iGPS: IDL tool package for GPS position time series analysis

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Abstract A new tool package written in Interactive Data Language (IDL) was developed for processing and analyzing daily continuous GPS position time series. This software package can read continuous GPS position time series in various formats, detect outliers, remove abnormal observation spans, locate epochs of offsets or post-seismic relaxation events, and estimate their amplitudes. It also provides functionalities for epoch statistics, site selection, periodic noise analysis, spatial filtering (by regional stacking), etc. This tool is referred to as iGPS.

Keywords GPS · Position time series · Offsets · Post-seismic relaxation · Common-mode errors · Interactive Data Language

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Introduction

The continuous GPS technique has been used to monitor crustal deformation for more than a decade. However, few software packages designed specifically for GPS position time series analysis are currently available for public use. Many institutes are producing daily GPS position time series in varied formats and graphics software such as GMT (Generic Mapping Tools) (Wessel and Smith 1998) or GGMatlab (Herring 2003) can be used to plot time series data. In many cases, however, the kinds of statistical, graphic, and data processing requirements needed are beyond the capacity of the available software, especially when it is necessary to get a quick display of a large number of time series, to screen data based on specific conditions, to detect possible offsets and transients, or to analyze seasonal variations. To meet these types of demands, a set of IDL (Interactive Data Language) program routines, together with a novel friendly UI (user interface), referred to here as iGPS, was developed. IDL is similar to Matlab, but more powerful in geographic-related data processing and visualization, and is widely used by scientists in fields such as remote sensing and astronomy. It is a good platform upon which to develop an efficient tool for GPS position time series analysis.

Installation

The iGPS UI is provided as a collection of IDL source files (*.pro). An installation of IDL 6.x or later (http://www.ittvis.com) is required to run iGPS. In UNIX-based systems, an X-window environment must be also installed. iGPS only needs the default IDL installation to run. It will use the Advance Math & Stats Module (if it is

available) to solve linear regression problems; otherwise, the IDL least squares function-LA_LEAST_SQUARES will be called. There is no need for the IDL Workbench if one only wants to run iGPS without editing the source code, or if one uses an external editor.

To start the iGPS graphic interface, unpack the compressed source file (igps.tar.gz) downloaded from http://sourceforge.net/projects/igps/, go to the *main* subdirectory, start the command-line IDL program, and then type *start_igps*. Alternatively, one can open the start_igps. pro file in the IDL Development Environment (IDLDE), compile, and run it. This script will automatically set the IDL path environment variable (!PATH) as needed for running iGPS in the current IDL session.

View time series

The ability to view time series instantly is critical for data quality checks. iGPS has the ability to read daily coordinate time series generated by the following sources:

- Scripps Institution of Oceanography (SIO) time series from SOPAC (Scripps Orbit and Permanent Array Center) (http://garner.ucsd.edu/pub/timeseries/readme.txt);
- Plate Boundary Observatory (PBO) time series (http://pboweb.unavco.org/; http://pboweb.unavco.org/dmsdocs/Root%20Folder/Data%20Management/Data%20Product%20Documentation/gps_timeseries_format.pdf);
- JPL time series (http://sideshow.jpl.nasa.gov/mbh/series.html);
- GAMIT-GLOBK software (Herring et al. 2006) time series produced by the glred program (http://www-gpsg.mit.edu/~simon/gtgk/);
- QOCA (Quasi-Observation Combination Analysis) software time series produced by the mload program (http://gipsy.jpl.nasa.gov/qoca/).

Conversion from other formats to SIO NEU is supported. Although other formats can be recognized, the NEU format produced by SIO is required for further processing.

