Investigations into a Dynamic Geocentric Datum

Jian Wang, Jinling Wang and Craig Roberts

Abstract A "dynamic" geodetic datum is a datum that consists of coordinates and velocities of control points, which can provide users with the realistic positions of sites within the network that reflects the result of local or regional motion induced by a number of causes. A new ITRF-linked scheme is proposed and discussed in order to process available geodetic data in real-time to establish a dynamic ITRF-like datum. The authors suggest providing a variety of such datums for different applications. The noise properties of the geodetic coordinate time series are crucial to reliably estimating positions, velocities, and their stability and uncertainties. A 'db3' wavelet transform is used to separate the noise of the velocity series and the autocorrelation. The histogram distribution and spectrum features of the residuals indicate that the outliers impact the denoising effect. A Kalman filter-based model with the outliers being detected and removed online is investigated to obtain the "purified" velocity series for ITRF modeling. For a local scale application, interpolation methods play an important role in improving the accuracy of the datum. Six interpolation methods are investigated using a simulated velocity data set. The "local patch" model is necessary for a local datum in order to handle unexpected events.

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1 Introduction

One of the ultimate goals of modern geodesy is to provide a highly stable geocentric reference datum for scientific goals, such as precise orbit determination, monitoring of sea level rise, measuring plate tectonics, etc. (Angermann et al., 2003). The International Terrestrial Reference System (ITRS) is proposed by the International Association of Geodesy (IAG) as the Terrestrial Reference System (TRS) that integrates the geometric contributions of the different geodetic techniques (Altamimi et al., 2002). The International Terrestrial Reference Frame (ITRF), a physical materialisation of the ITRS, has random errors and systematic biases and is conventionally realised by an assumption of constant velocities for a set of global tracking sites. In reality, the assumption is not consistent with the non-linear effects caused by the mass movement of planetary fluids (atmosphere, oceans, surface hydrology, etc.) relative to the solid earth, with a crust that deforms due to plate tectonic motion.

A series of ITRFs were defined by the responsible ITRS Product Center (Institute Geographique National, IGN, Paris), from ITRF88 to ITRF2000 and ITRF2005 (Muller & Tesmer, 2003). Each subsequent ITRF is calculated with more data from different geodetic techniques than the previous one. Significant efforts to improve the consistency, precision and dynamic features of the ITRFs have been made over the years. The ITRF2000 solution is usually considered to be the most extensive and accurate one ever developed;

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containing about 800 stations located at about 500 sites, with better distribution over the globe compared to past ITRF versions (Altamimi et al., 2002). It includes primary core stations observed by VLBI, LLR, SLR, GPS and DORIS techniques as well as using regional GPS networks for its densification (Altamimi et al., 2002). To further improve the consistency and stability of the datum, time series of station positions and EOP from different geodetic observations is used to develop ITRF2005. The advantage of using time series of station positions is that it allows monitoring of station non-linear motion and discontinuities and to examine the temporal behavior of the frame physical parameters, namely the origin and the scale. (Altamimi et al., 2007). They do suggest using so-called "semi-dynamic datums" by assigning deformation models to specific geodetic datums for regional terrestrial reference frames, for instance the New Zealand Geodetic Datum 2000. Long term deformation trends and deformation triggered by unexpected events (e.g. seismic or volcanic effects) could be considered when developing the datum (Jordan et al., 2005).

The philosophy of ITRS realisation is by updating the station positions and constant velocities of a set of points to achieve a higher precision ITRF. The main update work of the ITRS is to derive more precise positions while omitting any non-linear variation of the velocity. The suggested regional semi-dynamic datum realisation initiates another approach by correcting the velocities using regional deformation models. With the increasing quantity of geodetic measurements from different observation techniques, it is now possible to more accurately realise the ITRS by introducing non-linear velocity models. Also, by combining regional spatial interpolation techniques, the regional control network can be connected to the ITRF (Grant & Pearse, 1995). To realise the non-linear velocity ITRF scheme, and promote its use for regional applications, this paper will investigate a new scheme based on the available geodetic measurements that takes into account a non-linear velocity model.

