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1 Introduction

GNU Gama package is dedicated to adjustment of geodetic networks. It is intended for use with traditional geodetic surveyings which are still used and needed in special measurements (e.g., underground or high precision engineering measurements) where the Global Positioning System (GPS) cannot be used.

In general, surveying is the technique and science of accurately determining the terrestrial or three-dimensional spatial position of points and the distances and angles between them.\(^1\)

Adjustment is a technical term traditionally used by geodesists and surveyors which simply means “application of the least squares method to process the over-determined system of measurements” (statistical methods other than least squares are used sometimes but are not common). In other words, we have more observations than needed and we are trying to get the best estimate for adjusted observations and/or coordinates.

Adjustment of geodetic networks means that we have a set of fixed points with given coordinates, a set of points with unknown coordinates (possibly with approximate values available) and a set of observations among them. What is typical of adjustment of special geodetic measurements is that the resulting linearized system might be singular (we can have a network with no fixed points) and we are not only interested in the values of ‘adjusted parameters and observations’ but also in the estimates of their covariances. This is what Gama does.

Gama was originally inspired by Fortran system Geodet/PC (1990) designed by Frantisek Charamza. The GNU Gama project started at the department of mapping and cartography, faculty of Civil Engineering, Czech Technical University in Prague (CTU) about 1998 and its name is an acronym for geodesy and mapping. It was presented to a wider public for the first time at FIG Working Week 2000 in Prague and then at FIG Workshop and Seminar at HUT Helsinki in 2001.

The GNU Gama home page is [http://www.gnu.org/software/gama/](http://www.gnu.org/software/gama/) and the project is hosted on [http://savannah.gnu.org/git/?group=gama](http://savannah.gnu.org/git/?group=gama)

GNU Gama is released under the GNU General Public License and is based on a C++ library of geodetic classes and functions and a small C++ template matrix library matvec. For parsing XML documents GNU Gama calls the expat parser version 1.1, written by James Clark. The expat parser is not part of the GNU Gama project, but it is used by the project.

Adjustment in local Cartesian coordinate systems is fully supported by a command-line program gama-local that adjusts geodetic (free) networks of observed distances, directions, angles, height differences, 3D vectors and observed coordinates (coordinates with given variance-covariance matrix). Adjustment in global coordinate systems is supported only partly as a gama-g3 program.

---

1.1 Download

GNU Gama can be found in the subdirectory /gnu/gama/ on your favourite FTP GNU mirror (http://www.gnu.org/prep/ftp.html) or cloned from the GIT. See our project page at savannah (https://savannah.gnu.org/projects/gama/) for more information.

To get anonymous read-only access to the GIT repository for the latest GNU Gama source, issue the following command

    git clone git://git.sv.gnu.org/gama.git

1.2 Install

GNU Gama is developed and tested under GNU/Linux. A static library libgama.lib and executables are build in folders lib and src. You can compile Gama easily yourself if you download the sources from a FTP server. The preferred way is to have expat XML parser installed on your system, if not, GNU Gama will be build with internally stored expat older source codes version 1.1.

Change to the directory of Gama project and issue the following commands at the shell prompt (with some optional parameters)

    $ ./configure [--enable-extra-tests --bindir=DIR --infodir=DIR]
    $ make

For GNU Gama test suite run

    $ make check

If the script configure is not available (which is the case when you download source codes from the git server (https://git.savannah.gnu.org/cgit/gama.git)), you have to generate it using auxiliary script autogen.sh. To compile and build all binaries. Run

    $ ./autogen.sh
    $ ./configure

and

    $ make install [--prefix=/your/prefered/install/directory]

if you also want to install executables and info documentation.

Typically, if you want to download (see Section 1.1 [Download], page 2) and compile sources, you will run following commands:

    $ git clone git://git.sv.gnu.org/gama.git gama
    $ cd gama
    $ ./autogen.sh
    $ ./configure
    $ make

You should have expat XML parser and SQLite library already installed on your system. For example to be able to compile Gama on Ubuntu 10.04 you have to install following packages:

    make doxygen git automake autoconf libexpat1-dev libsqlite3-dev

To compile user documentation in various formats (PDF, HTML, ...) run the following commands

    $ cd doc/
$ make download-gendocs.sh
$ make run-gendocs.sh

The documentation should be in doc/manual directory. To compile API documentation run

$ doxygen

in your gama directory. Doxygen output will be in the doxygen directory.

### 1.2.1 CMake

Alternatively you can use CMake to generate makefiles for Unix, Windows, Mac OS X, OS/2, MSVC, Cygwin, MinGW or Xcode. Configuration file CMakeLists.txt is available from the root distribution directory. For example to build gama-local binary for Linux run

$ mkdir build_dir
$ cd build_dir
$ cmake .. [ -G generator-name ]
$ make --build .

where build_dir is an arbitrary directory name for out-of-place build and optional generator-name specifies a build system generator, for example Ninja.

### 1.2.2 pkgsrc

pkgsrc is a framework for managing third-party software on UNIX-like systems, currently containing over 26,000 packages. It is the default package manager of NetBSD and SmartOS, and can be used to enable freely available software to be built easily on a large number of other UNIX-like platforms. The binary packages that are produced by pkgsrc can be used without having to compile anything from source. It can be easily used to complement the software on an existing system.

Gama is available via pkgsrc as geography/gama, see https://www.pkgsrc.org/ for more information.

### 1.2.3 Precompiled executables for Windows

qgama is a Qt application for adjustment of geodetic networks with database support, where the database can be a simple SQLite3 flat file, used for storing geodetic network data, or any full-featured relational DBMS with Qt driver available like PostgreSQL or MySQL. It is build on the GNU gama adjustment library.

Windows executable qgama.exe with all DLL libraries is available from the GNU FTP server


together with command-line interface executables gama-local.exe and gama-g3 in the subdirectory bin.

### 1.3 Program gama-local

Program gama-local is a simple command line tool for adjustment of geodetic free networks. It is available for GNU Linux (the main platform on which project GNU Gama is being developed), BSD or Windows.
Program gama-local reads input data in XML format (Chapter 2 [XML input data format for gama-local], page 9) and prints adjustment results into ASCII text file. If output file name is not given, adjustment results in XML format are sent to the standard output device. If development files for Sqlite3 (package libsqlite3-dev) are installed, gama-local also supports reading adjustment input data from sqlite3 database. When run without arguments gama-local [--help] prints a review of runtime options.