To view time series, simply pick the path where the files were stored on the hard disk, choose the appropriate time series type, and a list of available sites will be shown. A single click on the site name will display the north, east, and up time series in the drawing areas. iGPS supposes that filenames of most time series begin with a unique 4-character site name and end with certain suffix (e.g., *neu* for SIO NEU files) which indicates the type of time series. Once the time series is plotted, it is easy to get a closer view of a subset of interest with the zoom buttons: zoom in ("+"), zoom out ("−"), zoom to the whole extent ("|− −|"), or zoom to the time span in decimal years specified in the

starting and ending text fields (" ~ "). To easily compare the time series of many sites, the time axis of view can be fixed by selecting the "Fix" checkbox next to the time span fields. Time series can be repositioned using either the slider or the middle mouse button. The current positions of the mouse cursor are shown in the information bar above the plots when moving the mouse over the drawing areas. To find the exact value of point, just hold down the left button when moving the mouse, the data values will be shown in the information bar and the current point will be highlighted in blue. This is of great importance for finding the epochs of problematic blunders. iGPS can plot time series in several styles of symbols (point, triangle, asterisk, etc.), which are chosen from the line style droplist.

Time series editing and modeling

The main tasks of time series operations are organized into a popup menu ("tools>") as shown in Fig. 1. Various parameter controls will be shown at the lower left portion of iGPS window below the sites list, when choosing an individual menu item. A tip button ("Tip") is also supplied with each functionality to provide clues and quick instructions on how to run the program. The output path and options can be specified at the bottom of the iGPS window. Most of the operations are only applied to selected sites near the top left of the window. To select multiple sites, hold down the "Shift" or "Ctrl" keys when clicking. One can also use "INV", "A", or "N" buttons below the sites list to inverse the selection, to select all sites, or to select none, respectively.

The first step of analysis is usually choosing the sites to be used. For temporally correlated noise analysis, the length of the time series is needed to satisfy certain requirements. iGPS provides the ability to find sites whose length, starting, and ending times satisfy the thresholds entered, then copy/move the defined time series from a large sum of files (e.g., those produced by SOPAC) to a new directory, or to search time series for sites in a given geographic rectangle or a specific GPS network (sites names are read from a text file: lines with a non-blank first character are comments; 4-character site names are separated by at least one blank; file suffix is *sit* by default but can vary). The spatial distribution of sites can be viewed by creating a quick site map by selecting "Site Map" under the "Map" menu. One can also create statistics of available epochs for each site using the "Observation Statistics" tool in the "tools>"popup menu and then decide which sites should be used. Outliers and abnormal spans in the time series, or unwanted sites, can also be easily deleted by the "Outliers", "Cut", and "File Manager" tools, respectively. The detection of outliers is done by examining the formal