2 The Scheme of the Proposed Dynamic ITRF

As distinct from the existing situation, we prefer to introduce long term and non-linear movements of the Earth's surface into the velocity and propose a realization of the ITRS (named Dynamic ITRF) by a set of geodetic positions with respect to a specific epoch and a dynamic velocity model. The geodetic positions as well as the velocity time series are decided by the similar realization model of the series of ITRFs with all the available geodetic observation techniques such that accurate definitive reference station positions are given. Based on the analysis of the historic time-series of the specific station, an available model of the velocity series can be given the velocity v_t of a arbitrary epoch t as:

$$v_t = f_1(t) + f_2(t) + f_3(t) + f_4(t) \qquad (1)$$

Let $f_1(t)$, $f_2(t)$, $f_3(t)$ and $f_4(t)$ denote trend variation, periodic variation, the other non-linear variation and unexpected variations, respectively, with respect to epoch t. If there are more accurate models available or there is some revision to the established model, one can update the datum by only modifying the velocity model. For regional applications, the spatial velocity field at epoch t can be obtained by several interpolation models. In order to accommodate unexpected events in the real-time velocity field, a "local patch" model is suggested. The basic realisation scheme of the proposed Dynamic ITRF datum is shown in Fig. 1 in a more general sense. It is a more flexible approach to a continuous ITRF in time and spatial scales with the available data sets.

The International Earth Rotation and Reference Systems Service (IERS) has been responsible for the establishment and maintenance of the ITRF since 1988. To compute the positional coordinates of the reference stations, novel data processing techniques and some standards have been developed by the IERS authorised institutes. For more information the reader is referred to Angermann et al. (2003).

3 Temporal Velocity Modeling

One of the most challenging tasks in building a Dynamic ITRF is to model temporal velocity variation. There are three basic difficulties to contend with:

(1) Discrimination between real geophysical signals and random noise signals,
(2) Real-time outlier detection and elimination and,
(3) Modeling of the velocity time series.

This paper proposes the following approach. A wavelet model is used to allow the isolation of velocity

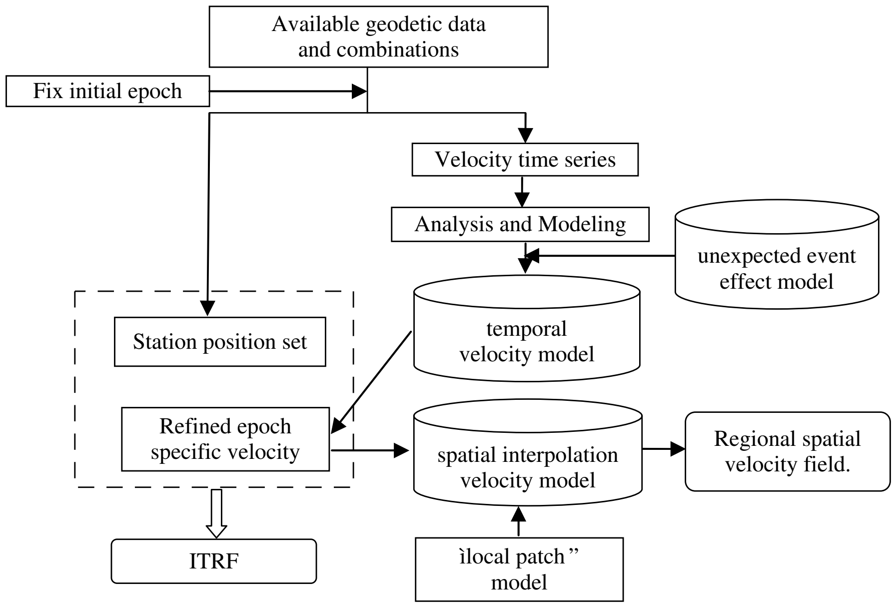


Fig. 1 The basic realisation scheme of the proposed Dynamic ITRF datum

variation trends from the noise signal. A Kalman filter is then used to model the velocity time series, as well as handling outliers online. According to the model, the velocities of the reference control points defining the ITRS at a given epoch are available. Such an approach is expected to realise a more accurate geocentric datum as it captures the non-linear movements of the reference points.

