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Real-Time Ray-Tracing through Numerical Weather Models for Space Geodesy

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Abstract. Numerical weather models have undergone an improvement of spatial and temporal resolution in the recent years, which made their use for space geodetic applications feasible. Ray-tracing through such models permits the computation of total troposphere delays and ray-bending angles. At the National Institute of Information and Communications Technology (NICT) the so-called KAshima RAy-tracing Tools (KARAT) have been developed which allow to obtain troposphere delay corrections in real-time. Together with fine-mesh weather models from the Japanese Meteorological Agency (JMA) huge parts of the East Asian region, including Japan, Korea, Taiwan and East China, can be covered. Thus a short overview about the capabilities and functions of KARAT will be given and computation performance issues will be discussed. The ray-traced total troposphere slant delays can be used as a correction of space geodetic data on the observation level.

1. Introduction

The introduction of new mapping functions (e.g. [1, 5]) in recent years significantly improved space geodetic techniques. Although modern mapping functions are derived from numerical weather models the information from such meteorological data sets is reduced to a few time-dependent and location-dependent coefficients which relate slanted troposphere quantities to equivalent zenith measures. Moreover, the spatial variations of the troposphere above each station have to be estimated in the analysis process in the form of gradient parameters. As numerical weather models of regional size have undergone an improvement of accuracy and precision it became feasible to utilize ray-traced troposphere slant delays directly for the geodetic analysis of space geodetic techniques.

1.1. Mesoscale Analysis Models from the JMA

The Japanese Meteorological Agency (JMA) provides a variety of weather models ranging from global models to fine-mesh models which cover an area of only a few tens of kilometers. The meso-scale 4D-Var model (i.e. Meso-scale Analysis Data (MANAL)) from JMA [4] with its horizontal resolution of about 10 km was found to have the best trade-off between grid-spacing and area size. This model covers large parts of Eastern Asia, including Japan and its Southern islands, Korea, Taiwan, and Eastern China (Fig. 1). Moreover, the three hour time-resolution of the data sets makes the appliance of this model for positioning applications feasible.

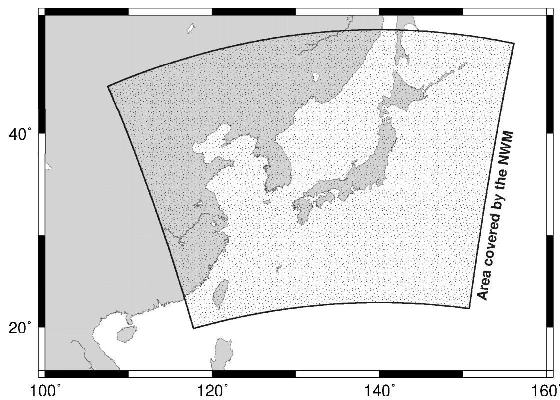

Figure 1. The spatial domain for which JMA meso-scale weather models are available

2. Kashima Ray-Tracing Tools (KARAT)

Based on the requirement to deliver ray-traced delays in real-time (assuming that numerical weather models are available as forecast data) a set of tools has been created in order to carry out the ray-tracing tasks. Coding in C++ does not only permit to design the modules close to machine language, but also allows to interface external classes which enable multi-core/multi-processor support. A detailed description about KARAT and its performance can be found in [2].

2.1. Preparing the Data

Since the grid points of the JMA mesoscale weather models are not equally spaced on a geographic coordinate system it is necessary to interpolate them onto a rectangular grid. Moreover, it is mandatory to transform the geopotential heights, which are used by the meteorologists, into geometric heights, which can be used for ray-tracing calculations. Thus, the first tool of KARAT handles all these tasks, using a sophisticated interpolation algorithm which allows to compute refractivity values on a geographic grid with user-defined boundaries, resolution, and height steps. Each epoch of the numerical weather model is processed by this tool and binary files are created for follow-on processing. As described by [3], a dedicated height system helps to reduce the number of necessary height levels without accuracy degradation of the ray-traced slant delays.

