Development of a VMF1-like service at UNB

Landon Urquhart and Marcelo C. Santos

Department of Geodesy and Geomatics Engineering,
University of New Brunswick, Fredericton, NB, E3B 5A3

Abstract

The International Association of Geodesy, under the Global Geodetic Observing System (GGOS) project [Plag and Pearlman, 2009], has been engaged in providing its *stamp of approval* to geodetic parameters generated as a service to the scientific community at large. One of them is the Vienna Mapping Functions (VMF1) and accompanying ray-traced zenith delays. These products are provided on an operational basis through the GGOS Atmosphere project. They are generated by the group at the Technical University of Vienna using data from the European Centre for Medium-Range Weather Forecasts (ECMWF). At UNB, we have developed capabilities to generate VMF1 (called hereinafter as the UNB VMF1) using data from the Global Environmental Multiscale (GEM) and from the National Center for Environmental Prediction (NCEP) models. The benefits of the service would include: 1) a backup in the event of the ECMWF VMF1 or zenith delays being unavailable; 2) greater compatibility with other NWM derived corrections, such as atmospheric pressure loading and; 3) the availability of tropospheric delay products derived from an independent source and ray-tracing algorithms should provide more robustness for combination products which use these models. Since the UNB-VMF1 uses different ray-tracing algorithm and different NWM they will also provide additional data for scientific investigations. The UNB VMF1 has been generated on a test-basis for a few months and first results comparing it with the VMF1 will be presented at the 2011 International Union of Geodesy and Geophysics (IUGG) General Assembly [Landon et al., 2011]. This white paper elaborates on the idea and motivation behind the UNB VMF1 and potential future steps.

Introduction

In recent years, numerical weather models have been used operationally to improve the accuracy of space geodetic techniques. The Vienna Mapping Function 1 (VMF1) Service, which falls under the Global Geodetic Observation System: Atmosphere (GGOS Atmosphere http://ggosatm.hg.tuwien.ac.at/), provides ray-traced zenith delays and slant factor models derived from numerical weather model data on a 6 hour basis, which can then be applied for modeling the tropospheric delays in space geodetic observations.

The VMF1 mapping functions have been shown to be the most accurate mapping function to date [Tesmor et al., 2007]. They are currently recommended for all precise geophysical applications, in particular if geophysical signals are to be investigated [Boehm and VanDam, 2009]. At this time the International GNSS Service (IGS) has not adopted the VMF1 in the operational analysis routines, which may be due to concerns in the products availability. The VMF1 mapping functions are recommended by the International Earth and Reference Frame Service (IERS) in their most recent publication of the *IERS Conventions*.

The provision of a UNB VMF1-like service, would improve the availability of VMF1 mapping functions making it less likely of a disruption in the service. Additionally, the independent source of the VMF1 mapping functions and the ray-traced zenith delays may be beneficial in improving the robustness of the IGS/IERS combined products as it would provide an independent source for tropospheric corrections. A UNB service would also act as a basis for developing improved tropospheric products such as azimuth dependent VMF1 or ray-traced slant factors at the observation level.

First, a review of the current VMF1 service is provided. Next, we describe the benefits to providing an alternative source of corrections to the geodetic community. Finally, we look into the implementation of the VMF1-like service, discussing the distribution to users, NWM data provider and ray-tracing algorithms.

Current VMF1 Service

The VMF1 service relies on a numerical weather model produced by European Center for Mid-range Weather Forecasting (ECMWF) and is implemented on the super-computing facilities of the ECMWF. The underlying functional formulation for describing the elevation angle dependence of the tropospheric delay is given by Marini [1972], normalized to yield unity at the zenith by Herring [1992]:

$$\kappa(\epsilon) = \frac{1+\frac{a}{1+\frac{b}{1+c}}}{sin\epsilon+\frac{a}{sin\epsilon+\frac{b}{sin\epsilon+c}}}.$$

The b_h and c_h coefficients for the hydrostatic mapping function are determined from a least squares fit of ray-traced observations taken at 9 elevation angles, through monthly mean profiles of the ECMWF 40 year reanalysis data. The b_h coefficient is equal to 0.0029, while the c_h coefficient is fit to the expression:

$$c = c_0 + \left[\left(\cos\left(\frac{doy-28}{365}\cdot 2\pi + \psi\right) + 1\right)\cdot \frac{c_{11}}{2} + c_{10}\right]\cdot(1-\cos\phi),$$

where doy is the day-of-the-year, ψ specifies either the northern or southern hemisphere and ϕ is the station latitude. The value of the coefficients are shown in Table 1.0.