3.1 Possible Models for Velocity Time Series Analysis

Many time series analysis models can be used for velocity time series. For example gray system theory, time series analysis, and more recently Wavelet Theory, Kalman filter models and Neural Networks (e.g. Kalman, 1960; Liang & Fang, 1995; Patterson et al., 1993). For the analysis of the GPS velocity time series we have used daily solutions processed by SOPAC (ftp://garner.ucsd.edu/pub/). Using the COSO site for instance, NEU velocity time series are analysed for the model application, wavelet transform and Kalman filter model.

3.1.1 Wavelet Noise Reduction

The wavelet threshold noise reduction method is applied to extract the real signal. The noised signal is firstly divided with a bandpass filter function. By evaluating wavelet transform coefficients at different levels for different threshold value, real signals are restored by reconstruction using quantified wavelet coefficients with the thresholds. There are two methods (soft-threshold and hard-threshold) for wavelet coefficient quantification, which has been presented widely in previous literature. For more detailed information, one can refer to Mallat (1989). The ‘db3’ wavelet is chosen as an analysis function as the ‘dbN’ wavelet functions has the following advantages:

(1) The ‘dbN’ wavelet functions possess orthogonality, compacted support blocks and approximate symmetry.
(2) The ‘dbN’ wavelet function can be used to perform discrete wavelet transforms with the MALLAT fast decomposition and reconstruction algorithm.
(3) In order to satisfy the need for time precision for outlier detection, the selected ‘dbN’ wavelet function with efficient support block length of $2N-1$ should be short.
The ‘db3’ wavelet function is applied to de-noise the time series. Noises and the scale function, wavelet function and corresponding filters are given in Fig. 2.

The statistical features of the residual values are further investigated using histogram statistics, autocorrelation analysis and spectrum analysis. The situation for N and E components has a similar performance. Only N and U direction residuals are shown in Figs. 3 and 4.