2.2. The Ray-Tracer

The main module of KARAT is the ray-tracing engine which reads consecutive binary weather models, covering a 24-hour period and loads the refractivity fields into free memory. Once all the data is put to memory, ray-tracing cores can be launched independently. Each core is at idle status until station position and ray-geometry (i.e., time, azimuth, and elevation) are parsed to it. As KARAT uses OpenMP to take advantage of multi-core and multi-processor architectures, the number of available ray-tracing cores is only limited by the number of CPU cores which share the same memory. KARAT offers three different modes (Fig. 2) in which the ray-tracing can be carried out. The fastest,

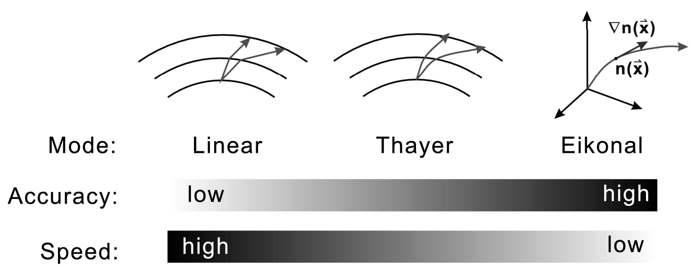

Figure 2. The three ray-tracing modes of KARAT together with their accuracy and speed performance

but least accurate one assumes linear ray-propagation between two height levels and computes the refraction when the ray-crosses a layer. The more advanced mode, considers that the ray is also bent when propagating between two levels. This mode is called Thayer, named after the corresponding paper [6]. Both modes fully consider the 3D refractivity field, but do not allow for out-of-plane propagation of the ray. The most sophisticated, but also slowest mode solves the Eikonal equation numerically and provides the 3D ray-path together with the total delay. As the differences between the Thayer and the Eikonal model hardly exceeds the mm-level at lowest elevations (3 deg) the Thayer mode is often selected as a compromise between speed and accuracy.
The ray-tracing module allows to handle geometry or reads RINEX files and computes the observing geometry using IGS orbit information. Moreover the reduction of troposphere delays is supported by correcting code and phase measurements directly in the RINEX files.

3. Ray-Traced Troposphere for Space Geodesy — First Results

In [2] the impact of ray-traced troposphere delays on precise point positioning with GPS was analyzed. As the numerical weather models currently do not allow to obtain mm-accurate slant troposphere delays, it was necessary to estimate a residual troposphere delay, when using ray-traced data sets. Station height repeatabilities of several GPS sites in East Asia could be improved when KARAT data was used. Moreover the RMS of the residuals were found to be at the same levels as those obtained from modern mapping functions and gradient estimation. Additionally, the authors could show that positioning solutions with cm-range accuracy could be achieved when the ray-traced data was analyzed without residual troposphere estimation.
In order to apply such corrections to VLBI measurements it is necessary that both stations are either within the same high-resolution weather model or that several regional numerical weather models are used to consider the weather conditions at each site. Although KARAT is currently only dealing with mesoscale data from JMA it is possible to handle numerical weather models from other weather agencies. Tests with ray-traced troposphere slant delays for East Asian VLBI networks are planned for the close future.

4. Kashima Ray-Tracing Service

In order to enable users of space geodetic techniques to take advantage of KARAT without the need to access numerical weather models by their own it was decided to provide ray-tracing as a service. Thus the ray-tracing tools will be embedded in an automatic processing chain, called Kashima Ray-Tracing Service (KARATS), which can be started via a Web interface. Fig. 3 shows how KARATS is expected to operate. Once a user (from the GPS or VLBI

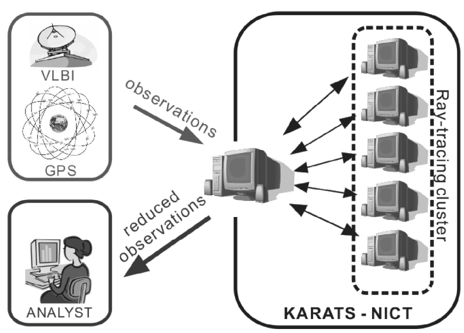

Figure 3. Flow chart of the KARATS processing chain. KARATS will subtract troposphere delays from the user's observation based on the geometry computed from precise orbits (GNSS) or source positions (VLBI)

community) has taken his observations, he can send the data in a common format (which will be RINEX for GPS and MK3/FITS for VLBI initially) via Internet to KARATS. Thereafter the Web server will do a rough data-check and compute the geometry from the observation file. As soon as a ray-tracing client becomes available it will send the geometry file to that machine. The client performs the ray-tracing through the weather model and sends the tropospheric delays back to the server. Thereafter the ray-traced delays are subtracted from the user's data and a "reduced" observation file is sent back to the user. Thus the analyst can estimate his target parameters without spending too much effort on estimating tropospheric delays. In the case that VLBI observations are submitted it is checked that both stations lie within the boundaries of the NWM and thereafter the tropospheric delays are computed at each station. In a final step the server will compute the differenced corrections and apply them to the VLBI observations.
Moreover it is planned to run KARATS for real-time applications. Since this mode needs weather prediction data from the JMA it will be limited to a selected user group. The KARATS post-processing mode will be free of charge and a turn-around time of one minute per (RINEX) file is anticipated.

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