shapes in polycrystalline samples in cases where the lattice structure of the individual grains is undeformed.

(c) Developing algorithms for simultaneous computation of grain boundaries, deformation and strain in polycrystalline samples.

*T3: Fluorescence contrast*

This Working Group deals with the problem of computing 3D reconstructions with chemical sensitivity by fluorescence contrast tomography. The fact that the X-rays transmitted by the sample are attenuated by the surrounding materials leads to a complex, nonlinear reconstruction problem. Research tasks for this Working Group include:

(a) Incorporating approximate object models in the reconstruction algorithm to simulate the

absorption of the transmitted X-rays.
(b) Developing algorithms for combined reconstruction of the emitted X-ray signal and the surrounding absorbing materials.

## E. ORGANISATION

### E.1 Coordination and organisation

The Action will facilitate and coordinate joint European research on advanced X-ray tomography. The actual research work is carried out by the participants of the Action and financed by national sources in their respective countries. The instruments of COST will lead to a "network of excellence" that links the strong expertise already available in the various sub-domains in a concerted action, which will run for four years.

The Action will be chaired by the Action Chair and coordinated by the Management Committee (MC), as outlined in the "Rules and procedures for implementing COST Actions". Once the initial MC has been formed, a Working Group leader will be elected from its members for each of the six Working Groups. In addition, a Short Term Scientific Mission Coordinator (STSMC), a Coordinator for the involvement of Early Stage Researchers (ESRC), a Coordinator for ensuring gender balance (GBC), and an Exploitation Manager (EM) will be appointed. A committee of three participants will be appointed who will operate as Dissemination Managers (DMs) and share the responsibility of setting up an Action specific website that will provide detailed information on the Action, its results and the possibilities for joining. This will ensure a proper balancing of the work involved. They will depend on input from the Action Chair, who collects reports on the scientific progress from each of the Coordinators.

The MC will meet at least twice during every year of the Action, supported by frequent contact using email and videoconferencing. The Working Group leaders will each form a Working Group Committee for their respective Working Groups for coordinating the research and networking within these Working Groups, who will also meet at least twice every year.

Throughout the period of the Action, the MC and WGs can be augmented with new members and new research topics can be added to the scientific agenda.

The EM will act as a coordinator for contacts with industrial partners and will be responsible for dealing with intellectual property (IP) issues that may arise and will be responsible for liaison activities between the academic and industrial participants. In particular, the EM will chair a workshop that is dedicated specifically to X-ray imaging in industry, where industrial partners can present their case studies and possibilities for collaborative research can be explored.

*Milestones for the Action*

The following Milestones can be identified for the Action:

(a) Scientific Meetings: MC and WG meetings, Workshops, and International Conferences.

(b) Workshop on industrial applications of advanced X-ray tomography.

(c) Training Schools for familiarizing ESRs with all the fields in the interdisciplinary scope of the Action.

(d) The Action website, which will serve as the central hub for dissemination of the results of the Action.

(e) A software and data repository that contains data formats, datasets, benchmark data and reference software for the key problems in each of the X-ray tomography problems considered in the Action.

*Coordination of networking and capacity building activities*

Each of the networking activities in the Action will be coordinated by the MC, in collaboration with one or more WGs connected to that specific activity, jointly referred to as the Coordinating Committee (CC). For each activity, a local organizing committee will be appointed that will take care of the local organization details and act in close collaboration with the CC. To maximize the connection with national research programmes, each of the individual workshops and meetings of the Action will be assigned a theme, connected to the research of the local organizing committee. This theme will be highlighted during the event, along with the general scheduled topics of the Action. As a result, the participants of the Action will become aware of the various local expertise available throughout the Action and new opportunities for joint national and international funding applications will emerge.

By means of the Short Term Scientific Missions (STSMs), as well as a program of international guest lectures between the various participating groups, detailed results and ideas from the national research projects will be exchanged. In particular, the STSMs between experimental groups and the algorithmic groups provide the collaborative research time that is needed to establish fruitful collaborations between the interdisciplinary groups.

## E.2 Working Groups

To effectively coordinate research that takes the specific problems into account yet also benefits from their similarities, two types of Working Groups will be formed, focused on specific parts of the tomography workflow (W1-W3) and on specific imaging techniques (T1-T3), respectively. These two types of workgroups are orthogonal, in the sense that each aspect of the tomography workflow considered in W1-W3 has problem-specific details for each of the imaging techniques considered in T1-T3. Participants of the Action will typically be a member of at least two Working Groups, one of the W1-W3 and one of the T1-T3 Working Groups.

