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GSI
Suirbhéireacht Gheolaíochta Éireann
Geological Survey of Ireland

Geological Survey of Ireland Research Programme
- Short Call 2015, Final Report -

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Organisation name	Dublin Institute for Advanced Studies		
Organisation type:	☒HEI	☐Public Sector (other)	☐Private Sector
Department/section	School of Cosmic Physics		

Project Title	Spatially constrained Bayesian inversion of frequency- and time-domain electromagnetic data from the Tellus projects
Contract No.	2015-sc-04

INFOMAR
Integrated Mapping for the Sustainable Development of Ireland's Marine Resource

Tellus
Understanding Underground

Marine Institute
Foras na Mara

2. Project information:

Title of project	Spatially constrained Bayesian inversion of frequency- and time-domain electromagnetic data from the Tellus projects
Did you make any formal amendment to the project workplan / budget?	☒ yes ☐ no Budget amendment (see Appendix 2)

<u>Project Report:</u>

(i) Objectives and scientific/engineering targets beyond the state of the art

The objective of this project was to

1. develop and implement Bayesian methods for the quantitative interpretation of Tellus AEM data and provide open-source tools for inversion of these data for further research;
2. assess any differences in resolution and sensitivity between the time domain and frequency domain data within a test area;
3. take steps in building national expertise for the interpretation and the optimal use of Tellus airborne data.

We have been successful in reaching these goals in most areas. Concerning the first objective, the toolbox for constrained inversion has been realised, with a number of constrained inversion methods, which can be used for frequency- and time-domain data. Beyond the capability for resistivity inversion, which is possible with most existing software, it allows for the estimation of magnetic susceptibilities and Cole-Cole induced polarisation parameter within all implemented algorithms. We were not able to fully reach our second objective. The implementation of the developed methods for the North Midlands survey with the *CGG Genesis* system (see below) was not possible due to missing information from the contractor. This made a true field comparison of the two systems used in the Tellus surveys impossible. However, we compared the two methods based on synthetic data for a *Genesis*-like system. We believe that the availability of an easy-to-use and very flexible software tool is a first step in reaching the third objective. It does not only allow the interpretation of the Tellus data with the already existing different 1-D inversion algorithms, but is the starting point for further developments. This will not only increase the particular AEM capabilities (2-D and 3-D), but also opens the way for the many sophisticated tools already available in the Python community, including geo-information tools and mapping (e.g., *GDAL*), statistics (e.g., *Pandas*), imaging, machine learning, visualisation, and more.

(ii) Implementation

In this paragraph, we describe how the project milestones were implemented. The commencement of the project was later than planned, as we were unable to fill the Post-Doc position until March 2016. We would like to acknowledge the GSI Tellus team, who were most helpful and co-operative, and thus contributed considerably to our success.

Milestone I: Statistical analysis *of FD/TD data on selected flightlines/areas*

Some basic statistical analysis was carried out in order to determine the error characteristics of the observed data. For the analysis, a high-fly area, where the variances of the recorded data are supposed to be an estimate of the internal accuracy of the measurements, was used. However, error estimation derived from a high-fly area represents only one source of the errors to be used in the inversion process. For a realistic estimation, also influences related to unresolved heterogeneity and cultural noise need to be included, as they contribute to data uncertainty. Though part of the noise is suppressed by the spatial averaging of the data, some data had to be flagged as spurious in the pre-processing and left out or interpolated for the inversion.

Milestone II: *Forward modelling modules for FD/TDEM including interfaces finished. Software for the flight line roll-along technique implemented and tested*

We implemented an easy-to-use and highly flexible toolbox using Python language for the 1-D inversion of frequency- and time-domain AEM data. The computational core is based on an adapted forward model derived from the well-tested open-source code *AirBeo*. This code was developed by the AMIRA consortium (http://www.amirainternational.com), and the latest version is available from https://sourceforge.net/projects/p223suite).