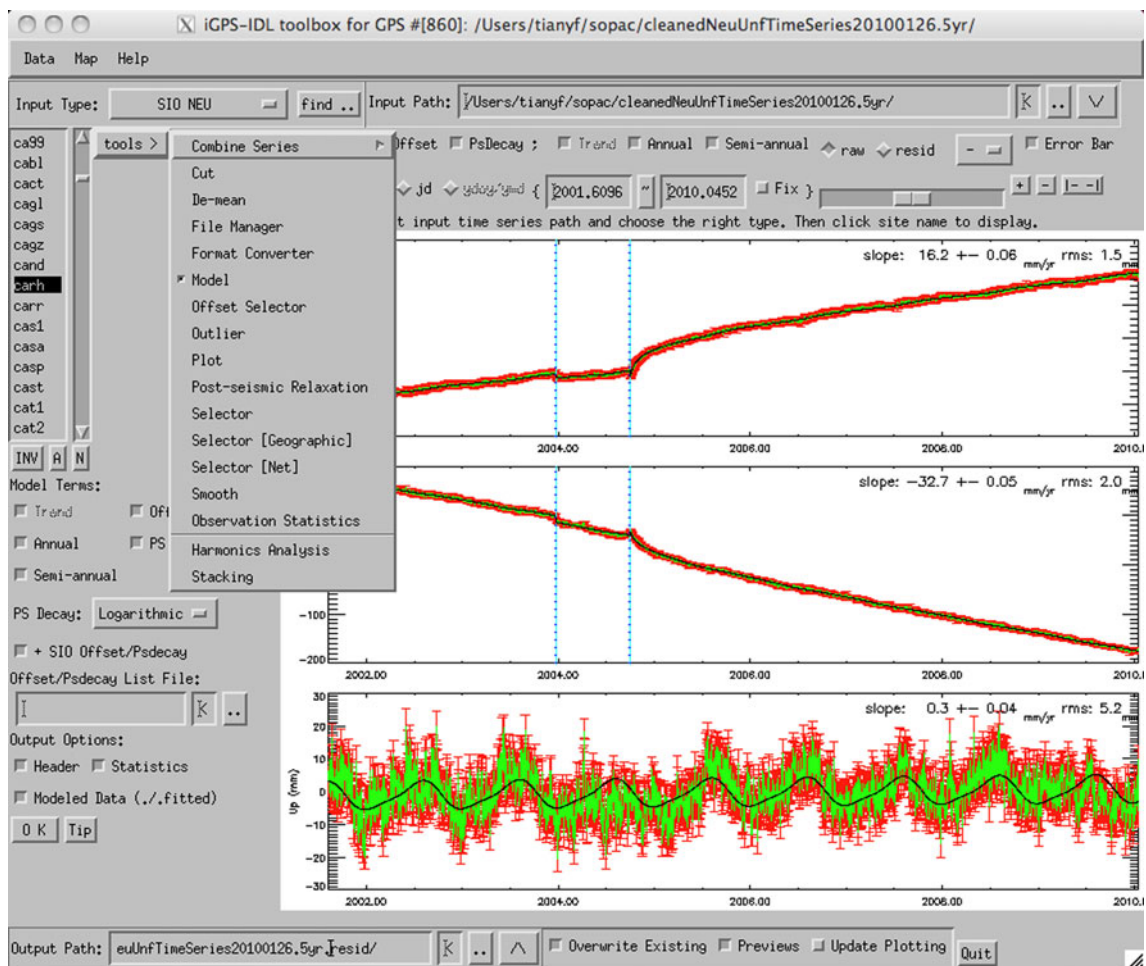**Fig. 1** A view of a time series in iGPS. The raw time series *in green* for site *carh* is shown along with the modeled data *in black*, which includes the linear trend, annual and semi-annual terms, offsets *solid vertical lines*, post-seismic logarithmic decays (starting from dotted vertical lines), and rate changes. The parameters were estimated using the least squares method, assuming only white noise exists. The time series was acquired from ftp://garner.ucsd.edu/pub/timeseries/

errors of daily solutions and the post-fit residual deviations from the RMS (root mean square) or IQR (Interquartile Range) values (Dong et al. 2006; Nikolaidis 2002). The thresholds for filtering out outliers are usually chosen from a priori knowledge about errors.

Offset and post-seismic relaxation events are other kinds of non-linear movements in a time series. According to SOPAC (http://garner.ucsd.edu/pub/gamit/setup/siteOffsets.txt), the origins of offsets can be classified into a variety of categories, including software upgrades, hardware changes, coseismic events, and unknown causes. Undetected offsets can greatly influence the estimation process. The identification of offsets is usually carried out through examination of the raw or residual time series. iGPS provides a tool ("Offset Selector") to add, remove, save, or restore offset epochs. The significance of offset existence can be examined by fitting a curve to a time series when offset epochs

