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Exploration of spatial and temporal signatures in multiple components of a Geodetic Earth System Model

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Abstract: Aim of this project is to develop novel methods for a better understanding of temporal signatures - both in their spatial and spectral domains - arising from multiple components (subsystems) of a Geodetic Earth System model (GESM). This model is specifically dedicated to predicting geodetic measurements, either coupled or independent for each subsystem. Methods of interactive visualization provide the means to subsequently explore variations of mass signals over time in the spatial and spectral domains, assess their superpositions in the geodetic measurements, and identify their signal and noise characteristics. This information is important to assess the sensitivity of the geodetic measurement to a specific processes, and to explore methods for separating superimposed signals.

In this paper, we present requirement on the system's design and the visual interface to support exploration of mass signals over time in the spatial and temporal domain. As a first result of our research, we propose a data model that supports the retrieval of all relevant spatial and temporal aspects of the data in real-time.

Keywords: Exploratory Data Analysis, Earth System Model, Geodesy, Spatial and Temporal Signatures, System Design

1 INTRODUCTION

Space geodetic observations have advanced our knowledge of processes in the Earth System, and are valuable constraints for initializing and validating complex Earth System models. A geodetic measurement is characterized by its distinct spatial and temporal properties, as well as by the interrelated observational signal and noise. Geodetic measurements usually reflect superimposed signals originating from different processes within the sub-systems of the Earth (e.g., hydrological water storage, ice-dynamic flow, etc.), and the interpretation of a geodetic observable may require simultaneous consideration of multiple components of the Earth System.

In the last decade, satellite measurements of the temporal variations of Earth's gravity field have advanced to become an important new geodetic observable (Tapley et al. [2004]). Gravity field variations are difficult to interpret without considering all subsystems in the Earth; according to Newton's law of gravitation, each mass causes a disturbance of the gravitational potential also in the far-field of the source, decaying with the inverse of the distance. Therefore, satellite gravimetry measurements over a certain region always contain a signal exerted by mass variations in another region, sometimes within the same, sometimes within a different sub-system. The interpretation of satellite gravimetry measurements over a certain region therefore requires exploring how other mass variations influence the measurement, and assessing the possibility for their separation.

In this paper, we present the system requirements and the initial steps in the development of a visualization tool for exploring – in a quantitative manner – spatial and temporal signatures. in satellite gravimetry observations arising from mass variations in multiple sub-systems of the Earth. Associating the mass variation with the gravitational signal requires providing a spatial and temporal context, which allows the attribution of the mass variation and its signal to the respective sub-systems. Efficient and interactive visualization can assist with this task by providing an environment for a geographic depictions, an overall quality assessment of the GESM outputs, and, if dedicated algorithms are implemented, a quantitative exploration of the spatial and temporal signatures.

Since the underlying purpose of the components of the Earth System lies in the simulation/calculation of geodetic observations, we henceforth refer to our model as a Geodetic Earth System Model (GESM).

2 Exploration of Spatial and Temporal Signatures

The aim of our exploration tool is to support scientists to gain insight into the spatial and temporal signatures in satellite gravimetry observations. Our tool supports scientists to see an overview of the variation of the mass signal in its spatial context (see Figure 3), and its temporal context (see Figure 5). Since a proper understanding and interpretation of satellite gravimetry measurements requires to explore how mass variations of other sub-systems influence the measurement, our tool allows scientists to explore the influence of these variations by synthesizing a GESM through adding or removing different sub-systems in real-time. After a description of the data, we present in this section the requirements on our system, which arise from making the spatial and temporal context of the GESM readily accessible by interactive visualization, and the resulting object-oriented design of our system.

2.1 Data: Subsystems of a GESM

The components of the GESM represent independent or coupled physical models of the sub-systems in the Earth; here, it includes continental hydrology, cryosphere, ocean, and the Earth's interior. The output, here, surface-mass changes, of the models are provided as standardized text files. Each file describes a geo-spatial grid with over one million grid points. The tuple (longitude,latitude) represents a grid point. A single file describes the mass variation signal for each grid point of a component at a particular time lag. The schema <component>.<region>.<year>.<month> describes the files. A similar model was assembled and provided for download, e.g., by Gruber et al. [2011].

2.2 System Requirements

Our system has to fulfill two main requirements: the synthesis of a GESM from multiple components and the exploration of the spatial and temporal signatures arising from the mass variation in the synthesized GESM. Interactive visualization needs to provide timely, defensible and understandable assessments of these signatures. To support exploratory analysis of the spatial and temporal signatures, the visual interface needs to have efficient access to spatial (grid points) and temporal data (time series describing the variation of the mass signal). Since scientists may use other exploration tools, the design of our system supports the adaptation to future requirements of the working environments and application scenarios. This is important since the exploration of spatial and temporal signatures is an important initial step in our scenario. In the following sections, we discuss our design decisions in our tool to meet these system requirements.