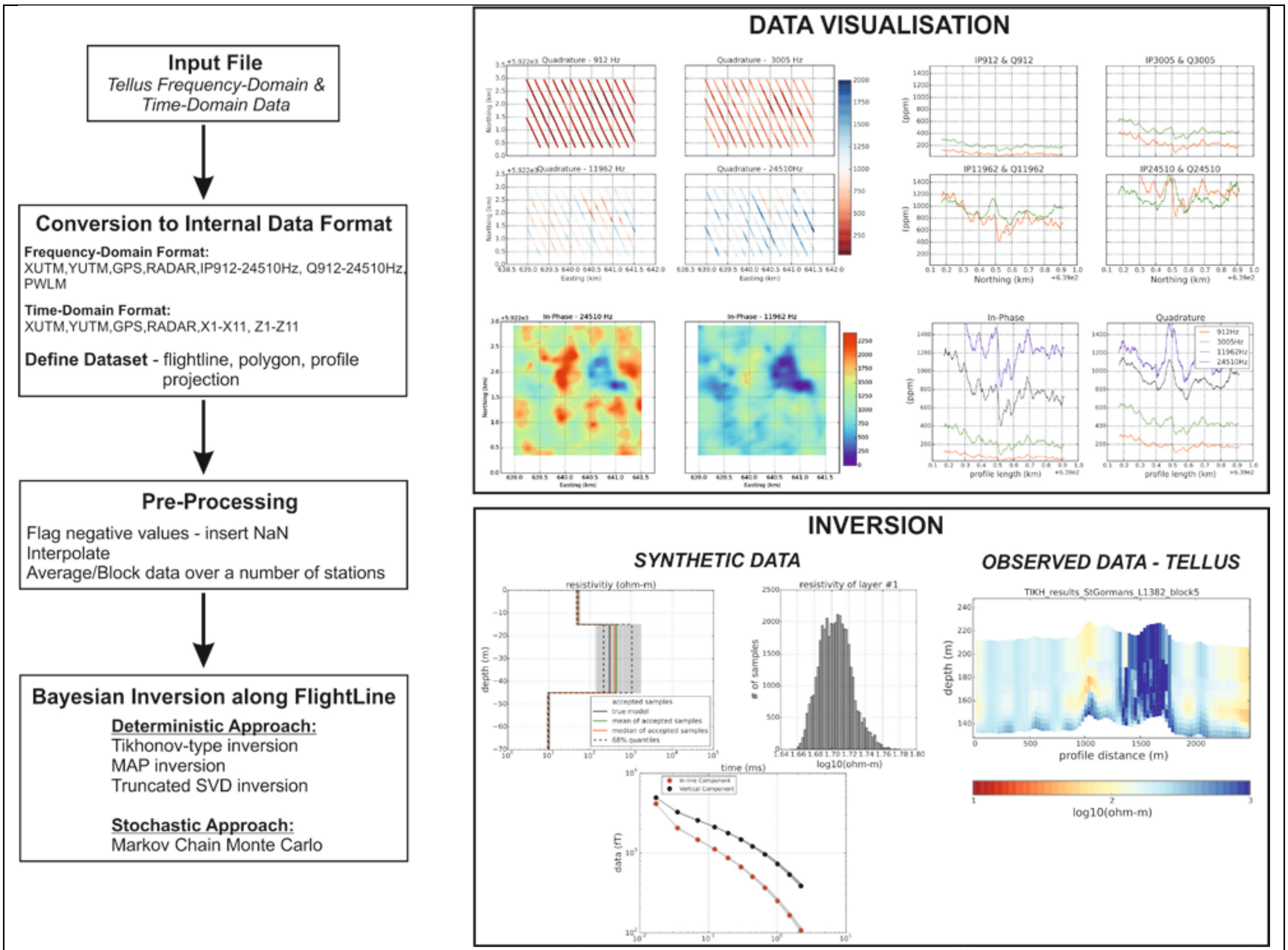
We implemented several basic inversion techniques:

- Tikhonov-type inversion including optimal regularisation methods (Aster et al. 2012, Zhdanov, 2015)
- Bayesian MAP inversion in parameter and data space (Tarantola & Valette 1982a, b; Tarantola 2005)
- Full Bayesian inversion by Markov Chain Monte Carlo (Mosegaard & Sambridge 2002; Sambridge & Mosegaard 2002)

These are implemented high-level scripts including a full work flow from loading of raw data over pre-processing to inversion. They rely on functions implemented in callable modules, which contain functions providing numerical procedures, constraint methods, processing tools, and utilities. In the Figure below, we give an overview of the typical workflow for an inversion which is constructed from these building blocks.