Usage:
```
gama-local --input-xml input.xml [options]
gama-local --input-xml input.xml --sqlitedb sqlite.db --configuration name [options]
gama-local --sqlitedb sqlite.db --configuration name [options]
gama-local --sqlitedb sqlite.db --readonly-configuration name [options]
```

Options:
```
--algorithm gso | svd | cholesky | envelope
--language en | ca | cz | du | es | fi | fr | hu | ru | ua | zh
--encoding utf-8 | iso-8859-2 | iso-8859-2-flat | cp-1250 | cp-1251
--angular 400 | 360
--latitude <latitude>
--ellipsoid <ellipsoid name>
--text adjustment_results.txt
--html adjustment_results.html
--xml adjustment_results.xml
--octave adjustment_results.m
--svg network_configuration.svg
--cov-band covariance matrix of adjusted parameters in XML output
  n = -1 for full covariance matrix (implicit value)
  n >= 0 covariances are computed only for bandwidth n
--iterations maximum number of iterations allowed in the linearized
  least squares algorithm (implicit value is 5)
--export updated input data based on adjustment results
--verbose [yes | no]
--version
--help
```

Report bugs to: <bug-gama@gnu.org>
GNU gama home page: <https://www.gnu.org/software/gama/>
General help using GNU software: <https://www.gnu.org/-gethelp/>

Program version is followed by information on compiler used to build the program (apart from GNU g++ compiler other possibilities are Clang, Intel C++ compiler and Visual C++, when build under Microsoft Windows).
Program *gama-local* can read XML input from the standard input if you put "-" (hyphen) after the option *--input-xml*. This option is special because it is optional (you can specify XML input file name or "." without it). Elective *--input-xml* enables backward compatibility with the usage of older versions.

Adjustment results (*--text, --xml*) and others can be similarly redirected to standard output if instead of a file name is used "." string. If no output is given, XML adjustment format is implicitly send to standard output.

Option *--algorithm* enables to select numerical method for solution of the adjustment. Implicit algorithm is sparse matrix *envelope*. Another possibilities are Cholesky decomposition of semidefinite matrix of normal equations (*cholesky*), block matrix algorithm GSO by Frantisek Charamza based on Gram-Schmidt orthogonalization (*gso*) and Singular Value Decomposition (*svd*). In the last two cases (*gso* and *svd*) project equations are solved directly without forming normal equations.

Option *--language* selects language used in output protocol. For example, if run with option *--language cz*, *gama-local* prints output results in Czech language using UTF-8 encoding. Implicit value is *en* for output in English.

Option *--encoding* enables to change implicit UTF-8 output encoding to iso-8859-2 (latin-2), iso-8859-2-flat (latin-2 without diacritics), cp-1250 (MS-EE encoding) cp-12251 (Russian encoding).

Option *--angular* selects angular units to be used in output.

Options *--latitude* and/or *--ellipsoid* are used when observed vertical and/or zenith angles need to be transformed into the projection plane. If none of these two options is explicitly used, no corrections are added to horizontal and/or zenith angles. If only one of these options is used, then implicit value for *--latitude* is 45 degrees (50 gons) and implicit ellipsoid is WGS84. Mathematical formulas for the corrections is given in the following section.

Option *--octave* is used to output simplified adjustment results for GNU Octave ([https://www.gnu.org/software/octave/](https://www.gnu.org/software/octave/)), i.e. in an .m file. The following information is give in the output file

- general adjustment parameters (number of unknowns, observetions etc.)
- list of fixed points’ ids (may be empty)
- adjustment points; ids
- adjustment indexes of unknowns
- indexes of constrained coordinates (subset of adjustment indexes)
- approximate and adjusted coordinates (zero if not available)
- full covariance matrix of adjusted coordinates
- sparse design matrix, rhs and weights (*Ax = b, P = inv(C_{ll})*)
- and adjustment results in matrix format

In the case of free networks system of normal equations is augmented with matrix of constrains. Adjustment can be then computed independently in Octave and compared with results from Gama for unknown coordinates. We suggest that for comaprision of Gama and Octave results number of itereations is set to zero (\*--iterations 0\*).
This Octave output is currently available only for algorithm \textit{envelope} (Gama version 2.10), also adjustment in Octave is not supported for the special case of \textit{one fixed point and one constrained} (where normal equation cannot be directly augmented with constraints because of different number of unknowns).

Option \texttt{--cov-band} is used to reduce the number of computed covariances (cofactors) in XML adjustment output. Implicitly full matrix is written to XML output, which could degrade time efficiency for the \textit{envelope} algorithm for sparse matrix solution. Explicit option for full covariance matrix is \texttt{--cov-band -1}, option \texttt{--cov-band 0} means that only a diagonal of covariance matrix is written to XML output, \texttt{--cov-band 1} results in computing the main diagonal and first codiagonal etc. If higher rank is specified then available, it is reduced do maximum possible value \texttt{dim-1}.

Option \texttt{--iterations} enables to set maximum number of iterations allowed in the linearized least squares algorithm. After the adjustment \texttt{gama-local} computes differences between adjusted observations computed from residuals and from adjusted coordinates. If the positional difference is higher than 0.5mm, approximate coordinates of adjusted points are updated and the whole adjustment is repeated in a new iteration. Implicit number of iterations is 5.

\subsection*{1.3.1 Reductions of horizontal and zenith angles}

For evaluating of reductions of horizontal and zenith angles, \texttt{gama-local} computes a helper point \( P_1 \) in the center of the network. Horizontal and zenith angles observed at point \( P_2 \) are transformed to the projection plane perpendicular to the normal \( z_1 \) of the helper point \( P_1 \). Coordinates \((x_2, y_2)\) of point \( P_2 \) are conserved, but its normal \( z_2 \) is rotated by the central angle \( 2\gamma_{12} \) to be parallel with \( z_1 \).

For observations from point \( P_2 \) to point \( P_3 \) we denote the zenith angle \( z_{m23} \) and horizontal direction \( \sigma_{m23} \). Now, transformed zenith angle \( z_{23} \) and horizontal direction \( \sigma_{23} \) can be expressed as

\[
\cos z_{23} = \cos z_{m23} \cos 2\gamma_{12} + \sin z_{m23} \cos (180^\circ - \sigma_{m23}) \sin \gamma_{12},
\]

\[
\sin(180^\circ - \sigma_{m23}) \cot \sigma_{23} = - \cos(180^\circ - \sigma_{m23}) \cos 2\gamma_{12} + \cot z_{m23} \sin 2\gamma_{12}
\]

and after arrangement

\[
\cos z_{23} = \cos z_{m23} \cos 2\gamma_{12} - \sin z_{m23} \cos \sigma_{23} \sin \gamma_{12},
\]

\[
\cot \sigma_{23} = \cot \sigma_{m23} \cos 2\gamma_{12} + \frac{\cot z_{m23} \sin 2\gamma_{12}}{\sin \sigma_{23}^m}
\]

These formulas can be simplified for small networks, roughly up to the size of 6 kilometers, where

\[
\cos 2\gamma_{12} \approx 1 \quad \text{and} \quad \sin 2\gamma_{12} \approx \frac{2\gamma_{12}''}{\varrho''},
\]

and

\[
\cos z_{23} = \cos z_{m23} - \sin z_{m23} \cos \sigma_{23}^m \frac{2\gamma_{12}''}{\varrho''},
\]

\[
\cot \sigma_{23} = \cot \sigma_{m23} + \frac{1}{\sin^2 \sigma_{23}^m} \cot z_{m23} \sin \sigma_{23}^m \frac{2\gamma_{12}''}{\varrho''}.
\]
Comparing these expressions with first members of Taylor series

\[ f(x) \approx f(x^0) + \frac{df(x^0)}{dx} \]

do not hold that \( z_{23} = z_{23}^m + \Delta z_{23} \) and \( \sigma_{23} = \sigma_{23}^m + \Delta \sigma_{23} \). 

