COST Action STSM, ES0701-6484, May 26th – May 31st 2010

Scientific report

1. Motivation for STSM

The principal aim of the STSM mission was to collaborate with Dr David Lavallée on the realization of a reference frame for the globally reprocessed GPS solutions that have been undertaken as part of a long-term project by the mission participant, Ian Thomas, in Newcastle. Dr Lavallée has great expertise in this field, and is the principal author and developer of the TANYA software that is to be used for the reference frame realization aspects of the Newcastle GPS reprocessing work. The main stated objectives of the visit were thus to gain an increased understanding and appreciation of both the underlying theory, and the practicalities of using the TANYA software.

The timing of the STSM was chosen to enable sufficient work to be undertaken in Newcastle prior to the mission, so as to arrive with a full set of GPS solutions to work on. The mission was timely in providing an intensive period of time working on the reference frame aspects of the project, which would be of fundamental importance in obtaining vertical rates during the the remainder of 2010, the research project culminating at the end of 2010 and the AGU Fall Meeting. The aim is to present GPS derived vertical rates to the GIA community at this conference—hence the clear relevance to this COST Action.

2. Background

Over the months prior to the STSM, I developed a strategy to carry out a global reanalysis of GPS data, with the ultimate aim of obtaining accurate vertical surface velocities in regions of GIA, largely in Antarctica, but also for Greenland and North America. The strategy developed, with much testing, has involved the processing of 80-station global GPS networks using the GIPSY GPS analysis software. At the time of the visit, the time period, 1997.0—2010.0 had been processed. I have particularly focussed on using well distributed global networks of sites, as well as on using the latest GPS analysis models (e.g. VMF1 mapping function, absolute antenna phase centre calibrations) in a consistent manner.

The realization of a temporally stable terrestrial reference frame is of fundamental importance when seeking to obtain accurate rates from GPS. The daily global solutions undertaken with

the GIPSY software are loosely constrained or ‘non-fiducial’, i.e., each daily global network is in an individual, unique realization of an Earth centred, Earth fixed (ECEF) reference frame. In order for site velocities to be estimated from the GPS station time series, each of the daily solutions thus require aligning (i.e., rotating, translating and scaling, e.g. by means of a Helmert similarity transformation) to a common coordinate frame. This can be achieved by (i) aligning each daily solution to an externally determined realization of the ITRS (e.g. IGS05, ITRF2005) by estimating and applying a 7-parameter Helmet transformation (the so-called ‘external’ approach) or (ii) Using (upto) 14 Helmert parameters in a consistent ‘internal’ approach, simultaneously estimating the site velocities, and using a No Net Rotation (NNR) criteria to create a ‘GPS only’ frame.

The TANYA software has the capability to undertake the alignment of the daily solutions using either the simple ‘external’ approach or the fully rigorous ‘internal’ approach that is independent of any external frame effects. The software has been written and developed over several years by Dr Lavallée, with additional contribution and development by members of the geodesy group in Newcastle. The chance to visit Dr Lavallée to work with him on the TANYA software, as well as discussion of the underlying theory, has proved invaluable.

The collaborative work undertaken with Dr Lavallée in Delft, that was funded and made possible by this STSM, is clearly in close alignment with the overall objectives and motivations of COST Action 03701. The final GPS derived rates from the project will subsequently be provided to collaborators in the GIA modelling community – most notably to project partners in Durham – many of whom are members of the COST Action, to be used as constraints on their Antarctic GIA models.

3. Description of STSM

3.1 Work carried out during the visit

The 5 days of collaboration with Dr Lavallée was largely spent working with the full GPS dataset that had previously been processed in Newcastle (i.e., daily loose, or 'non-fiducial' solutions for the period 1997.0-2010.0). Much of the work focused on the practicalities of using the TANYA software, as well as identification and fixing of bugs in the software. Working together with Dr Lavallée in Delft facilitated the development and enhancement of the software in an efficient and productive manner. Such development would have proved more difficult to achieve working in Newcastle without the direct input of Dr Lavallée. Alongside these practicalities, we spent several hours time discussing the underlying theory of the alignment procedure and the approaches to reference frame alignment – the 'internal' and 'external' approaches mentioned above.

For the majority of the five day mission, we focused on the alignment of the daily GPS solutions to the IGS05 reference frame. This provided daily estimates of the 7 Helmert Parameters (three rotations, three translations and a scale) required to go from the daily non-fiducial frame to IGS05. These have since been put in GIPSY x-file format. This allows the use of Precise Point Positioning (PPP) from the orbits extracted from the global solutions. Ultimately this is a powerful tool, allowing later densification of our 80-station network from our cutting edge consistently analysed orbit and clock products. This will allow us to make use of many hundreds of stations worldwide in our GIA and Tide Gauge work.

On the final two days of the visit, we worked towards an internally generated GPS frame, free of any distortion that might exist in the external frames. This was left as work in progress at the end of the mission as something to continue to aim for in the coming months.

Finally, on day five of the mission, we worked on detection of offsets in the time series, as well as outlier detection. These are important issues that have a huge impact on vertically derived rates. There is a degree of subjectivity in the detection of offsets and it an area of research that Working Group IV of this COST Action are continuing to investigate. The idea with our solutions was to add offsets visually present from the time series to a known list of offsets that is stored in the TANYA software for the IGS stations.