The idea behind this approach is to be able to combine the existing functions for fast prototyping new and improved workflows. This can be on the level of the inversion algorithm, but also for designing more complicated procedures, such as using the output of MAP inversion for the prior in MH simulations, or a two-stage procedure for obtaining susceptibility using the results from prior resistivity-only inversion. The setup for these inversions is highly flexible, as activity indicator matrices are used to choose the data to be used for inversion, and more important, the inversion parameters can be determined likewise.

The pre-processing functions include amongst others the masking of ‘unphysical’ data, interpolation, PCA filtering of data (Minsley et al. 2012). Inversion algorithm can be combined with different type of couplings (Covariance matrices in MH or differential operators in Tikhonov inversions), or regularisation. Utilities include data managing tools, such as reformatting raw data to an internal format, data choice from a polygon, or profile projection, and various visualisation methods.



AEM inversion toolbox **`aempy`**: *(Left panel): Simplified inversion flow diagram. (Right top panel): Examples for visualisation of data with different methods. (Right bottom panel): Examples for outputs from a stochastic site inversion (left) and a deterministic flight line inversion (right).*

<u>Milestone III: Comparison of FD/TDEM in an appropriate areas (month 8/12).</u>

Unfortunately it was not possible to do the comparison of the two systems use in the Tellus surveys. While the tools for the frequency domain data from *Sander Geophysics* are fully functional, we are missing essential information for the time-domain, which can only be provided by the contractor. We are currently working with the GSI Tellus group on a solution.

The time-domain data were delivered as normalized amplitudes, with detailed information on the normalisation method missing. This is essential for the forward modelling of the responses. As the CGG system is derived from Fugro's *TEMPEST* system (Kaufman et al. 2015) we have adapted the *TEMPEST* setup parameters (transmitter loop size, geometry, etc) to the existing information on *Genesis*. Calibration information is still missing. From consultations with colleagues (Aarhus) we know that beyond the *TEMPEST* calibration which is done with a fixed geometry, it is highly desirable to include the geometry as free inversion parameters, as the movement is an additional source of error (Brodie 2015; Vest Christiansen et al. 2016). This has not yet been done but will be approached once the information on the data is complete.

During this project, a comparison of the two systems based on synthetic responses derived from a different modelling code (*AirBeo*, *ArjunAir*) was done. Though it is possible to draw some conclusions from this approach about theoretically achievable resolution, a true field test is necessary on the available data from flight-lines where both systems were used. This can only be achieved when the aforementioned problems have been solved.

Milestone IV: Map production implemented

Basic mapping capabilities have been implemented in the toolbox, however the necessary interpolation to (or estimation on) a regular grid will need more attention. This is mainly because of the line sampling geometry, which poses some problems for traditional methods of data interpolation and mapping (anisotropy). A more thorough treatment of this problem with more evolved methods (e.g., anisotropic kriging) is desirable and remains a task for the near future.

Milestone V: Report on the method and results and publication in peer-reviewed journal submitted. Documented software published (month 12/12).

Outcomes of the project have been presented on several national and international workshops, and also will be disseminated at the European Geosciences Union (EGU) General Assembly, April 23-28, 2017, in Vienna, Austria. Two peer-reviewed publications (see below) will be submitted in early 2017. The inversion toolbox itself (including a manual) will be publicly available in early 2017, when a clean and stable release is possible.

(iii) Outputs

- A Python toolbox was developed to the point of practical use in flightline-oriented inversion for frequency domain data, and for time domain data with the mentioned reservations. It is expected to be available to the public in early 2017.
- The Python toolbox currently contains (for both time and frequency domain) forward modelling, three deterministic (MAP, TIKH, TSVD) and one stochastic (MH) inversion scripts, including related plotting tools. Many callable toolbox functions (called by the scripts) allow the easy prototyping of further and more sophisticated pre-processing and inversion methods. Constraints are possible in the data and parameter domains. Methods were tested on synthetic and field data from the Tellus Block A1.
- Results from this project was used in a paper (Delhaye et al. 2016) submitted to a peer reviewed journal, while two publications in peer-reviewed journals are currently in preparation (working titles):
    - *Inversions of airborne electromagnetic data from the Tellus data: a toolbox for spatially constrained inversion* (Kiyan, Rath)
    - *Joint interpretation of airborne electromagnetic and surface magnetotelluric measurements neat Irish warm springs (Blake, Kiyan, Delhaye, Rath, order TBD)*
- Some results were presented at different national and international meetings (see appendix 1). Further outcomes will be disseminated at the EGU General Assembly, April 23-28, 2017, in Vienna, Austria.