2.3 System Design

Figure 1 summarizes the main components and the data flow of our tool. Albeit many interactive visualization tools utilize a similar data flow schema Upson et al. [1989], our system design is specifically targets the synthesis of a GESM and the exploration of spatial and temporal signatures of the mass variation.

Our system design separates the procedure to read data from a data source from the organization of the data in main memory and the visual interface. The separation provides a flexible abstraction from raw data for interactive visualization. It allows us to read components from different physical representation and location, to query any detail of the components such as a particular grid point at a certain time step, and to perform analytical operation in main memory such as synthesis of different versions of the Earth

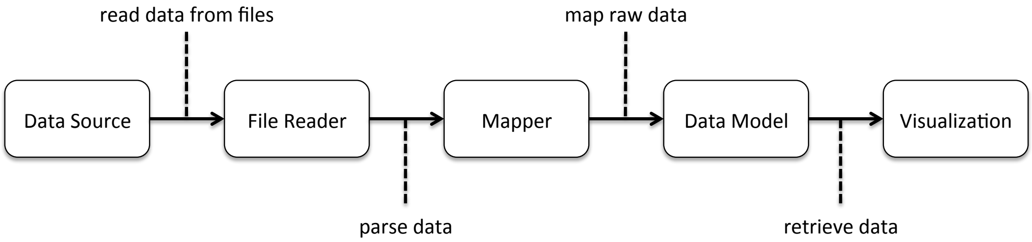


Figure 1: **Components of our systems and data flow**

System model from various ensembles of components. We plan to adapt our tool along the requirements of our specific application scenario, such as higher spatial resolution of the sub-systems or time series covering a long time horizon. The research issues related to consider our tool as part of a distributed system to handle the synthesize large GESM and their interactive exploration is left for future work.

Our system design utilizes flexible software components. An interesting approach is to provide our exploration system as a web-based software where the causal user does not care about the underlying implementation of the components. Flexible software components provide an abstract description of the responsibilities of each component. The professional analyst can use this abstract description to easily customize each step of the exploration pipeline. The benefit of flexible software components is that the advanced user can easily substitute an existing class, e.g., to replace a file with a database as data source, or modify objects.

We utilize an object-oriented design since it helps to implement flexible software components, to organize our design decisions, and the thoughts of users to design future extensions of the system.

3 Our System

3.1 Data Source and Mapper: Fast and easy access to sub-systems

To support the access of components with different formats and locations, we model the locations of raw data as the class *Data Source*. The Data Source class implements a well-defined interface, and the user can easily implement its own Data Source version. A *Mapper* transforms raw data from a Data Source into the index scheme of the *Data Model*. The Mapper class involves to parse the raw data into single tokens, which are then inserted into the index scheme. The well-defined interface of the Data Source allows us to transform the data into the index scheme of the Data Model with arbitrary Mappers.

3.2 Data Model: Fast In-Memory Synthesis of the GESM

For a real-time retrieval of all relevant issues of the data, we employ in-memory computing. In-memory computing means the efficient organization of all components of a GESM in main memory, as well as the synthesis of the Earth System and all necessary details in main memory. The organization of the data in main memory is described by a data model, which allows us to easily find data and to associate data items with each other. It also supports the synthesis of the GESM model in main memory by an integration of different components from many different formats.

Figure 2 illustrates the basic idea of our data model. Our data model is a hierarchical index that organizes the spatio-temporal data according to their TimePoint, according to their Subsystem and according to their spatial grid point, which we will refer to as GeoItem. The data model has associated manager classes, which compute unique indices for each time step, sub-system and grid point.

TimePoint: Hierarchical Organization of the Subsystems. Our data model organizes the components of a GESM in a set of TimePoint objects. Each TimePoint object