\[ \cos z_{23} = \cos z_{23}^m - \sin z_{23}^m \frac{\Delta z_{23}^{''}}{\rho''} \]

\[ \cot \sigma_{23} = \cot \sigma_{23}^m - \frac{1}{\sin^2 \sigma_{23}^m} \frac{\sigma_{23}^{''}}{\rho''}, \]

it holds that \( z_{23} = \cos z_{23}^m + \Delta z_{23}^{''} \) and \( \sigma_{23} = \cos \sigma_{23}^m + \Delta \sigma_{23}^{''} \).

Equations for reductions of horizontal and zenith angles now can be expressed as

\[ z_{23} = \cos z_{23}^m + 2\gamma_{12}^{''} \cos \sigma_{23}^m \]

\[ \sigma_{23} = \sigma_{23}^m - 2\gamma_{12}^{''} \cot z_{23}^m \sin \sigma_{23}^m. \]

1.4 Reporting bugs

Undoubtedly there are numerous bugs remaining, both in the C++ source code and in the documentation. If you find a bug in either, please send a bug report to

\texttt{bug-gama@gnu.org (mailto:bug-gama@gnu.org)}

We will try to be as quick as possible in fixing the bugs and redistributing the fixes. If you prefer, you can always write directly to Aleš Čepěk (mailto:cepek@gnu.org).

1.5 Contributors

The following persons (in chronological order) have made contributions to GNU Gama project: Aleš Čepěk, Jiří Veselý, Petr Doubrava, Jan Pytel, Chuck Ghilani, Dan Haggman, Mauri Väisänen, John Dedrum, Jim Sutherland, Zoltan Faludi, Diego Berge, Boris Pihtin, Stéphane Kaloustian, Siki Zoltan, Anton Horpynich, Claudio Fontana, Bronislav Koska, Martin Beckett, Jiří Novák, Václav Petráš, Jokin Zurutuza, (Vim Xiang), Tomáš Kubín, Greg Troxel, Kristian Evers, Oleg Goussev, Petra Millarová, Jan Holešovský and Friedhelm Krumm.

Jiří Veselý is the author of calculation of approximate coordinates by intersections and transformations (class Acord). Václav Petráš is the author of Chapter 4 [SQL schema SQLite and gama-local], page 29. Petra Millarová is the main author of class Acord2 and other helper classes for combinatorial solution of medians of approximate coordinates.

Friedhelm Krumm, Geodätisches Institut Universität Stuttgart, contributed numerical examples for the adjustment of geodetic networks (1D, 2D and 3D) published in his Geodetic Network Adjustment Examples, Rev. 3.5, January 20, 2020. https://www.gis.uni-stuttgart.de/ In version 2.18 the format of input data used in his Examples was implemented in GNU Gama and is used in command line conversion program \texttt{gama-local-krumm2xml} and also directly in \texttt{qgama} GUI.
2 XML input data format for gama-local

The input data format for a local geodetic network adjustment (program gama-local) is defined in accordance with the definition of Extended Markup Language (XML) for description of structured data. The XML definition can be found at http://www.w3.org/TR/REC-xml

Input data (points, observations and other related information) are described using XML start-end pair tags <xxx> and </xxx> and empty-element tags <xxx/>.

The syntax of XML gama-local input format is described in XML schema (XSD), the file gama-local.xsd is a part of the GNU gama distribution and can formally be validated independently on the program gama-local, namely in unit testing we use xmllint validating parser, if it is installed.

For parsing the XML input data, gama-local uses the XML parser Expat copyrighted by James Clark which is described at http://www.jclark.com/xml/expat.html

Expat is subject to the Mozilla Public License (MPL), or may alternatively be used under the GNU General Public License (GPL) instead.

In the gama-local XML input, distances are given in meters, angular values in centigrades and their standard deviations (rms errors) in millimeters or centigrade seconds, respectively. Alternatively angular values in gama-local XML input can be given in degrees and seconds (see Section 2.1 [Angular units], page 9). At the end of this chapter an example of the gama-local XML input data object is given.

2.1 Angular units

Horizontal angles, directions and zenith angles in gama-local XML adjustment input are implicitly given in gons and their standard deviations and/or variances in centicentigons. Gon, also called centesimal grade and Neugrad (German for new grad), is 1/400-th of the circumference. For example

<direction from="202" to="416" val="63.9347" stdev="10.0" />

The same angular value (direction) can be expressed in degrees (sexagesimal graduation) as

<direction from="202" to="416" val="57-32-28.428" stdev="3.24" />

In XML adjustment input degrees are coded as a single string, where degrees (57), minutes (32) and seconds (28.428) are separated by dashes (-) with optional leading sign. Spaces are not allowed inside the string. Gons and degrees may be mixed in a single XML document but one should be careful to supply the information on standard deviations and/or covariances in the proper corresponding units.

Sexagesimal seconds (ss) are commonly called arcseconds, they are related to the metric system centicentigons (cc) as

\[
ss = cc/400/100/100 \times 360 \times 60 \times 60 = cc \times 0.324.
\]

Internally gama-local works with gons but output can be transformed to degrees using the option --angular 360.

Another angular unit commonly used in surveying is the milligon (mgon), 1 mgon = 1 gon/1000 (similarly as 1 mm = 1 m/1000) and 10 cc = 1 mgon.
2.2 Prologue

XML documents begin with an XML declaration that specifies the version of XML being used (prolog). In the case of gama-local follows the root tag <gama-local> with XML Schema namespace defined in attribute xmlns:

```xml
<?xml version="1.0" ?>
<gama-local xmlns="http://www.gnu.org/software/gama/gama-local"
```

GNU Gama uses non-validating parser and the XML Schema Definition namespace is not used in gama-local but it is essential for usage in third party software that might need XML validation.

2.3 Tags <gama-local> and <network>

A pair tag <gama-local> contains a single pair tag <network> that contains the network definition. The definition of the network is composed of three sections:

- <description> of the network (annotation or comments),
- network <parameters /> and
- <points-observations> section.

The sections <description> and <parameters /> are optional, the section <points-observations> is mandatory. These three sections may be presented in any order and may be repeated several times (in such a case, the corresponding sections are linked together by the software).

The pair tag <network> has two optional attributes axes-xy and angles. These attributes are used to describe orientation of the xy orthogonal coordinate system axes and the orientation of the observed angles and/or directions.