Impact/value of the project:

The better quantitative characterisation of the subsurface significantly serves many of the aims formulated for the GSI call. This concerns the area of improved 3D land mapping (including corresponding data bases) but also the understanding Irish groundwater resources and their protection, geohazards and heritage.

The most important outcome of this project, an Airborne EM inversion toolbox, will add value to the existing Tellus data by improving the ability to interpret the distribution of electrical conductivity in the shallow subsurface within the regional dataset, and by giving better estimates of where the potential of these underlying models to detect features relevant to the aims formulated for the GSI call. It will also be useful in areas where magnetisation or induced polarisation effects play a role (e.g., ore deposits or shales/clays).

The toolbox will be available to GSI, scientific researchers, university teachers, industry partners, and the interested public. The techniques of spatially constrained 1-D proposed here is a step in building expertise for the use of Tellus AEM data for society's needs, and will lead to future research into the development of more sophisticated interpretation methods. These further developments will include fully 3-D interpretation schemes which imply fewer assumptions than the hitherto implemented methods. Furthermore, it will play an important role in the future ICRAG Geohazards & Geoengineering spoke, and will be the starting point for other scientific projects in DIAS and elsewhere.

Appendix 1 – Publications & Presentations:

[Conference Publication] Kiyan, D.; Rath, V.; Delhaye, R. (2016) Spatially constrained Bayesian inversion airborne electromagnetic (AEM) data from the Tellus projects. Oral at Stakeholder's Meeting, Unearthed - Impacts of the Tellus surveys of the north of Ireland, organized Geological Survey of Ireland, October 5, 2016, Royal Irish Academy, Dublin. Ireland

[Conference Publication] Kiyan, D.; Rath, V.; Delhaye, R. (2016) Spatially constrained Bayesian inversion of frequency- and time-domain electromagnetic data from the Tellus projects. Poster at at Stakeholder's Meeting, Unearthed - Impacts of the Tellus surveys of the north of Ireland, organized Geological Survey of Ireland, October 5, 2016, Royal Irish Academy, Dublin. Ireland

[Conference Publication] Kiyan, D.; Delhaye, R.; Rath, V.; Blake, S. (2016) Results from the Tellus A1 airborne electromagnetic data near Irish warm springs. Poster at IRETHERM Workshop, April 1, 2016, Dublin, Ireland, and poster at Geothermal Association of Ireland Conference at the SEAI Energy Show, April 7, 2016, Dublin, Ireland

[Conference Publication] Delhaye, R.; Rath, V.; Jones, A.G.; Muller, M.; Reay, D. and the IRETHERM Team (2016) Accurate Estimation of Sediment Conductivities in the Rathlin Basin Using Magnetotellurics. Oral at IRETHERM Workshop, April 1, 2016, Dublin, Ireland , and poster at Geothermal Association of Ireland Conference at the SEAI Energy Show, April 7, 2016, Dublin, Ireland

[Conference Publication] Delhaye, R.; Rath, V.; Jones, A.G.; Muller, M.; Reay, D. and the IRETHERM Team (2016) Improving Resistivity Estimate Accuracy in 3D Inversion of MT Data with Airborne EM Data. Poster at the XXIII. Workshop on EM induction in the Earth, Chiang Mai, Thailand

[Journal Paper] Delhaye, R. P.; Rath, V.; Jones, A. G.; Muller, M. R., Reay, D. , and the IRETHERM MT Team (2016) Correcting for Static Shift of Magnetotelluric Data with Airborne Electromagnetic Measurements: A Case Study from Rathlin Basin, Northern Ireland, submitted to Geophysical Journal International.

Appendix 3 – References

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