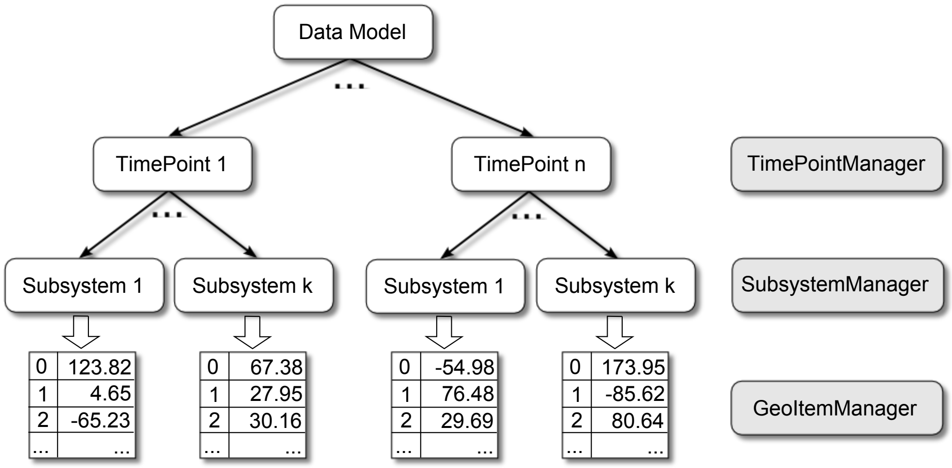


Figure 2: **Data Model for fast access to temporal and spatial information**

describes the grid points at a particular time step. TimePoint objects use Subsystem objects to store the GeoItem objects of a component at a particular time step.

Subsystem: In-Memory Synthesis of the Earth System Model. Subsystem objects manage and store all grid points in main memory as GeoItems with an associated mass variation signal.

Subsystem objects implement a merge function to synthesize the Earth System model by combining different components. The merge function is one of the key algorithms for in-memory computing. The parameters of the merge function are two Subsystems, and it returns the merged Subsystem as result. Depending on the application scenario, additional algorithms for in-memory computing can be implemented.

GeoItem: Representation of Grid Points of a Subsystem. The GeoItem object represents a grid point in main memory. Each grid point has an associated mass variation signal. To efficiently find GeoItems in main memory, the GeoItemManager assigns a unique ID to each GeoItem object.

Our GeoItem-ID is a 32-bit integer value, which is derived from the longitude and latitude coordinates. We assume a 32-bit double precision coordinate u in the format $u = s \times m \times 2^E$, with s as the sign and m as the mantissa. Longitude coordinates range from -179.75 to 180.00, latitude coordinates from -89.75 to 90.00. Considering a grid resolution of 0.01, by shifting the bits of the mantissa m twice to the left, we need to encode $36,000$ or $18,000$ values. Therefore, every value within the longitude and latitude range can be encoded using 16 bits. As a result, both components, longitude and latitude coordinate, can be encoded within one 32-bit integer value. The two least significant bytes represent the latitude coordinate and the two most significant bits represent the longitude coordinate.

Mapping two 32-bit double precision values to one 32-bit integer enables an efficient utilization of the main memory. Note, the feasibility of encoding geo-spatial coordinates into a single integer depends on the grid resolution and, thus, on the precision of the longitude and latitude coordinates.

4 Visual Interface

Exploration is an iterative process of asking questions, creating visual views to the data, and discovering potentially interesting patterns Andrienko and Andrienko [2006]. In our application, we are interested in spatial and temporal patterns of the mass-variation signal. To support this cycle of exploration, our data model enables scientists to easily