are added or removed when the modeling checkboxes ("Trend", "Annual", and "Semi-annual") are turned on. iGPS also supports specifying post-seismic decay epochs using the "Post-seismic Relaxation" tool. Offsets and post-seismic decay lists can be sorted by site, component, and time, by selecting the "Site", "N/E/U", and "Time" radio buttons, respectively. A text file (file suffix is *def* by default but can vary) is used to store these events. A sample file is shown in Fig. 2. For post-seismic decays, two relaxation models can be chosen: exponential or logarithmic. The latter has been proven to be more accurate in recent studies, e.g., Langbein (2008). A post-seismic rate change is also considered. The raw and residual time series can be viewed by switching between the "raw" and "resid" radio buttons. All parameters are estimated using the least squares method, assuming there is only white noise in the time series. For colored noise analysis, readers may refer to the

```
# Offset and psdecay
 OFFSET bgis 2006.84520 U 2006 308
 OFFSET bgis 2006.03970 U 2006 014
 OFFSET cand 2006.84520 U 2006 308
x ...
 PSDECAY cand 2003.97670 N 2003 356
 PSDECAY cand 2004.74450 N 2004 272
 PSDECAY cand 2003.97670 E 2003 356
x ...
I
```

Fig. 2 Sample of an offset and post-seismic decay *psdecay* events file. The file is case-insensitive. Lines with a non-blank first character are comments. The first three fields, which indicate the type *offset* or *psdecay*, 4-character site name, and time of event in decimal year, are prerequisite. If the second field is *all*, then the event is for all sites. The fourth field, if present, indicates the component ("N", "E", or "U"); otherwise, the event is for all three components. The last two fields are year and day of year and are currently ignored by iGPS

CATS (Williams 2008) or est_noise (Langbein 2008) programs.

It is widely accepted that annual and semi-annual periodicities are present in GPS time series. Without knowing the full signal sources, these two terms are usually removed by fitting sinusoids. iGPS will estimate the annual and semi-annual terms if the corresponding checkboxes are selected in the Model Terms control panel (left side of Fig. 1) when estimating rates and will output the results as header lines in the residual time series files, in a convention similar to that of the SIO NEU format.

In addition to annual and semi-annual terms, other periodicities have been found in global GPS time series. Ray et al. (2008) proposed the fundamental frequency of 1.040 cpy and up to 6 multiples of it. iGPS also provides a module for estimating the amplitudes of a customized periodicity in units of cpy (cycles per year). The seasonal signal is modeled by fitting a sinusoid: $A\sin(P\mathbf{t} + \varphi)$, where A, P, and φ are amplitude, period, and phase lag, respectively. Offset and post-seismic decay parameters are estimated using the convention in Langbein (2008) and the refined model adopted by Nikolaidis (2002).

Spatial filtering of common-mode errors

Even after removing the linear trend, annual and semi-annual terms, offsets and post-seismic decays, there can still be appreciable spatial correlation between sites in a regional area representing effects common to the region. These are often called common-mode errors (CME) (Wdowinski et al. 1997; Nikolaidis 2002; Dong et al. 2006). The existence of CME noise poses great difficulties in detecting weak or transient tectonic signals, and their origins are still open questions. iGPS implements the regional stacking filtering proposed by Nikolaidis (2002). The calculation of daily

CME bias is based upon the residual time series of a group of stable sites. These sites must be carefully selected, because their number and geographic locations can greatly affect the results (Williams et al. 2004). The correction for CME is done by subtracting the biases directly from the raw time series.

Further developments

Aside from enhancements and improvements for current available modules, data interfaces for related packages (e.g., QOCA at http://gipsy.jpl.nasa.gov/qoca/) are planned for future releases of iGPS. Planned objectives of iGPS also include the capability of handling geographic data (rasters and vectors) and creating professional plots. A versatile mechanism for incorporating codes contributed by others will also be implemented.
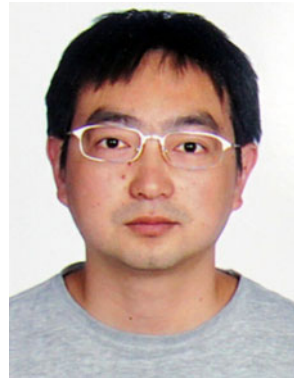
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