Integrating Point and Image Geodesy: Mutual Benefits and Requirements

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Introduction

The most demanding scientific and non-scientific requirements concerning positioning and terrestrial geodetic reference frames do not only demand increasing accuracy and temporal stability, but also high spatial and temporal resolution and low latency (Gross et al., 2007). In order to meet these demands, it is increasingly important to be able to predict reference trajectories for all points on the Earth surface, against which “anomalous motion” can be detected. In order to achieve this, is has been proposed to develop a *Dynamic Reference Earth Model* (DREM), which predicts the motion of points on the Earth based on a dynamic Earth system model assimilating geodetic and geophysical observations (Herring et al., 2007). The model will have to account for all geophysical processes known accurately enough to be modeled with a predefined target accuracy derived from the user requirements. On the one hand, this dynamic system model will require consistent assimilation of geodetic observations of surface displacements, gravity field changes and Earth’s rotation perturbations, and, on the other hand, the model will provide a reference against which displacements can be determined that are to a large extent decontaminated for known geophysical processes. Ultimately, the DREM will allow a consistent integration of point and image geodesy on the basis of an Earth system model with high spatial and temporal resolution. The DREM will be particularly useful for applications such as geohazards, monitoring of infrastructure, off-shore activities, and studies of processes in deformation zones not yet modeled by the DREM.

Current Geodetic Reference Frames

Current global *Geodetic Reference Frames* (GRF) consist of a set of globally distributed reference points with coordinates $\vec{X}^{(i)},\ i = 1, N$ at a reference epoch t_{R} and constant velocity vectors $\vec{V_0}^{(i)}$, where N is of the order of 500. The points implicitly determine the axes, the *Reference Frame Origin* (RFO), and the scale of the underlying reference system. The temporal evolution of the secular polyhedron defined by these points over time t is given by $\vec{X}^{(i)}(t) = \vec{X_0}^{(i)} + \vec{V_0}^{(i)}(t - t_0)$, i.e., the so-called regularized coordinates. In addition to the secular polyhedron, the frame also includes a set of models that describe deviations of the actual motion of the Earth’s surface from the secular polyhedron. In order to be able to assign predicted (expected) reference coordinates to any point on the Earth’s surface, knowledge of the global velocity field $\vec{V_0} = f(\vec{X})$ would be required. This is currently not available. However, with the help of precise satellite obits and clocks, precise point coordinates can be determined in the GRF defined by the polyhedron. Precise orbits and clocks are determined on a daily basis in a free solution which is then aligned to the reference frame. The methodology used for this alignment as well as the mathematical model for the reference point motion determines the degree to which geophysical signals are filtered and potentially aliased into the displacement time series.

The simple mathematical model of regularized coordinates has three major problem: (1) The actual motion of the reference points is not linear in general. Deviations from linear motion are due to tides, surface loading, and processes in the solid Earth, including pre-, co-, and postseismic displacements. For large earthquakes, the latter can be of regional to global nature. Currently, only tides are taken into account. (2) The methodology used for the alignment of solutions to the GRF as well as the mathematical model for the reference point motion constitute a technique- and solution-dependent filtering of unaccounted geophysical signals, which alias these signals into displacement time series and hampers comparison of observations to model predictions and between techniques. (3) The velocity vectors have errors, which over time can deform the polyhedron considerably, thus requiring frequent updates of the GRF.

References

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Towards a Dynamic Reference Earth Model (DREM)

Having more elaborate models for the prediction of the Earth’s surface motion available, the secular model could be replaced by $\vec{X}(t) = \vec{X_0} + \delta\vec{X}(t)$, where the displacement field $\delta\vec{X}(t)$ is predicted by a DREM. In principle, this DREM predicts the displacement field $\delta\vec{X}(t)$ for any point on the Earth’s surface and for any time t. ’Anomalous motion’ is defined as deviation from the motion predicted by the reference model. This rigorous approach is sketched by Herring et al. (2007). It is the anomalous motion, which is of interested both scientifically and for practical purposes such as monitoring potentially hazardous (seismic, volcanic, instable) areas.

In order to achieve physically meaningful GRFs, the DREM has to account for most of the known geophysical signals. In the absence of a sufficiently elaborated Earth system model, a DREM will have to be composed of a set of independent nested models, with each of them representing a subset of the relevant physical processes, including coseismic and postseismic displacements of great earthquakes, atmospheric, hydrological, and cryospheric loading, ocean tidal and non-tidal loading, and postglacial rebound. Thus, in a first implementation of the DREM, we will describe the displacement field by $\delta\vec{X}(\vec{X}, t) = \sum_{j=1}^{M} \vec{g}^{(j)}(\vec{X}, t)$, where the $\vec{g}^{(j)},\ j = 1, M$ are the displacement fields determined from the M geophysical models representing Earth tides, surface loading, earthquake processes, and other surface displacements. In a later step, an Earth system model with coupled atmosphere, ocean and solid Earth modules could be used to achieve a self-consistent modeling of most of these processes.