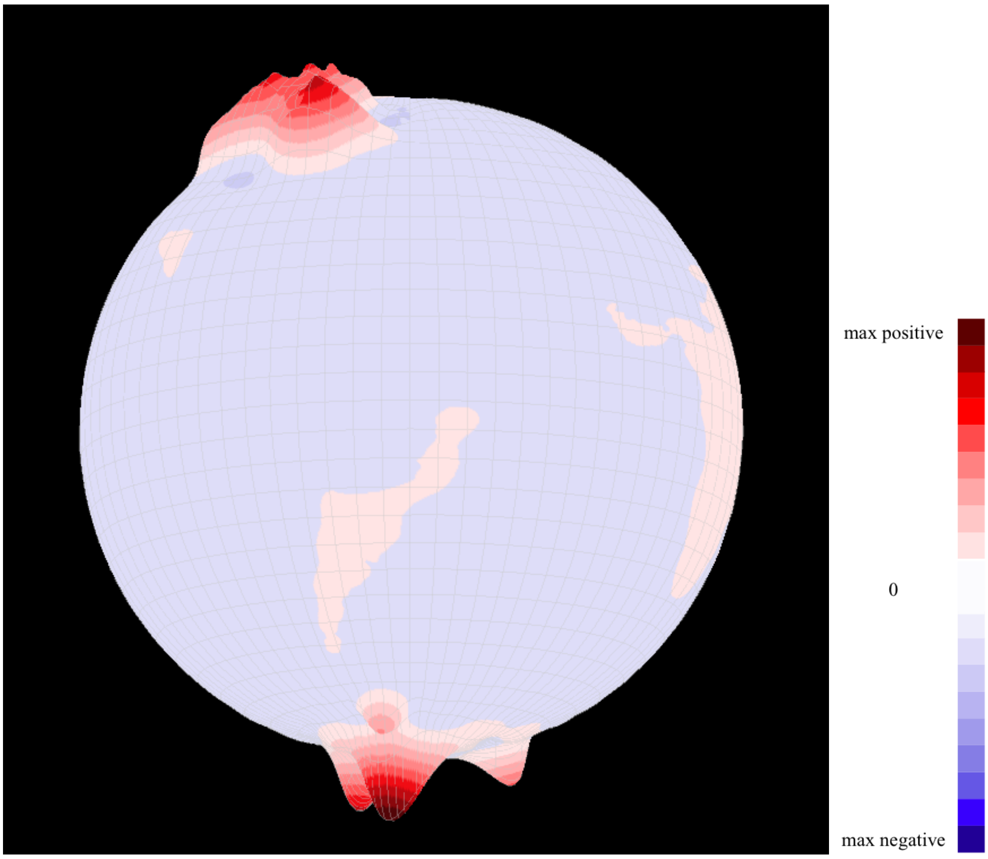
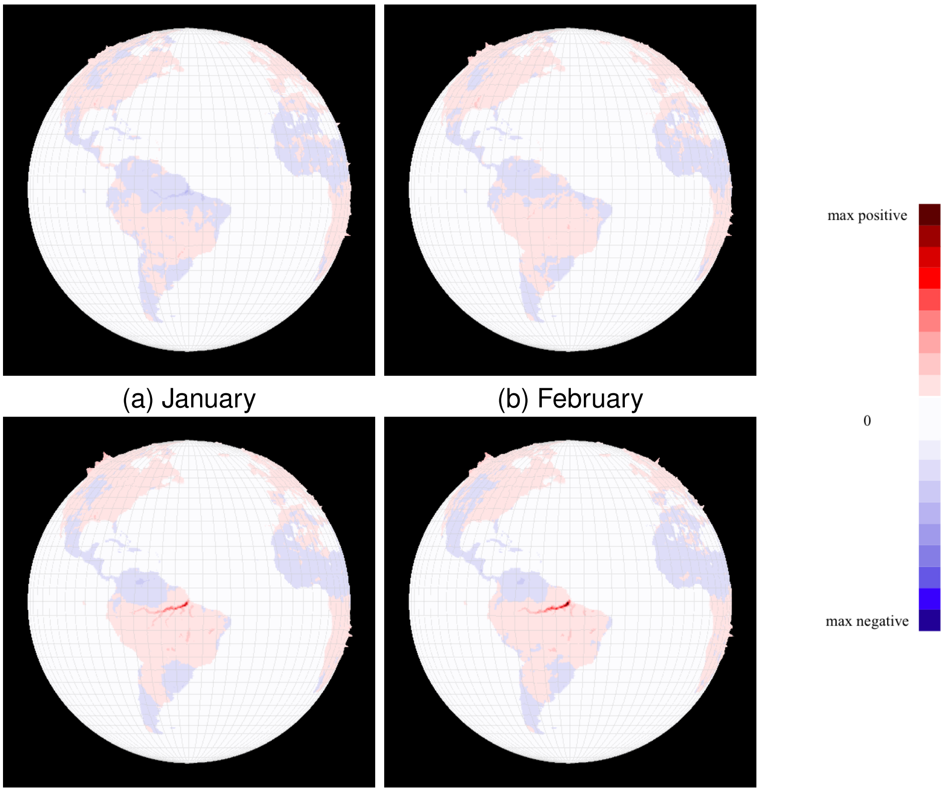


Figure 3: Visualization of the spatial context of GIA mass variation signal in the GESM

and incrementally change the synthesized GESM in real-time. The focus of our future research is on the development of novel visual views of the temporal signatures of the mass variation in its temporal and spatial context.

Figure 3 shows the spatial context of the GIA mass variation signal (here, at time step December 2005). Note, white lines represent the underlying grid of the GESM. GIA describes the slow adjustment of the Earth's interior to glacial loads present at the last glacial period. The visual encoding of the mass variation at each grid point is twofold. First, we map each mass variation value to a height value; the resulting positive variation of many grid points results in mountain landscape in Figure 3 on the sphere. This visual encoding focus the attention of the user to potentially interesting spatial signatures. Second, we map each mass variation value to a color. The color presents the magnitude of the variation to the user. Users can generate customized color palette based on hue, saturation, and contrast of the colors. We implemented an algorithm that computes color palette with arbitrary number of color based on these three parameters. In contrast to other mass variation processes, GIA is approximately characterized by a temporal linear trend, which is nearly constant over decanal time scales.