Each Working Group will meet at least once per year. One of the meetings may be organized jointly with a larger international conference to allow substantial dissemination of the Action results. During this meeting, at least one "brain storming" discussion will be scheduled to support the emergence of novel research approaches, experiment and applications; a round table with an evaluation of past activities and addressing future tasks will be organized.

**E.3 Liaison and interaction with other research programmes**

Interaction with other research programmes, both national and international European programs, is crucial to the success of the Action, and at the same time very natural. As an international project, the BioStruct-X project is mentioned, funded by the Seventh Framework Programme (FP7) of the European Commission that establishes a state-of-the-art coordinated and multi-site infrastructure to support access for established and emerging key methods in structural biology. Advanced X-ray imaging plays an important role in structural biology and therefore several members of BioStruct-X will also participate in the Action. Vice versa, this will open up the infrastructure of BioStruct-X to the network established in the Action. Efforts will be made to collaborate in the organization of workshops and training events between these networks.

Once the Action has started, a list will be compiled by the MC of all national and international related projects and common objectives will be identified. Exchange of information between these programmes will take place by joint membership of participants of the Action in these programmes, guest presentations at meetings organized by these programmes, and active research collaborations. The topic of liaison and interaction will be a recurring item on the MC agenda. As the Action is open for new participants, it can be joined by interested participants from any related domain. International experts in the domain of the Action, both from COST countries and from other countries, will be invited to give lectures at the workshops of the Action, which will link the Action to related research initiatives worldwide.

The calls and projects of the Horizon 2020 program will be closely monitored, and whenever possible new joint applications will be prepared by members of the Action and connections will be sought with other projects.

### E.4 Gender balance and involvement of early-stage researchers

This COST Action will respect an appropriate gender balance and considerable involvement of early stage researchers (ESR) in all its activities and the Management Committee (MC) will place this as a standard item on all its MC agendas.

Below, the specifics of the Gender Balance and ESR aspects of the Action will be outlined in more detail.

*Gender Balance*

It is clear that a gender imbalance is currently present in both Mathematics and in Physics. This is also reflected in the list of participants of the Action, in which female researchers account for 33 percent of the list. To strengthen the participation of women in the network formed by the Action, the following steps will be taken:

(a) Female researchers will be encouraged to become a member of the MC, and will be selected if both male and female would like to take this role and if they are similarly suited.

(b) A similar policy applies for each of the Working Groups.

(c) From the start of the Action, the participants will be called upon to actively approach female colleagues in their respective countries for participation in the Action.

(d) The Gender Balance Coordinator will actively monitor the participation of women in the Action and will take steps to connect to other networks, such as the "European Women in Mathematics", an international association of women working in the field of mathematics in Europe.

*Opportunities for Early Stage Researchers*

Early Stage Researchers will find ample opportunities in the Action to perform cutting-edge research, to obtain high level education in interdisciplinary research, and for international visits to other research institutes. In particular, the following activities will be specifically aimed at Early Stage Researchers:

(a) At each Workshop, there will be a poster session for young researchers to present their work.

(b) Training Events will allow young researchers with varying backgrounds to learn new aspects of the interdisciplinary research topic of the Action.

(c) Young researchers will be asked to participate in the organization of the events of the Action, to gain organizing and management experience.

(d) Early Stage Researchers, who have already built up strong expertise in one of the topics of the Action, will be invited as plenary speakers during the workshops.

(e) Short Term Scientific Missions will provide an opportunity for young researchers to visit institutes abroad and gain expertise in new fields.

## F. TIMETABLE

| | Y1 | | | | Y2 | | | | Y3 | | | | Y4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| Kick-off | X | | | | | | | | | | | | | | | |
| Annual evaluation and activity report | | | | X | | | | X | | | | X | | | | X |
| Updates of website | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| General WG Workshop | | X | | | | X | | | | X | | | | X | | |
| MC/SG Meeting | X | | X | | X | | X | | X | | X | | X | | X | |
| Specialized WG Workshop | | | | X | | | | X | | | | X | | | | X |
| Workshop Industrial Applications | | | | | | | X | | | | | | | | | |
| Email newsletter | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| STSM Call | X | | X | | X | | X | | X | | X | | X | | | |
| Training Event | | | X | | | | X | | | | X | | | | X | |
| Closing Meeting | | | | | | | | | | | | | | | | X |
| Follow-up Plan | | | | | | | | | | | | | | | | X |

## G. ECONOMIC DIMENSION

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest: BE,CH,DE,DK,EL,ES,FR,HU,IL,IT,MK,NL,PL,SE,UK. On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at 60 Million € for the total duration of the Action. This estimate is valid under the assumption that all the countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total cost accordingly.