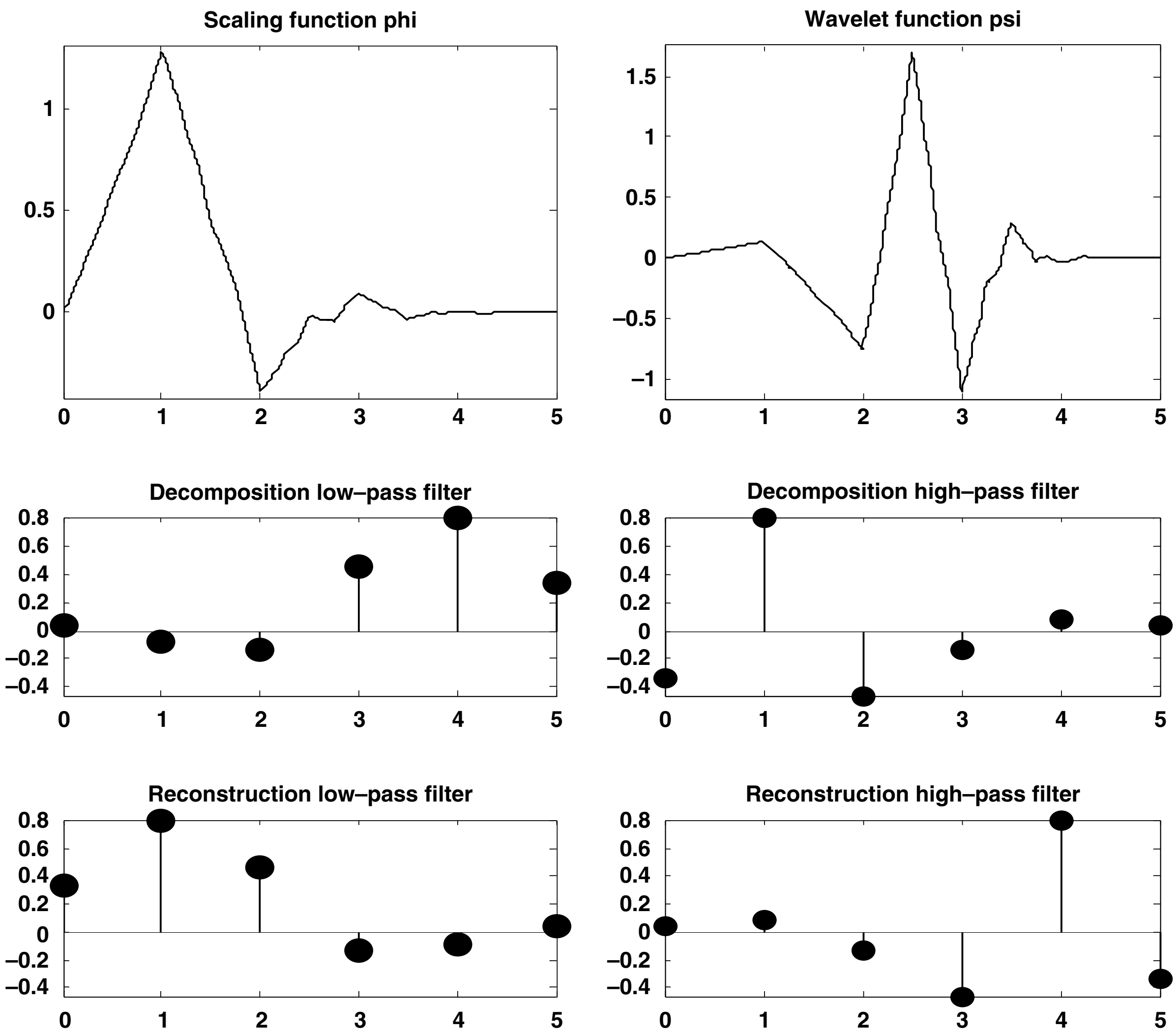


Fig. 2 Scale function, wavelet function and corresponding filters

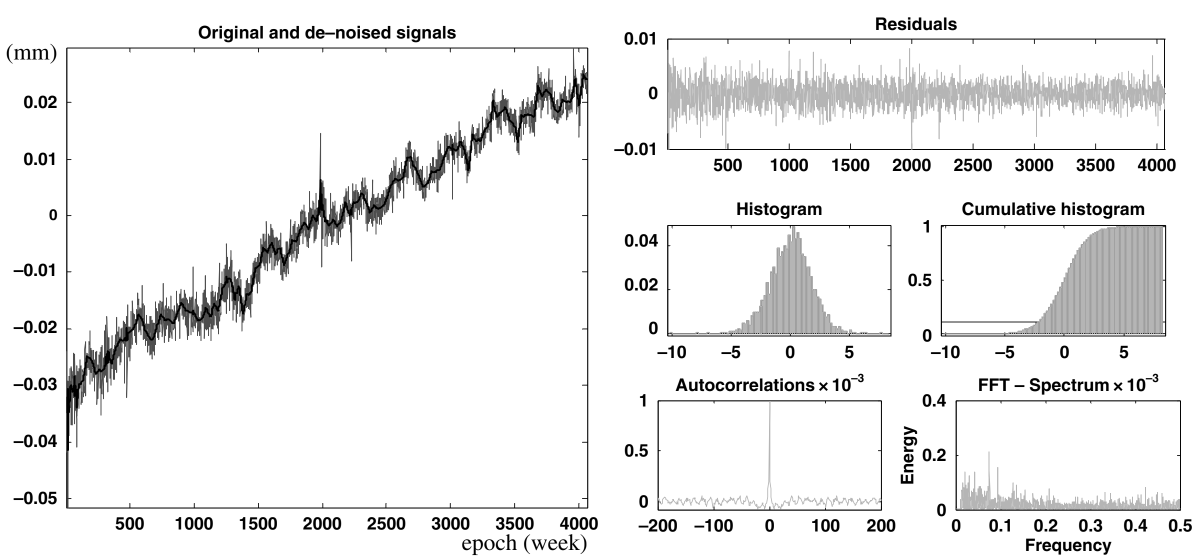


Fig. 3 Velocity series (E) wavelet noise reduction

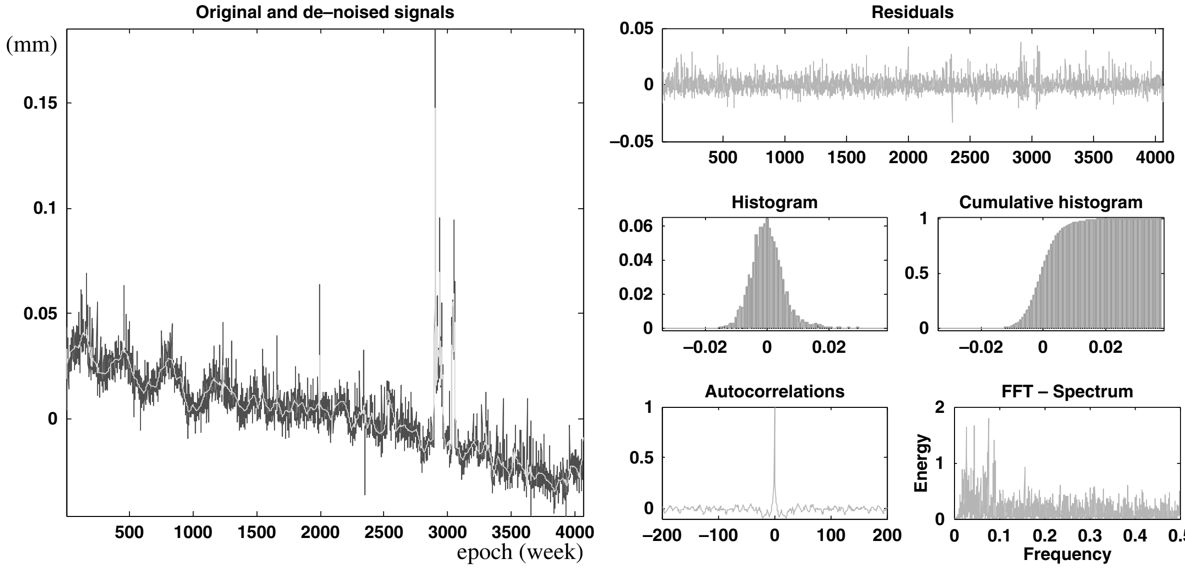


Fig. 4 Velocity series (U) wavelet noise reduction

It is noted that: (1) outliers existing in the velocity series (U) affect the wavelet noise reduction model similar to most of the other time series processing models; (2) wavelet noise reduction models perform well; and (3) the unexpected velocity outlier affect on the FFT-spectrum is manifested in the U direction.

3.1.2 Kalman Model for Time Series Modeling

Let the linear dynamic system and the observation equation be given by (Yang et al., 2001):

$$\begin{aligned} X_k &= \Phi_{k,k-1} X_{k-1} + \Gamma_{k,k-1}\Omega_{k-1} \\ L_k &= B_k X_k + \Delta_k \end{aligned} \tag{2}$$

where X_k, X_{k-1} denotes the state vector including positioning parameters and velocity parameters in three dimensions; $\Phi_{k,k-1}$ and B_k denote the transition and design matrices respectively, which are assumed known; L_k the observations vector specified at k; $\Gamma_{k,k-1}$ the noise matrix of the system from $k-1$ to k; Ω_{k-1} the stochastic accelaration state noise; and Δ_k denotes the observation noise. The stochastic model is:

$$\begin{aligned} &E(\Omega_k) = 0, E(\Delta_k) = 0, \mathrm{cov}(\Omega_k, \Delta_j) = 0 \\ &\mathrm{cov}(\Omega_k, \Omega_j) = D_\Omega(k)\delta_{kj}, \mathrm{cov}(\Delta_k, \Delta_j) = D_\Delta(k)\delta_{kj} \end{aligned}$$

where $D_\Omega(k)$ and $D_\Delta(k)$ denote the covariance matrices of the system dynamic noise and the observation noise respectively and δ_{kj} is the

$$\text{Kronecker function: } \delta_{kj} = \begin{cases} 1, k = j \\ 0, k \neq j \end{cases}$$