During the visit, much progress was made working with Dr Lavallée on the TANYA software that would not have been possible working with David remotely from Newcastle. During the course of the mission one particular problem was identified, and many smaller

problems and bugs were fixed. The significant outstanding problem on completion of the visit was concerned with the unexpectedly large Z-axis rotations that were required to rotate our 'loose' solutions to IGS05 / ITRF2005, of the order of 1E-7 radians. This is an order of magnitude larger than is seen by the IGS Analysis Centres, and caused numerical instabilities in the TANYA software, when attempting to complete a rigorous 'internal' GPS-only alignment. Such a large rotation of the whole network does not necessarily in itself affect the derived coordinate time series or the derived rates, as this information comes from the internal geometry of the network. However, there is clearly an issue within the GIPSY processing strategy as used prior to the mission that needs correcting prior to the next full set of solutions, to obtain solutions with tighter rotational constraints. This will result in rotations of similar order of magnitude to those obtained by the IGS ACs, and to enable the TANYA software to align the solutions successfully using the 'internal' approach. This was further investigated over the course of the summer in Newcastle, and after much testing and investigation, is now believed to be related to how the Earth Orientation Parameters (EOPs) were being handled in GIPSY. At the time of writing this report it is anticipated that this issue has been resolved (see below)

3.2 Immediate Scientific Results Obtained

The principal short term outcome of the 5 days (after some continued input from Dr Lavallée after the mission had finished) was a set of time series and velocities in the IGS05 frame, This was produced soon after the STSM was completed, and in time to present preliminary results in a poster at the IGS workshop in Newcastle in early July (Poster presentation, Appendix 1). This poster contains example coordinate time series from the aligned solutions for GPS sites in Antarctica (DUM1), Norway (NYAL, NYA1) and Scotland (ABER). Additionally it discusses the alignment procedure discussed above, and presents the time series of Helmert parameters derived during and soon after the STSM

In addition to these scientific advances with the work, many bug fixes and enhancements to the software were made, with functionality increased. In particular, during and after the mission, Dr Lavallée worked on implementing faster algorithms in TANYA to speed up the alignment for the GPS only solutions. Other, less tangible, but nevertheless important outcomes were an increased understanding of the reference frame realization procedure, and the effects of the realization on coordinate time series and vertically derived rates. The

knowledge gained from the visit will be of immediate benefit to the current project, but additionally, I will be able to pass on my increased appreciation of reference frame issues, and the operation of the TANYA software itself, to colleagues working on related projects in the Newcastle Geodesy group.

4. Post Mission

4.1 Ongoing work carried out since completion of STSM

Since June 2010, work has continued on the project, with significant progress being made, particularly on the rotation problem uncovered at the time of the STSM. This has required significant investigation over the course of the summer, with the cause having been identified as a mis-interpretation as to how the GIPSY software handled the EOPs, together with a number of errors in the processing scripts. Contact with Dr Lavallée had been ongoing. A second full set of global solutions has been processed in September and October 2010. This is currently undergoing the alignment procedure in TANYA, with the aim of obtaining vertical rates from precise point positioning by the end of November 2010, in time for presentation at the AGU Fall Meeting. The presentation to be given at this conference will build upon the poster presented at the IGS workshop soon after completion of the STSM in June (Appendix 1).

Further issues to be considered over the coming months include the addition of atmospheric loading corrections at the alignment stage of the process, as well as completion of the full rigorous 'internal' GPS-only alignment.

4.2 Future collaboration with Dr Lavallée

The geodesy group at Newcastle, will continue utilize the Tanya software. This software is undergoing continuous development by Dr Lavallée as well as by members of the Newcastle group. I envisage future contract with Dr Lavallée both by myself and colleagues in the geodesy group will continue at regular intervals.

4.3 Projected publications resulting from the STSM

- Dr Lavallée was a co-author on a poster presentation at the IGS workshop meeting in Newcastle, 28th-1st July 2010 (Appendix 1)
- It is envisaged that vertical rates for Antarctica will be presented in December 2010 at the AGU Fall meeting.
- Vertical rates will also be shared with the COST community as and when appropriate.

- A number of publications based on the vertical rates from this project, to which this STSM has contributed, are in progress or at the planning stage. These will include (i) a publication, with Thomas as the lead author, on the Antarctic vertical rates themselves, including a description of the advances made with the Newcastle processing and a comparison with previously determined rates (e.g. Bevis *et al*. 2009) (ii) a paper using the derived rates to correct tide gauge records for vertical land motion, in a global sea-level study. These will be submitted in the early part of 2011.

5. Conclusions

The STSM provided 5 days collaboration with Dr Lavallée that were invaluable in terms of knowledge gained by the mission participant, Dr Ian Thomas. The mission significantly benefited the project in Newcastle, and by dissemination of the knowledge gained, the wider Geodesy group. The STSM has had substantial impact on the project, which will eventually feed through to the GIA community and provide more accurate constrains on their models. It will also contribute to further work on understanding the effect of realization of reference frames on vertical rates. In addition to providing GIA constraints, the work is useful for correcting tide gauges for vertical land movement in global sea-level studies.

Reference

Bevis, M., et al. (2009), Geodetic measurements of vertical crustal velocity in West Antarctica and the implications for ice mass balance, *Geochem. Geophys. Geosyst.*, 10, Q10005, doi:10.1029/2009GC002642.

Appendix 1

Poster presentation given at the IGS2010 workshop in Newcastle, June 2010.

Appendix 2

Confirmation from Dr Lavallée at the host institute, Delft, of the successful execution of the STSM.