- axes-xy="ne" orientation of axes x and y; value ne implies that axis x is oriented north and axis y is oriented east. Acceptable values are ne, sw, es, wn for left-handed coordinate systems and en, nw, se, ws for right-handed coordinate systems (default value is ne).
- angles="right-handed" defines counterclockwise observed angles and/or directions, value left-handed defines clockwise observed angles and/or directions (default value is left-handed).

Many geodetic systems are right handed with x axis oriented east, y axis oriented north and counterclockwise angular observations. Example of left-handed orthogonal system with different axes orientation is coordinate system Krovak used in the Czech Republic where the axes x and y are oriented south and west respectively.

GNU Gama can adjust any combination of coordinate and angular systems.

Example

```xml
<gama-local>

<network>

<description> ... </description>

<parameters ... />

<points-observations> ... </points-observations>
```
Chapter 2: XML input data format for gama-local

It is planned in future versions of the program to allow more <network> tags (analysis of deformations etc.) and definitions of new tags.

2.4 Network description

The description of a geodetic network is enclosed in the start-end pair tags <description>. Text of the description is copied into the adjustment output and serves for easier identification of results. The text is not interpreted by the program, but it may be helpful for users.

Example

<description>
A short description of a geodetic network ...
</description>

2.5 Network parameters

The network parameters may be listed with the following optional attributes of an empty-element tag <parameters />

- \texttt{sigma-apr = "10"} value of a priori reference standard deviation—square root of reference variance (default value 10)
- \texttt{conf-pr = "0.95"} confidence probability used in statistical tests (default value 0.95)
- \texttt{tol-abs = "1000"} tolerance for identification of gross absolute terms in project equations (default value 1000 mm)
- \texttt{sigma-act = "aposteriori"} actual type of reference standard deviation use in statistical tests (aposteriori | apriori); default value is aposteriori
- \texttt{algorithm = "gso"} numerical algorithm used in the adjustment (gso, svd, cholesky, envelope).
- \texttt{language = "en"} the language to be used in adjustment output.
- \texttt{encoding = "utf-8"} adjustment output encoding.
- \texttt{angular = "400"} output results angular units (400/360).
- \texttt{latitude = "50"}
- \texttt{ellipsoid}
- \texttt{cov-band = "-1"} the bandwith of covariance matrix of the adjusted parameters in the output XML file (-1 means all covariances).

Values of the attributes must be given either in the double-quotes ("...") or in the single quotes (’...’). There can be white spaces (spaces, tabs and new-line characters) between attribute names, values, and the equal sign.
Example

```xml
<parameters sigma-apr = "15"
         conf-pr = '0.90'
         sigma-act = "apriori" />
```

2.6 Points and observations

The points and observations section is bounded by the pair tag `<points-observations>` and contains information about points, observed horizontal directions, angles, and horizontal distances, height differences, slope distances, zenith angles, observed vectors and control coordinates.

Optional attributes of the start tag `<points-observations>` allow for the definition of default values of standard deviations corresponding to observed directions, angles, and distances.

- `direction-stdev = "..."` defines the implicit value of standard deviation of observed directions (default value is not defined)
- `angle-stdev = "..."` defines the implicit value of standard deviation of observed angles (default value is not defined)
- `zenith-angle-stdev = "..."` defines the implicit value of standard deviation of observed zenith angles (default value is not defined)
- `azimuth-stdev = "..."` defines the implicit value of standard deviation of observed azimuth angles (default value is not defined)
- `distance-stdev = "..."` defines the implicit value of standard deviation of observed distances, horizontal or slope (default value is not defined)

Implicit values of standard deviations for the observed distances are calculated from the model with three constants $a$, $b$, and $c$ according to the formula

$$a + bD^c,$$

where $a$ is a constant part of the model and $D$ is the observed distance in kilometres. If the constants $b$ and/or $c$ are not given, default values of $b = 0$ and $c = 1$ will be used.

Example

```xml
<points-observations direction-stdev = "10"
                      distance-stdev = "5 3 1" >
    <!-- ... points and observation data ... -->
</points-observations>
```

2.7 Points

Points are described by the empty-element tags `<point/>` with the following attributes:

- `id = "..."` is the point identification attribute (mandatory); point identification is not limited to `numbers`; all printable characters can be used in identification.
- `x = "..."` specifies coordinate $x$
• \( y = \ldots \) specifies coordinate \( y \)
• \( z = \ldots \) specifies coordinate \( z \), point height
• \( \text{fix} = \ldots \) specifies coordinates that are fixed in adjustment; acceptable values are \( xy, Xy, z, Xz, XYZ, xyZ \) and \( XYz \).
• \( \text{adj} = \ldots \) specifies coordinates to be adjusted (unknown parameters in adjustment); acceptable values are \( xy, Xy, z, Xz, XYZ, xyZ \) and \( XYz \).

With exception of the first attribute (point id), all other attributes are optional. Decimal numbers can be used as needed.

Control coordinates marked using the \( \text{fix} \) parameter are not changed in the adjustment. Uppercase and lowercase notation of coordinates with the \( \text{fix} \) parameter are interpreted the same. Corrections are applied to the unknown parameters identified by coordinates written in lowercase characters given in the \( \text{adj} \) parameter. When the coordinates are written using uppercase, they are interpreted as constrained coordinates. If coordinates are marked with both the \( \text{fix} \) and \( \text{adj} \), the \( \text{fix} \) parameter will take precedence.

Constrained coordinates are used for the regularization of free networks. If the network is not free (fixed network), the constrained coordinates are interpreted as other unknown parameters. In classical free networks, the constrained points define the regularization constraint

\[
\sum dx_i^2 + dy_i^2 = \min.
\]

where \( dx \) and \( dy \) are adjusted coordinate corrections and the summation index \( i \) goes over all constrained points. In other words, the set of the constrained points defines the adjustment of the free network (its shape and size) with a simultaneous transformation to the approximate coordinates of selected points. Program gama-local allows the definition of constrained coordinates with 1D leveling networks, 2D and 3D local networks.

Example

```xml
<point id="1" y="644498.590" x="1054980.484" fix="xy" />  
<point id="2" y="643654.101" x="1054933.801" adj="XY" />  
<point id="403" adj="xy" />
```

2.8 Set of observations

The pair tag \(<\text{obs}>\) groups together a set of observations which are somehow related. A typical example is a set of directions and distances observed from one stand-point. An observation section contains a set of

• horizontal directions \(<\text{direction} \ldots />\)
• horizontal distances \(<\text{distance} \ldots />\)
• horizontal angles \(<\text{angle} \ldots />\)
• slope distances \(<\text{s-distance} \ldots />\)
• zenith angles \(<\text{z-angle} \ldots />\)
• azimuths \(<\text{azimuth} \ldots />\)

The band variance-covariance matrix of directions, distances, angles or other observations listed in one \(<\text{obs}>\) section may be supplied using a \(<\text{cov-mat}>\) pair tag with attributes \text{dim}
(dimension) and band (bandwidth). The band-width of the diagonal matrix is equal to 0 and a fully-populated variance-covariance matrix has a bandwidth of dim-1.