Epoch Kalman filter residuals can be given as:

$$r_k = L_k - B_k X(k/k-1) \tag{3}$$

where

$$X(k/k-1) = \Phi_{k,k-1} X(k-1/k-1)$$

if there are no outliers in the observations. r_k has a Gaussian white noise distribution with square deviation given by:

$$A_k = B_k D_X(k/k-1) B_k^T + R_k$$

The outliers can be discriminated by the test:

$$\begin{aligned} &H_0 : E\{r_k\} = 0, E\{r_k r^T k\} = A_k \\ &H_1 : E\{r_k\} = \mu, E\{[r_k - \mu][r_k - \mu]^T\} = A_k \end{aligned}$$

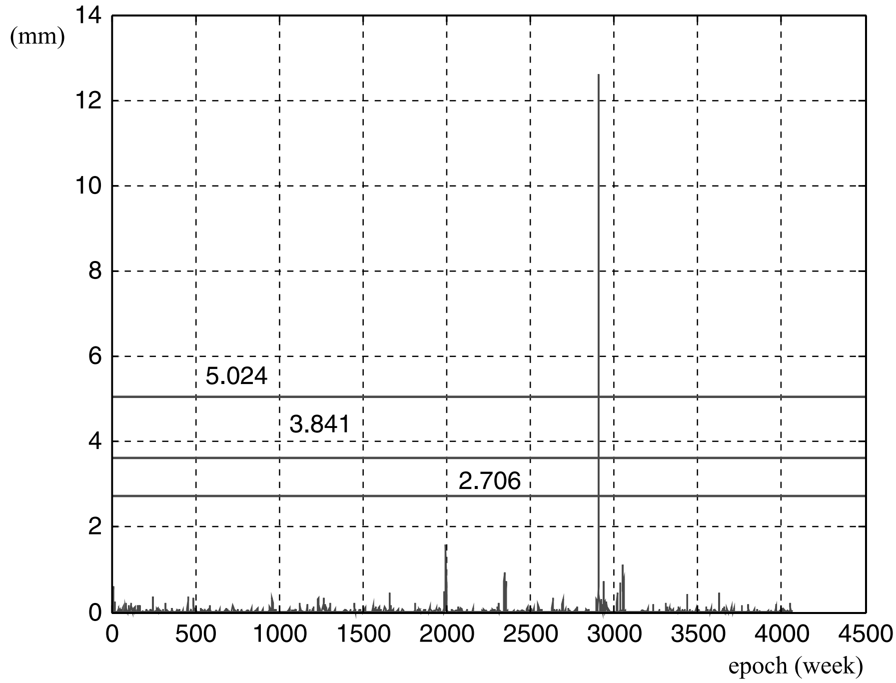


Fig. 5 Outlier detection results with χ^2 test

The outliers isolation function has the form:

$$\lambda_k = r_k^T A_k^{-1} r_k$$

λ_k has a χ^2 distribution with degree of freedom m, where m denotes the dimension of the observation vector L_k. The critical value T_D used for outlier detection was set by the χ^2 test for a given significance level and alarm criteria:

$$\begin{array}{lll} \lambda_k > T_D & outlier & detected \\ \lambda_k \le T_D & without & outlier \end{array}$$

T_D has the critical values 2.706, 3.841 and 5.024 for given probability values $\alpha = 0.1$, 0.05 and 0.025 respectively. One outlier detection result is shown in Fig. 5. A local Kalman filter can be designed for each group of observations, and then an outlier detection procedure is used. At the same time, a main Kalman filter is running. If a group of fault observations are detected, the predicted Kalman filter states are used as the estimated state to eliminate outlier effects on the unknown parameters (e.g. Chui & Chen, 1991; Qin et al., 1998).