Table 1 Coefficients for the VMF1 mapping functions

Hemisphere	c_0	c_{10}	c_{11}	ψ
Northern	0.062	0.001	0.005	0
Southern	0.062	0.002	0.007	π

The b_{nh} and c_{nh} coefficients for the non-hydrostatic mapping function were deemed to be less important as the non-hydrostatic delay is typically 10 times smaller than the hydrostatic and therefore the coefficients remain to be fixed to those of the NMF [Niell, 1996] at the 45° elevation angle, where b_{nh} and c_{nh} equal 0.00146 and 0.04391 respectively.

The a coefficient is determined by ray-tracing through the ECMWF analysis on a 6 hour basis at an initial elevation angle of 3.3° and then inverting equation 1. In this case, the corresponding outgoing elevation angle, which should be equal to approximately 3°, must be determined from the ray-tracing procedure in order to solve for the a coefficient. This approach is used for both the hydrostatic and non-hydrostatic mapping functions.

Originally, the VMF1 was produced on a site specific basis, however, this was seen as a limitation as it constrained its use to only those stations for which the coefficients were computed. For this reason, the VMF1-grid coefficients are produced to allow users to simply interpolate the coefficients to the required location. Kouba [2008] showed that the difference between the gridded and site VMF1 were negligible and therefore the VMF1-grid is more desirable as it can be applied for all locations.

In the case of the VMF1-grid, the a coefficients are provided on a 2.0° X 2.5° lat/lon grid and are computed every 6 hours at 0, 6, 12, and 18 UT at elevations corresponding to the grid nodes of the file *orography_ell* which provides ellipsoidal heights over the entire globe[1]. The a coefficients are reduced to the ellipsoid (referred to as "zero height") and in order to apply them, the subroutine vmf1_ht.m must be used which applies a height correction to determine the a coefficient for the actual station height. The height correction to obtain the coefficient at the actual station height is simply the inverse of the height reduction to obtain the coefficients on the ellipsoid.

In addition to the mapping function, the zenith hydrostatic and non-hydrostatic delays are also provided in the gridded format. The zenith delays are provided at mean grid heights corresponding to the ellipsoid height in *orography_ell* and the zenith delays must be corrected for the difference in the gridded height and the actual station height. Several options are available and they are discussed in Kouba [2008] and Fund et al. [2009]. This correction is performed by the user and is not part of the VMF1-service.

UNB VMF1 SERVICE

The geodetic community is now in a transition from corrections based on relatively simple closed form mathematical models to corrections based on large amounts of external data. The VMF1 service is only one example of this shift. Even though the VMF1 mapping functions have been shown to be an improvement over the Global Mapping Functions [Boehm et al., 2006] and Niell Mapping Functions [Niell, 1996], at this time no IGS processing centers have adopted their use even though they are currently recommended by the *IERS Conventions* [IERS, 2010]. An alternative service provider could improve the availability of the products should the original VMF service become unavailable and perhaps make the use of the VMF1 corrections more appealing.

[1] The file orography_ell is available at: http://ggosatm.hg.tuwien.ac.at/DELAY/GRID/

An alternative source of mapping functions and ray-traced zenith delays could improve the robustness of the IGS/IERS combined solutions as it would provide an independent source of corrections which could be applied by the analysis centers. When producing the IGS combined products the results from all analysis centers are combined in a least squares approach, even though in reality many of these solutions are highly correlated due to applying the same correction models and some analysis centers even using the same software. A UNB VMF1 service would provide slant factor models based on an independent weather model and ray-tracing algorithms which would make the IGS combined solution more robust if the IGS did choose to switch to the VMF1 for operational use.