Observation variances and covariances (i.e. an upper-symmetric part of the band-matrix) are written row by row between <cov-mat> and </cov-mat> tags. If present, the dimension of the variance-covariance matrix must agree with the number of observations.

The following example of variance-covariance matrix with dimension 6 and bandwidth 2 (two nonzero codiagonals and three zero codiagonals)

\[
\begin{pmatrix}
1.1 & 0.1 & 0.2 & 0 & 0 & 0 \\
0.1 & 1.2 & 0.3 & 0.4 & 0 & 0 \\
0.2 & 0.3 & 1.3 & 0.5 & 0.6 & 0 \\
0 & 0.4 & 0.5 & 1.4 & 0.7 & 0.8 \\
0 & 0 & 0.6 & 0.7 & 1.5 & 0.9 \\
0 & 0 & 0 & 0.8 & 0.9 & 1.6 \\
\end{pmatrix}
\]

is coded in XML as

```xml
<cov-mat dim="6" band="2">
  1.1  0.1  0.2
  0.1  1.2  0.3  0.4
  0.2  0.3  1.3  0.5  0.6
  0  0.4  0.5  1.4  0.7  0.8
  0  0  0.6  0.7  1.5  0.9
  0  0  0  0.8  0.9  1.6
</cov-mat>
```

If two or more sets of directions with different orientations are observed from a stand-point, they must be placed in different <obs> sections. The value of an orientation angle can be explicitly stated with an attribute orientation="...". Normally, it is more convenient to let the program calculate approximate values of orientations needed for the adjustment. If directions are present, then the attribute station must be defined.

Optional attribute from_dh="..." enables to enter implicit height of instrument for all observations within the <obs> pair tag.

Observed distances are expressed in meters, their standard deviations in millimeters. Observed directions and angles are expressed in centigrades (400) and their standard deviations in centigrade seconds.

**Example**

```xml
<obs from="418">
  <direction to= "2" val="0.0000" stdev="10.0" />
  <direction to= "416" val="63.9347" stdev="10.0" />
  <direction to= "420" val="336.3190" stdev="10.0" />
  <distance to= "420" val="246.594" stdev="5.0" />
</obs>

<obs from="418">
  <direction to= "2" val="0.0000" />
</obs>
```
2.9 Directions

Directions are expressed with the following attributes in an empty-element tag `<direction />`

- `to = "..."` target point identification
- `val = "..."` observed direction; see Section 2.1 [Angular units], page 9,
- `stdev = "..."` standard deviation (optional)
- `from_dh = "..."` instrument height (optional)
- `to_dh = "..."` reflector/target height (optional)

The standard deviation is an optional attribute. However since all observations in the adjustment must have their weights defined, the standard deviation must be given either explicitly with the attribute `stdev="..."` or implicitly with `<points-observation direction-stdev="..." />` or with a variance-covariance matrix for the given observation set. A similar approach applies to all the observations (distances, angles, etc.)

All directions in the given `<obs>` tag (see Section 2.8 [Set of observations], page 13) share a common `orientation shift`, which is an implicit adjustment unknown parameter defining relation between the stand point directions and bearings

\[ direction_{AB} + orientation\ shift_A = bearing_{AB}. \]

Because one `<obs>` tag defines one orientation shift for all its directions, stand point `id` must be given in the `<obs from="id" />` tag, using attribute `from`, which in turn must not be used in `<direction />` tags, to avoid unintentional discrepancies.

Example

```xml
<direction to="2" val="0.0000" stdev="10.0" /> 
<direction to="416" val="63.9347" />
```

2.10 Horizontal distances

Distances are written using an empty-element tag `<distance />` with attributes

- `from = "..."` standpoint identification
- `to = "..."` target identification
- `val = "..."` observed horizontal distance
- `stdev = "..."` standard deviation of observed horizontal distance (optional)
• from_dh = "..." instrument height (optional)
• to_dh = "..." reflector/target height (optional)

Contrary to directions, distances in an observation set (<obs>) do not need to share a common stand-point. An example is set of distances observed from several stand-points with a common variance-covariance matrix.

Example

<distance from = "2" to = "1" val = "659.184" />
<distance to ="422" val="228.207" stdev="5.0" />
<distance to ="408" val="568.341" />

2.11 Angles

Observed angles are expressed with the following attributes of an empty-element tag <angle />

• from = "..." standpoint identification (optional)
• bs = "..." backsight target identification
• fs = "..." foresight target identification
• val = "..." observed angle; see Section 2.1 [Angular units], page 9,
• stdev = "..." standard deviation (optional)
• from_dh = "..." instrument height (optional)
• bs_dh = "..." backsight reflector/target height (optional)
• fs_dh = "..." foresight reflector/target height (optional)

Similar to distance observations, one observation set may group angles observed from several standpoints.

Example

<angle from="433" bs="422" fs="402" val="128.6548" stdev="14.1"/>
<angle from="433" bs="422" fs="402" val="128.6548" />  
<angle bs="422" fs="402" val="128.6548" stdev="14.1"/>
<angle bs="422" fs="402" val="128.6548"/>

2.12 Slope distances

Slope distances (space distances) are written using an empty-element tag <s-distance /> with attributes

• from = "..." standpoint identification (optional)
• to = "..." target identification
• val = "..." observed slope distance
• stdev = "..." standard deviation of observed slope distance (optional)
• from_dh = "..." instrument height (optional)
• to_dh = "..." reflector/target height (optional)
Similar to horizontal distances, one observation set may group slope distances observed from several standpoints.

Example

```xml
<s-distance from = "2" to = "1" val = "658.824" />
<s-distance to ="422" val="648.618" stdev="5.0" />
<s-distance to ="408" val="482.578" />
```

### 2.13 Zenith angles

Zenith angles are written using an empty-element tag `<z-angle />` with the following attributes

- from = "..." standpoint identification (optional)
- to = "..." target identification
- val = "..." observed zenith angle; see Section 2.1 [Angular units], page 9,
- stdev = "..." standard deviation of observed zenith angle (optional)
- from_dh = "..." instrument height (optional)
- to_dh = "..." reflector/target height (optional)

Similar to horizontal distances, one observation set may group zenith angles observed from several standpoints.

Example

```xml
<z-angle from = "2" to = "1" val = "79.6548" />
<z-angle to ="422" val="85.4890" stdev="5.0" />
<z-angle to ="408" val="95.7319" />
```

### 2.14 Azimuths

The azimuth is defined in GNU Gama as an observed horizontal angle measured from the North to the given target. The true north orientation is measured by gyrotheodolites, mainly in mine surveying. In Gama azimuths' angle can be measured clockwise or counterclockwise according to the angle orientation defined in `<parameters />` tag.