3.2 Purification and Prediction of Velocity Time Series

A feature extraction, modeling and prediction procedure to "purify" the velocity series for the ITRF model (Fig. 6) is suggested, as the effects of the noises and

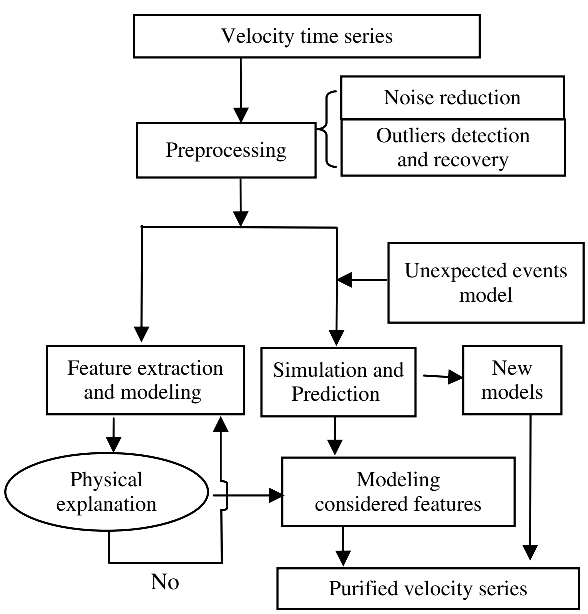


Fig. 6 Scheme for velocity series purification and prediction

some outliers in the velocity series will have an effect on the ITRF calculation. By preprocessing, feature extraction and modeling considered features, the purified velocity series can be given and used for further modeling applications.

4 Regional Velocity Field for Local Datum

4.1 Velocity Field Interpolation

Different interpolation algorithms can be used for regional velocity fields. Different interpolation method give different results. A velocity field consisting of 60 points is simulated as the standard test velocity data set to test six different interpolation algorithms, Inverse Distance to a Power, Kriging, Minimum Curvature, Modified Shepard's Method, Radial Basis Function and Local Polynomial (e.g. Journel & Huijbregts, 1978).

It is shown that the local velocity field has something to do with the interpolation method. The Inverse Distance to a Power and Kriging methods are shown as examples in Fig. 7. Some of the interpolation methods have proven useful and popular in many fields. For example Kriging is a geostatistical interpolation method. This method produces interpolation values of unknown positions from irregularly spaced data. Kriging attempts to express the trends suggested in the data, so that high points might be connected along a ridge rather than isolated by bull's-eye type contours. One must choose a proper interpolation model for a specific region in order to compute a high precision velocity field.

4.2 "Local Patch" Model

To handle unexpected events or "jumps", it is recommended that a "local patch" model be introduced for each event. The "local patch" describes a local motion of the earth mass which only affect regional deformation. To ensure spatial continuity of the models, the "local patch" model would have zero velocity at its boundaries. By identifying which models adopted at a given time and place, reference control point velocities are rectified if they are within the region. At the same time, the spatial velocity field is modified by appending these relevant "local patch" models. Blick et al. (2003) and Jordan et al. (2005) discuss such models.

5 Potential Improvement in the ITRF

One of the core problems of the associated model is how to effectively manage the increasing volume of geodetic data. A dynamic datum could be generated by a geographic information based decision-making system with a database of all the GPS/GNSS data, and other unexpected event field survey data, and a model database.

The system could provide users with an interface to generate site velocities, baseline components at any epoch, new site coordinates on the basis of the tectonic motion model selected etc.