As was shown in Urquhart [2010] there exists a small latitude dependent bias in the VMF1 hydrostatic mapping function which is believed to be due to the assumption of a sphere of constant radius of the earth in the ray-tracing algorithms. This systematic bias results in an approximately 2 mm change in station height at the poles and at the equator. Although small, this systematic bias may be important for geophysical studies and for establishing reference frames.

Implementation

There are three main components to producing a VMF1-like service at UNB. The components to the service are: the server, for providing user access to the corrections, performing the ray-tracing, (i.e. choosing a numerical weather data provider/ray-tracing algorithms) and which products to produce.

The server would most likely be maintained at UNB. As the algorithms are developed in Matlab it may be difficult to use computing facilities at other organizations as it would require Matlab software licenses. Additionally depending on the numerical weather model provider it may not be a possibility to run the service at any place other than UNB.

The processor requirements to provide the VMF1-like service are achievable on a standard computer. The routines have been developed in Matlab and would require access to the archived NWM data. Although it would be possible to create an executable version to run the routines, it can be run in Matlab using non-interactive command line mode using the command:

matlab –nodisplay –r doit

where *doit* is the function name. If this is included in a batch file then it could be setup in a task scheduler to run the files for the required epochs.

The NWM provider should be able to offer uninterrupted access to the NWM data. Ideally, all NWM would be available for on demand downloading in the event that there was an interruption in the NWM data provider service. Historic data would be required for the producing the products for past dates. The NCEP/NCAR Reanalysis data is recommended as it would meet these requirements[2]. The data files necessary are temperature, specific humidity and geopotential height which can be downloaded from:

ftp://ftp.cdc.noaa.gov/pub/Datasets/ncep.reanalysis/pressure/airYYYY.nc

[2] Special arrangements need to be made with the Canadian Meteorological Center with this regard

ftp://ftp.cdc.noaa.gov/pub/Datasets/ncep.reanalysis/pressure/shumYYYY.nc
ftp://ftp.cdc.noaa.gov/pub/Datasets/ncep.reanalysis/pressure/hgtYYYY.nc

where YYYY is the four digit year. These files are in NetCDF format which can be read by the UNB ray-tracing algorithms under the option *opt.nwm_name='NCEP*'. The data can be downloaded using a similar scheme as used for the Canadian Metrological Center data. Some further testing is required to ensure proper handling of the NCEP data in the UNB ray-tracing algorithms.

An additional benefit of the NCEP data set is that the geodetic community already uses the NCEP data for other products such as those produced by the Global Geophysical Fluids entre Special Bureau for the Atmosphere < http://www.iers.org/IERS/EN/Organization/ProductCentres/GGFC/ggfc.html> which includes atmospheric pressure loading products. The production of consistent correction models rather than corrections based on many different data sets is one of the goals of GGOS [Rothatcher, 2009]. Using the NCEP Reanalysis data would be consistent with this goal.

The latency of the NCEP/NCAR Reanalysis is typically 2.5 days [Petrov, 2010]. However, in some cases it can be as long as 3.5 days. This is much shorter than the final IGS products which have a latency of more than 2 weeks and therefore is not a concern.

The ray-tracing algorithms would rely on the assumption of a spherical osculating atmosphere. Ray-tracing would need to be performed in the zenith direction and at an initial elevation angle of 3.3°. In order to compute the VMF1, the corresponding outgoing elevation angle must also be known. This value is included in the output.

The ray-tracing is performed on a 2.0° X 2.5° lat/lon grid at ellipsoid heights corresponding to those heights given in the file *orography_ell* shown in Figure. 1. The a coefficients are then determined using the routine mkvmf1.m, which is available at < http://www.hg.tuwien.ac.at/~ecmwf1/ >. This routine computes the a coefficient and reduces its value to a "zero height" using the height correction from the NMF [Niell, 1996]. The a coefficients are then applied using the routine vmf1_ht.m which will then reapply the height correction to the actual station height.

The ray-traced zenith delays are computed on the same grid as the a coefficients. Both the hydrostatic and non-hydrostatic delays components are provided. It is the responsibility of the user to correct for the height difference between the gridded heights from *orography_ell* and actual station heights. The file for computing the products is available in the folder *unbvmf1_service.zip*.