Taking into account the expected accuracy of the different models, the DREM to some degree will have to assimilate observations from a global network of GPS stations, as well as observations of the gravity field and the Earth’s rotation. In particular in deformation zones, assimilation of high resolution observations from SAR and other imaging techniques will also have to be considered.

Crustal Deformation Component of the DREM

One component of the DREM will be the crustal deformation field in plate boundary zones. Some of these zones are quite broad (e.g., $>$1000 km in the western U.S.), so a reference motion should include what we know about the (sometimes complex) crustal block interactions that occur between the reference points in the DREM. The respective component of the DREM would include information about the Earth’s structure and rheology, where the faults are located, how they respond to the application of far field stresses, how the solid Earth responds to earthquake events, and other time-dependent phenomena.

We provide here an example of the northern Walker Lane belt in western Nevada and eastern California. This zone accommodates $\sim$25% of the relative motion between the Pacific and North America plates, and is a integral part of the plate boundary system. Tectonic motion in this region includes contributions from secular (e.g., crustal deformation) and transient processes (e.g., viscoelastic postseismic relaxation) that together provide localized velocity gradients of 4-5 mm/yr over zones $\sim$50 km across (Figures 1 and 2), and include multiple fault systems with different styles and strikes (Figure 3). Furthermore, it is not certain that all instances of recent fault slip activity have been detected through geological investigation, so any block model might be incomplete.

We use block models of crustal deformation to integrate geodetic observations of surface motion with geological observations of crustal deformation. Because of the region’s complexity the models require relatively small blocks, with dimensions on the order of the crustal thickness or smaller ($\sim$30 km). When using only GPS to constrain these models the inversions can be underdetermined because the number of free parameters is large. Trade-offs between slip rates on nearby faults also can make it difficult to constrain block models with sparse GPS point measurements.

Acknowledgments

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InSAR Contribution to the DREM

InSAR can contribute to the development of a DREM by:

1) Constraining slip rates on block bounding faults via the block modeling, and thus better constrain the spatial complexity of surface motion between DREM reference points (provided by GPS);

2) Identifying places where faults exist, but have not been characterized by geologists and thus contribute to the development of more accurate and detailed block models;

3) Identifying and quantifying transient phenomena (e.g., earthquake cycle, volcanic events, mining effects) that can contribute to developing the DREM elastic and viscoelastic structure;

4) Identifying reference points (in particular GPS sites) with locally anomalous motion, potentially biasing the global reference polyhedron.

Benefits of the DREM for InSAR Applications

The DREM can contribute to InSAR applications by:

1) Providing as a standard product a reference phase map that can be based on all DREM processes affecting surface motion.

2) Comparing subsequent radar scene to this reference phase map rather than paired to previous single scenes, thus eliminating the noise sources on one side of the pair.

3) Using the predicted displacements in regions where the DREM is know to have a high reliability, to improve atmospheric estimates from InSAR.

4) Detecting of anomalous displacements through comparison of InSAR images to the DREM predictions.

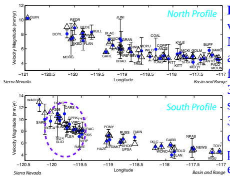

Figure 1: Magnitude of GPS velocity with respect to stable North America (SNARF, Blewitt et al., 2005) across east-west profiles for a) north profile (sites between 39.75° N and 40.5° N latitude), b) south profile (between 38.5° N to 39.75° N). GPS velocities (blue dots) have been corrected for postseismic relaxation from CNSB earthquakes, and are shown with the scaled 2-sigma uncertainty bars. Open triangles are the velocity predicted from the block model shown to the far right.

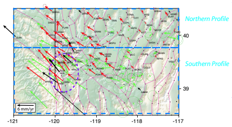

Figure 2: Block boundaries and GPS velocities from MAGNET (red), regional continuous sites (black), and campaign GPS sites (green) with respect to easternmost side of the area (average velocity between longitudes 117° W and 177.3° W). Ellipses around tips of vectors denote uncertainties at 95% confidence, (where they appear missing they are too small to see). Names of MAGNET and continuous sites are provided. Dashed blue blue boxes show which sites are part of the the southern and norther profiles.

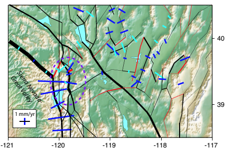

Figure 3: Slip rates on faults inferred from GPS velocities. Black (red) lines indicate inferred dextral (sinistral) slip, with line thickness indicating rate. Blue (cyan) segment crossing a fault indicates normal (reverse) slip with length indicating rate. Only slip rates that are significantly different that zero to 95% confidence are shown.