Azimuths are expressed with the following attributes in an empty-element tag `<azimuth />`

- from = "..." standpoint identification
- to = "..." target point identification
- val = "..." observed azimuth; see Section 2.1 [Angular units], page 9,
- stdev = "..." standard deviation (optional)
- from_dh = "..." instrument height (optional)
- to_dh = "..." reflector/target height (optional)

The standard deviation is an optional attribute. However since all observations in the adjustment must have their weights defined, the standard deviation must be given either explicitly with the attribute stdev="..." or implicitly with `<points-observation azimuth-stdev="..." />` or with a variance-covariance matrix for the given observation set.
Example

<points-observations azimuth-stdev="15.0">
  <azimuth from="1" to="2" val="96.484371" />
</points-observations>

2.15 Height differences

A set of observed leveling height differences is described using the start-end tag <height-differences> without parameters. The <height-differences> tag can contain a series of height differences (at least one) and can optionally be supplied with a variance-covariance matrix. Single height differences are defined with empty tags <dh /> having the following attributes:

- from = "..." standpoint identification
- to = "..." target identification
- val = "..." observed leveling height difference
- stdev = "..." standard deviation of levellin elevation and
- dist = "..." distance of leveling section (in kilometers)

If the value of standard deviation is not present and length of leveling section (in kilometres) is defined, the value of standard deviation is computed from the formula

\[ m_{dh} = m_0 \sqrt{D_{km}}. \]

If the value of standard deviation of the height difference is defined, information on leveling section length is ignored. A third possibility is to define a common variance-covariance matrix for all elevations in the set.

Example

<height-differences>
  <dh from="A" to="B" val="25.42" dist="18.1" />
  <dh from="B" to="C" val="10.34" dist="9.4" />
  <dh from="C" to="A" val="-35.20" dist="14.2" />
  <dh from="B" to="D" val="-15.54" dist="17.6" />
  <dh from="D" to="E" val="21.32" dist="13.5" />
  <dh from="E" to="C" val="4.82" dist="9.9" />
  <dh from="E" to="A" val="-31.02" dist="13.8" />
  <dh from="C" to="D" val="-26.11" dist="14.0" />
</height-differences>
2.16 Control coordinates

Control (known) coordinates are described by the start-end pair tag `<coordinates>`. A series of points with known coordinates can be defined using the `<point />` tag. The variance-covariance matrix for the entire set of points can be created with a single `<cov-mat>` tag. In the `<point />` tags, a point identification (ID) and its coordinates (x, y and z) must be listed. Although the order of the `<point />` tag attributes is irrelevant in the corresponding variance-covariance matrix, the expected order of the coordinates is x, y and z (the horizontal coordinates x, y, or the height z might be missing, but not both). The type of the points may be defined either directly within the `<coordinates>` tag or outside of it.

Example

```
<coordinates>
    <point id="1" x="100.00" y="100.00" />
    <point id="2" z="200.00" y="200.00" x="200.00" />
    <point id="3" z="300.00" />
    <cov-mat dim="6" band="5">
        ...
        <!-- covariances for 1x 1y 2x 2y 2z 3z -->
    </cov-mat>
</coordinates>
```

2.17 Coordinate differences (vectors)

Observed coordinate differences describe relative positions of station pairs (vectors). Contrary to the observed coordinates, the variance-covariance matrix of the coordinate differences always describes all three elements of the 3D vectors.

Optional attributes of empty element tag `<vec>` for describing instrument and/or target height are

- `from_dh = "..."` instrument height
- `to_dh = "..."` target height

Example

```
<vectors>
    <vec from="id1" to="id2" dx="..." dy="..." dz="..." />
    <vec from="id2" to="id3" dx="..." dy="..." dz="..." />
    ...
    <cov-mat dim="..." band="...">
        ...
    </cov-mat>
</vectors>
```

2.18 Attribute extern

The attribute `extern` is available for all observation types, including `<vector extern="..." />` and `<coordinates extern="..." />`. Its values have no impact on
processing in gama-local, it only transfers the attribute values from XML input into the corresponding XML tags in the adjustment output. The attribute extern="value" is provided to enable storing observations' database keys from an external database system in gama-local XML adjustment input and output. If you do not have such an external application, you probably will not need this attribute.

### 2.19 Example of local geodetic network

The XML input data format should be now reasonably clear from the following sample geodetic network. This example is taken from user's guide to Geodet/PC by Frantisek Charamza.

```xml
<?xml version="1.0" ?>
<gama-local xmlns="http://www.gnu.org/software/gama/gama-local">
<network axes-xy="sw">
<description>
XML input stream of points and observation data for the program GNU gama
</description>

<!-- parameters are expressed with empty-element tag -->
<parameters sigma-act = "aposteriori" />

<points-observations>
<!-- fixed point, constrained point -->
<p point id="1" y="644498.590" x="1054980.484" fix="xy" />
<p point id="2" y="643654.101" x="1054933.801" adj="XY" />
</points-observations>
</network>
</gama-local>
```
<!-- computed / adjusted points -->

<point id="403" adj="xy" />
<point id="407" adj="xy" />
<point id="409" adj="xy" />
<point id="411" adj="xy" />
<point id="413" adj="xy" />
<point id="416" adj="xy" />
<point id="418" adj="xy" />
<point id="420" adj="xy" />
<point id="422" adj="xy" />
<point id="424" adj="xy" />

<obs from="1">
  <direction to="2" val="0.0000" stdev="10.0" />
  <direction to="422" val="28.2057" stdev="10.0" />
  <direction to="424" val="60.4906" stdev="10.0" />
  <direction to="403" val="324.3662" stdev="10.0" />
  <direction to="407" val="382.8182" stdev="10.0" />
  <direction to="411" val="493.793" stdev="10.0" />
  <direction to="416" val="288.301" stdev="5.0" />
  <direction to="418" val="388.536" stdev="5.0" />
  <direction to="420" val="498.750" stdev="5.0" />
</obs>

<obs from="2">
  <direction to="1" val="0.0000" stdev="10.0" />
  <direction to="407" val="22.2376" stdev="10.0" />
  <direction to="409" val="73.8984" stdev="10.0" />
  <direction to="411" val="134.2090" stdev="10.0" />
  <direction to="416" val="203.0706" stdev="10.0" />
  <direction to="418" val="287.2951" stdev="10.0" />
  <direction to="420" val="345.6928" stdev="10.0" />
  <direction to="422" val="368.9908" stdev="10.0" />
  <direction to="407" val="388.562" stdev="5.0" />
  <direction to="409" val="257.498" stdev="5.0" />
  <direction to="411" val="360.282" stdev="5.0" />
  <direction to="416" val="338.919" stdev="5.0" />
  <direction to="418" val="292.094" stdev="5.0" />
  <direction to="420" val="261.408" stdev="5.0" />
  <direction to="422" val="452.249" stdev="5.0" />
</obs>

<obs from="403">
  <direction to="1" val="0.0000" stdev="10.0" />
</obs>
2</direction to="407" val="313.5542" stdev="10.0" />
<distance to="407" val="405.403" stdev="5.0" />
</obs>