To obtain an approximation of the computation time required, the ray-tracing schemes were run on a dual core, 2.10 GHz processor with 2.0 GB RAM. The time required for computing the four parameters a_h, a_w, zenith hydrostatic delays and zenith non-hydrostatic delays on the global grid is approximately 45 minutes per epoch. For each day, the parameters must be computed 4 times, at 0, 6, 12, and 18 UT. Although this is practical for operational use, the computation time is unreasonable for computing the historical data as it would take approximately 45 days of processing time per year.

Therefore it is recommended that for the task of processing past epochs AceNET[3] computing resources is used. Fortunately, all scripts are compatible with both UNIX and windows systems, therefore the changes need should be minimal.

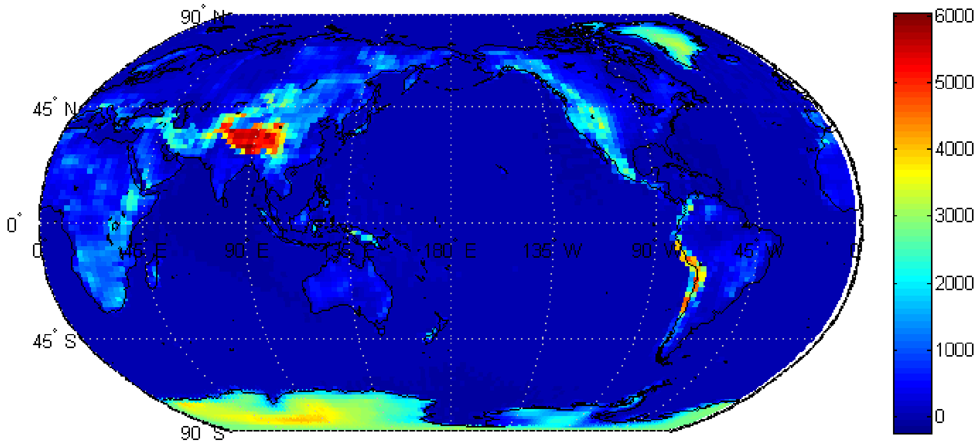

Figure 1 Ellipsoidal heights obtained from orography_ell, which are used for the ray-tracing calculations [Units of meters]

Future Considerations

In order for a product to be accepted as an IERS product the product provider must past through two phases. Phase 1 consists of putting forward the proposal for the new product to the directing board whereby they will accept or reject the proposal. Phase 2 consists of showing the operational capability of the product, demonstrating accuracy, availability and latency of the product of a 6 – 24 month period. If the evaluation is positive then it becomes an official operational IERS product [VanDam, 2009]. This is an important consideration for the development of the product as without the IERS support the product would not be of much use to the geodetic community. The UNB ray-tracing algorithms have been updated to accept the NCEP data set but further testing should be performed to ensure the consistency of the ray-traced delays derived from this data source versus the Canadian Meteorological Centre's data sets.

The development of a UNB VMF1-like service would be a good first step in providing future troposphere delay products. Munkane and Boehm [2010] discuss advantages of possibly developing azimuth dependent VMF, using three dimensional ray-tracing at eight azimuths and then performing linear interpolation in azimuth to obtain the desired direction. First, work would need to be performed to see if it is beneficial in terms of position accuracy to account for the azimuthal asymmetry using numerical weather models. Additionally, for smaller campaigns it could be possible to use the service to provide ray-traced slant factors at the observation level to users for research purposes.

[3] AceNet is a is a consortium of Atlantic Canadian Universities providing researchers with high performance computing (HPC) resources

Conclusion

The development of a VMF1-like service at UNB, would be beneficial for the geodetic community by providing an alternative to the current VMF1 mapping functions and zenith delays. This would improve the availability and provide tropospheric corrections using the NCEP Reanalysis data which is a very common data set for many geodetic applications thus improving compatibility and consistency. In addition, the same products could be generated using the GEM model, but not on an operational basis.

The operational requirements in terms of computing facilities are all available at UNB and therefore the product is feasible. The service would provide the hydrostatic and non-hydrostatic a coefficients and hydrostatic and non-hydrostatic zenith delays. These products can then be applied by users hoping to achieve the most accurate geodetic results possible. Finally, the development of this service will provide a means of developing further tropospheric products which can be distributed to the geodetic community.

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