## H. DISSEMINATION PLAN

### H.1 Who?

During the past century, X-ray imaging has had a profound impact on all aspects of society, in healthcare, industrial quality control, materials science, life science, security, and many other fields. Guided by an increasing understanding of X-ray physics and advances in the capabilities to perform complex experiments using all components of the X-ray/specimen interaction, the scope of X-ray imaging has broadened even much further and its versatility has strongly increased. The true power of X-ray imaging can be observed once measurements from many directions are combined in a tomogram, enabling 3D reconstruction of an object's attenuation, refractive index, crystal orientation and chemical composition. The experimental X-ray community has now reached a point where further major advancements require not only state-of-the-art experiments, but also advanced algorithms for computing the 3D images from the observed data. A concerted Action which involves both the experimental and the algorithm communities will yield advances that are highly relevant to a wide range of potential users and stakeholders, and an important objective of the Action is the effective dissemination of the results to the following communities:

(a) Academia and research institutes

- Experimental physicists working on the development of new X-ray imaging techniques will gain access to advanced algorithms and mathematical expertise.
- Applied mathematicians working on computational imaging will be provided with models, software and benchmarks datasets that allows them to apply new algorithms to relevant and challenging experimental datasets.
- Researchers in materials science, the life sciences, geosciences, and many other fields, will be able to use the new techniques for cutting-edge research on materials and biological specimens, with unprecedented spatial and temporal resolution.
- Early Stage Researchers in all the fields mentioned above will benefit specifically from the networking activities and Training Schools of the Action.

(b) Industry

- Industrial partners involved in the development of X-ray and scanner equipment can use the results to guide their R&D towards promising new directions.

- Industrial partners who are potential users of the new 3D imaging techniques can take part in the definition of benchmark datasets.

(c) General public

- The general public will be informed about the fascinating new imaging techniques, which may be just as common as medical CT-scanners are now within the next two decades.

**H.2 What?**

The Action entails a range of activities and projects that will be undertaken for the dissemination of the results. These activities include:

- A website will be set up that serves as the central hub for dissemination of the results of the Action. Part of the website will be accessible for all users, including those that are not members of the Action, whereas a reserved area will be used to publish information, software and datasets for members of the Action.

- Several mailing lists will be set up for communications between the different bodies of the Action, including the MC, each of the WGs and a mailing list for all members of the Action.

- Training Schools will be organized for young scientists to exchange knowledge and skills between the experimental X-ray community and the image reconstruction community from both academia and industry.

- Lectures by leading scientists and engineers from both academia and industry will be organized.

- The results of the Action will be published in highly visible scientific journals and proceedings.
- A series of regular Workshops will be organized where the research results of the Action will be communicated.
- The results of the Action will be actively communicated in external conferences and workshops.

**H.3 How?**

To achieve an efficient and fruitful dissemination of the results of the Action, the following strategies will be followed:

- The Action website will play a central role in the dissemination of the results of the Action. The public part of the website will be targeted at a broad audience and will contain an overview of the various types of X-ray tomography and their applications, written in an explanatory way where only elementary knowledge about the topic is assumed. The information will be augmented by several Youtube videos made to illustrate the experiments and their results. Laymen summaries of important breakthroughs made in the Action will be published here in and information on joining the Action will also be made available.
  The reserved part of the website will follow the format of a Wiki, which can be dynamically modified and updated by the participants of the Action. Here, reports will be collected of the results from the Working Groups, software will be shared and benchmark datasets will be made available. The three Dissemination Officers, as outlined in Section E.1, will jointly be responsible for maintaining this website.
- Setup and moderation of the mailing lists is performed by the Dissemination Officers. A public mailing list, which provides general public announcements about research results and plans of the Action, can be joined through the public website.
- The group of participants of the Action includes several large experimental X-ray facilities, which will an experimental Training School. A Training School on software and algorithms will be offered at an institute that has large computer room facilities available.

- The Workshops organized through the Action, as well as seminars organized as satellite events in larger conferences, will be a key dissemination point for exchanging results within the communities of the Action, as well as with other research communities.

- A special workshop focused on industrial applications of X-ray tomography, as well as guest lectures by industrial engineers and participation of R&D engineers in the Action events, will enable the dissemination of research results towards European industry.

During the course of the Action, the dissemination plan will be updated and revised according to the DC's Terms of Reference requirements. To monitor the success of the dissemination activities, the following indicators will be monitored:

- Number of scientific workshops and conferences in the field of the Action, compared to current numbers.

- Number of joint scientific publications between participants of the Action.

- Total amount of web-content made available (number of pages, number of software packages, number of benchmark datasets, etc.) on the website of the Action.

- Number of participants in STSMs, workshops and other events of the Action, in particular also for Early Stage Researchers