<obs from="407">
<direction to= "1" val="0.0000" stdev="10.0" />
<direction to="403" val="55.1013" stdev="10.0" />
<direction to="409" val="193.3410" stdev="10.0" />
<direction to= "2" val="239.4204" stdev="10.0" />
<direction to="422" val="323.5443" stdev="10.0" />
<distance to="409" val="281.997" stdev="5.0" />
<distance to="422" val="346.415" stdev="5.0" />
</obs>

<obs from="409">
<direction to= "2" val="0.0000" stdev="10.0" />
<direction to="407" val="102.2575" stdev="10.0" />
<direction to="411" val="310.1751" stdev="10.0" />
<distance to="411" val="296.281" stdev="5.0" />
</obs>

<obs from="411">
<direction to= "2" val="0.0000" stdev="10.0" />
<direction to="409" val="49.8647" stdev="10.0" />
<direction to="413" val="291.4953" stdev="10.0" />
<direction to="416" val="337.6667" stdev="10.0" />
<distance to="413" val="252.266" stdev="5.0" />
<distance to="416" val="360.449" stdev="5.0" />
</obs>

<obs from="413">
<direction to= "2" val="0.0000" stdev="10.0" />
<direction to="416" val="68.8647" stdev="10.0" />
<direction to="413" val="117.9922" stdev="10.0" />
<direction to="418" val="348.1606" stdev="10.0" />
<distance to="418" val="389.397" stdev="5.0" />
</obs>

<obs from="418">
<direction to= "2" val="0.0000" stdev="10.0" />
<direction to="416" val="63.9347" stdev="10.0" />
</obs>
<direction to="420" val="336.3190" stdev="10.0" />
<distance to="420" val="246.594" stdev="5.0" />
</obs>

<obs from="420">
  <direction to="2" val="0.0000" stdev="10.0" />
  <direction to="418" val="77.9221" stdev="10.0" />
  <direction to="422" val="250.1804" stdev="10.0" />
  <distance to="422" val="228.207" stdev="5.0" />
</obs>

<obs from="422">
  <direction to="2" val="0.0000" stdev="10.0" />
  <direction to="420" val="26.8834" stdev="10.0" />
  <direction to="424" val="225.7964" stdev="10.0" />
  <direction to="1" val="259.2124" stdev="10.0" />
  <direction to="407" val="337.3724" stdev="10.0" />
  <distance to="424" val="279.405" stdev="5.0" />
</obs>

<obs from="424">
  <direction to="1" val="0.0000" stdev="10.0" />
  <direction to="422" val="134.2955" stdev="10.0" />
</obs>

</points-observations>

</network>
</gama-local>
3 YAML input data format for gama-local

YAML is a human-readable data-serialization language. It is commonly used for configuration files and in applications where data is being stored or transmitted. YAML targets many of the same communications applications as Extensible Markup Language but has a minimal syntax which intentionally differs from SGML. [Wikipedia](https://en.wikipedia.org/wiki/Extensible_Markup_Language)

In version 2.12 YAML support was added for gama-local as an alternative to the existing XML input format. The YAML support is limited only to conversion program `gama-local-yaml2gkf` but it may be fully integrated in `gama-local` program later.

In GNU Gama YAML documents are based on four main nodes

```yaml
defaults:

description:

points:

observations:
```

Where `defaults` and `description` are optional and `points` and `observations` are mandatory and each can be used only once. The order of the nodes is arbitrary.

Let's start with a full example

```yaml
defaults:
  sigma-apr : 5
  conf-pr: 0.95

description: >-
  Example: a simple network

points:
  - id: 1783
    y: 453500.000
    x: 104500.000
    adj: xy

  - id: 2044
    y: 461000.000
    x: 101000.000
    fix: xy

observations:
  - from: 1783
    obs:
      - type: direction
        to: 776
        val: 29.51661
        stdev: 2.0
```
The `description` node is clearly the simplest one, it just describes a simple text attached to the data. But still there may be a catch. If the description contains `colon (;)`, it might confuse the YAML parser because it would be interpreted as a syntax construction. To escape colon(s) in the description node we use `>--` to prevent colons to be interpreted as a syntax construction. Always using `>--` with `description` is a safe bet.

The data structure of the YAML document is defined by `indentation`, this principle was inspired by Python programming language, where indentation is very important; Python uses indentation to indicate a block of code.

Practically all attribute names used in our YAML format are the same as in XML data format.

Let's have a look on some more examples. Within `observations:` section we can define height differences (another kind of a measurement).

```
- observations:
  - height-differences:
    - dh:
      from: A
      to : B
      val : 25.42
      dist: 18.1  # distance in km
    - dh:
      from: B
```
Two remaining observation types are vectors and coordinates.

```
observations:
- vectors:
  - vec:
    from: A
    to: S
    dx: 60.0070
    dy: 35.0053
    dz: 54.9953
  - vec:
    from: B
    to: S
    dx: -39.9974
    dy: 34.9928
    dz: 54.9976

and

observations:
- coordinates:
  - id: 403
    x: 1054612.59853
    y: 644373.60446
  - id: 407
    x: 1054821.17131
    y: 644025.97479

...  

- cov-mat:
  dim: 20
  band: 19
  upper-part:
    6.7589719e+01 1.8437742e+01 1.3176856e+01 ...
```

Typically any observation set can define its covariance matrix.

You may wish to compare YAML and XML data files available from Gama tests suite in tests/gama-local/input directory (files *.gkf and *.yaml).

The gama-local input xml data can be formally validated against the XSD definition. Unfortunatelly there is no formal definition of YAML input. Within the testing suite of GNU Gama project we have a test that validates all available YAML files converted to XML by the formal XSD definition, see the test `xmllint-gama-local-yaml2gkf`. 
3.1 YAML support

GNU Gama YAML input format is dependent on C++ YAML-CPP library written by Jesse Beder https://yaml.org/. With the Gama primary build system (autotools) you need to install the library at your system, for example on Debian like systems it is libyaml-cpp-dev package.

A different solution is used in the alternative Gama cmake based build, where the source codes are expected to be available from the lib directory. Change to "GNU Gama sources"/lib and clone the git repository.

```
cd "GNU Gama sources"/lib
   git clone https://github.com/jbeder/yaml-cpp
```
4 SQL schema, SQLite and gama-local

The input data for a local geodetic network adjustment (program gama-local) can be stored in SQLite 3 database file. The general information about SQLite can be found at http://www.sqlite.org/

Input data (points, observations and other related information) are stored in SQLite database file. Native SQLite C/C++ API is used for reading SQLite database file. It is described at

http://www.sqlite.org/c3ref/intro.html

Please note if you compile GNU Gama as described in Section 1.2 [Install], page 2, and SQLite library is not installed on your system, GNU Gama would be compiled without SQLite support.

SQL schema (CREATE statements) is in gama-local-schema.sql file which is part of GNU Gama distribution and is in the xml directory.