We developed a novel view to present this temporal information to the user. An established approach to present multiple time steps on the screen are small multiples (Tufte [1983]). Figure 4 shows a small multiple visualization of temporal signatures of the subsystem hydrology. It shows an interesting temporal signature of the Amazonas delta from negative to a positive mass variation. We extended this idea to present a small 'slice' of the spatial context for a particular time lag on the sphere. We visually encode a time period by mapping many of such slices according to their temporal order to the sphere. Figure 5 shows the resulting spatial and temporal signatures of mass variation of the



(a) January (b) February (c) March (d) April

Figure 4: Temporal variation of the mass signal of the subsystem hydrology (Jan – Dec 2005)

sub-system hydrology.

The second focus of our research is on the development of novel interaction methods for effective navigation in space and time. The involved time series describe a long time horizon, which is a challenging problem in exploratory data analysis. At the current state, the user can explore the temporal information in Figure 5 by rotating the sphere. An evaluation of the spatio-temporal visualization and its interaction is left for future work.

5 Outlook

After the visualization of mass variations, their superposition, and relation to the sub-systems is accomplished, algorithms will be implemented that simulate the geodetic observations; here, the temporal gravity field variations of satellites [ESA/ESTEC & The NG2 Team, 2011]. It is plasnned that the user will interact with the visualization interface to select individual sub-systems, individual regions or complete suites of sub-systems of the GESM, and interactively explore the connection between the source of mass change and the predicted geodetic measurement. Then, noise properties of the measurement instruments will be included in order to degrade the simulated signal, and from the degraded measurements mass variations will in turn be recovered. At the final stage, comparison with the initial and recovered mass variations will then form the basis for optimizing the instrumental setup – in the case of satellite gravimetry this will assist to design mission concept.

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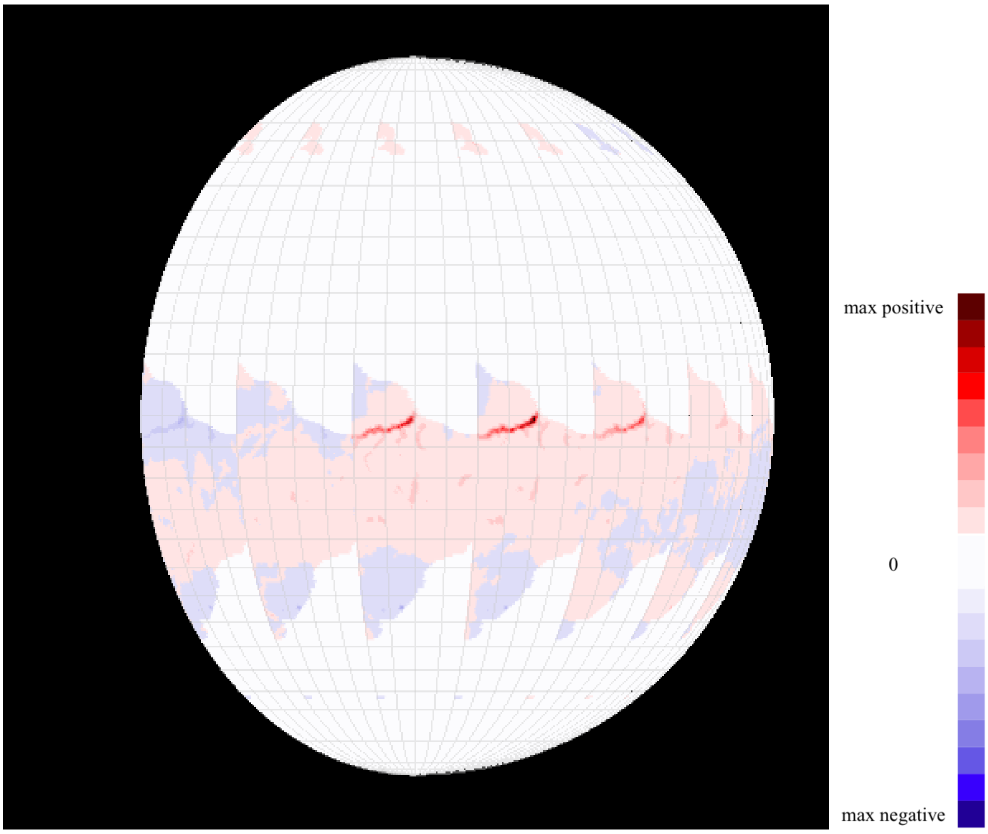

Figure 5: Spatio-Temporal context of the mass variation signal of the Amazon delta (Jan – Dec 2005)

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