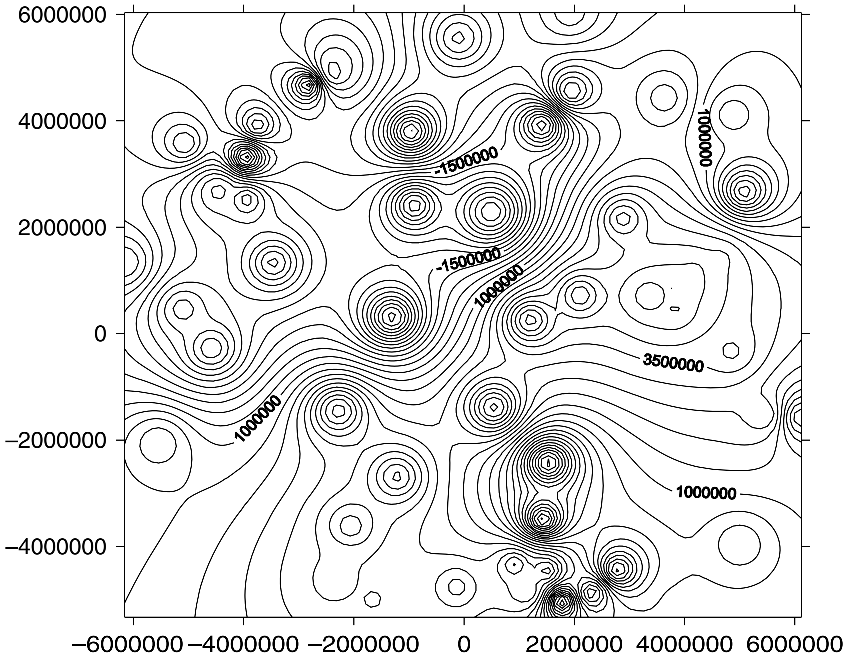
The system also generates a different level of precision for the Dynamic ITRF in terms of the user input information for different applications.

The system can choose core- or user-specified sites for the ITRF and can update a dynamic datum automatically, as well as provide users with a datum of a specific precision for each reference station. All these options will be researched in the future.

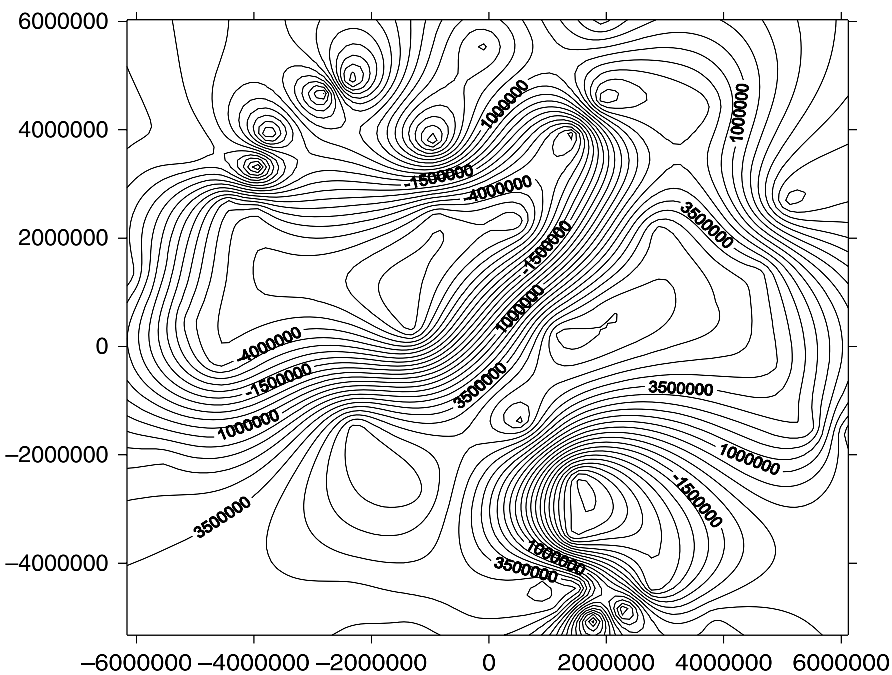
6 Summary

This paper has proposed a scheme to establish a dynamic geodetic datum which has such features as: (1) updating the derivatives (that is, velocity) of the positions considering non-linear variations, if necessary, driven by user-defined modeling precision; (2) automatic velocity series "purification"; and (3) incorporating different interpolation methods to improve the local datum precision. A purification and prediction scheme for the velocity series is discussed in order to provide velocity series is discussed in order to provide velocity series for the ITRF. Examples of wavelet noise reduction and Kalman outlier detection and elimination (of a velocity series) has been investigated with encouraging results being presented. Potential improvements of the dynamic model also include the proposition using a location based decision-making system to improve the efficiency of the proposed reference frame scheme.

Fig. 7 Different interpolation results of the simulated velocity field



(a) Inverse Distance to a Power Interpolation.



(b) Kriging Interpolation.

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