All tables for gama-local are prefixed with gnu_gama_local_. In the documentation table names are referred without this prefix. For example table gnu_gama_local_points is referred as points.

Database scheme used for SQLite database is also valid in other SQL database systems. Almost every column has some constraint to ensure correctness.

You can convert existing XML input file to SQL commands with program gama-local-xml2sql, for example

$ gama-local-xml2sql geodet-pc geodet-pc-123.gkf geodet-pc.sql

4.1 Working with SQLite database

First of all you have to create tables for GNU Gama in SQLite database file (here with db extension, but you can choose your own, e.g. sqlite).

$ sqlite3 gama.db < gama-local-schema.sql

You can check created tables by following commands (fist in command line, second in SQLite command line).

$ sqlite3 gama.db
sqlite> .tables

Output should look like this:

gnu_gama_local_clusters     gnu_gama_local_descriptions
gnu_gama_local_configurations gnu_gama_local_obs
gnu_gama_local_coordinates   gnu_gama_local_points
gnu_gama_local_covmat        gnu_gama_local_vectors

When you have created tables you can import data. One way is to process file with SQL statements.

$ sqlite3 gama.db < geodet-pc.sql

Another way can be filing database file in another program.

For using sqlite3 command you need a command line interface for SQLite 3 installed on your system (e.g. sqlite3 package).
4.2 Units in SQL tables

In the gama-local SQLite database, distances are given in meters and their standard deviations (rms errors) in millimeters. Angular values are given in radians as well as their standard deviations.

Conversions between radians, gons and degrees:

\[ \text{rad} = \text{gon} \cdot \frac{\pi}{200} = \text{deg} \cdot \frac{\pi}{180} \]

4.3 Network SQL definition

Network definitions are stored in the configurations table. This table contains all parameters for each network such as value of a priori reference standard deviation or orientation of the xy orthogonal coordinate system axes.

It is obvious that in one database file can be stored more networks (configurations).

Configuration descriptions (annotation or comments) are stored separately in table descriptions. The description is split to many records because of compatibility with various databases (not all databases implements type TEXT).

Field (attribute) conf_id identifies a configuration in the database. Field conf_name is used to identify configuration outside the database (e.g. parameter in command-line when reading data from database to gama-local).

Table configurations contains all parameters specified in tag <parameters /> (see Section 2.5 [Network parameters], page 11) and also gama-local command line parameters (see Section 1.3 [Program gama-local], page 3). The list of all table attributes (parameters) follows.

- **sigma_apr** value of a priori reference standard deviation—square root of reference variance (default value 10)
- **conf_pr** confidence probability used in statistical tests (default value 0.95)
- **tol_abs** tolerance for identification of gross absolute terms in project equations (default value 1000 mm)
- **sigma_act** actual type of reference standard deviation use in statistical tests (aposteriori | apriori); default value is aposteriori
- **update_cc** enables user to control if coordinates of constrained points are updated in iterative adjustment. If test on linearization fails (see Section 5.9 [Linearization], page 47), Gama tries to improve approximate coordinates of adjusted points and repeats the whole adjustment. Coordinates of constrained points are implicitly not changed during iterations. Acceptable values are yes, no, default value is yes.
- **axes_xy** orientation of axes x and y; value ne implies that axis x is oriented north and axis y is oriented east. Acceptable values are ne, sw, es, wn for left-handed coordinate systems and en, nw, se, ws for right-handed coordinate systems (default value is ne).
- **angles right-handed** defines counterclockwise observed angles and/or directions, value left-handed defines clockwise observed angles and/or directions (default value is left-handed).
- **epoch** is measurement epoch. It is floating point number (default value is 0.0).
• **algorithm** specifies numerical method used for solution of the adjustment. For Singular Value Decomposition set value to *svd*. Value *gso* stands for block matrix algorithm GSO by Frantisek Charamza based on Gram-Schmidt orthogonalization, value *cholesky* for Cholesky decomposition of semidefinite matrix of normal equations and value *envelope* for a Cholesky decomposition with *envelope* reduction of the sparse matrix. Default value is *svd*.

• **ang_units** Angular units of angles in *gama-local* output. Value 400 stands for gons and value 360 for degrees (default value is 400). Note that this doesn’t effect units of angles in database. For further information about angular units see Section 2.1 [Angular units], page 9.

• **latitude** is mean latitude in network area. Default value is 50 (gons).

• **ellipsoid** is name of ellipsoid (see Section 6.2 [Supported ellipsoids], page 53).

All fields are mandatory except *ellipsoid* field. For additional information about handling geodetic systems in *gama-local* see Section 2.3 [Network definition], page 10.

Example (configuration table contents):

```
conf_id|conf_name|sigma_apr|conf_pr|tol_abs|sigma_act |update_cc|
--------|---------|---------|--------|---------|---------|---------|
1 |geodet-pc|10.0 |0.95 |1000.0 |aposteriori|no |
... axes_xy|angles |epoch|algorithm|ang_units|latitude|ellipsoid
--------|--------|------|--------|---------|---------|---------|
... ne |left-handed|0.0 |svd |400 |50.0 |
```

The list of description table attributes follows.

• **conf_id** is id of configuration which description (text) belongs to.

• **id** identifies text in a database.

• **text** is part of configuration description. Its SQL type is VARCHAR(1000).

There can be more than one text for one configuration. All texts related to one configuration are concatenated to one description.

Example (description table contents):

```
conf_id|indx|text
--------|-----|------------------------
1 |1 |Frantisek Charamza: GEODET/PC, ...
```

### 4.4 Table points

• **conf_id** is id of configuration which points belongs to.

• **id** identifies point in a database and also in an output. It is mandatory and it is character string (SQL type is VARCHAR(80)). Point id has to be unique within one configuration. In documentation it is referred as point identification or point id.

• **x**, **y** and **z** coordinates of a point. Coordinate **z** is considered as height.

• **txy** and **tz** specify the type of coordinates **x**, **y** and **z**. Acceptable values are **fixed**, **adjusted** and **constrained** (there is no default value). For details see Section 2.7 [Points], page 12.
Example (table contents):

<table>
<thead>
<tr>
<th>conf_id</th>
<th>ccluster</th>
<th>dim</th>
<th>band</th>
<th>tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>obs</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>obs</td>
</tr>
</tbody>
</table>

4.5 Table clusters

The cluster is a group of observations with the common covariance matrix. The covariance matrix allows to express any combination of correlations among observations in cluster (including uncorrelated observations, where covariance matrix is diagonal). For explanation see Section 6.1 [Observation data and points], page 51.

In the database observations are stored in three tables: obs, coordinates and vectors. Cluster’s covariance matrix is stored in table covmat. Every observation, vector or coordinate in database has to be in some cluster.

- **conf_id** is id of configuration which cluster belongs to.
- **ccluster** identifies a cluster within one configuration.
- **dim** and **band** specify dimension and bandwidth of covariance matrix. The bandwidth of the diagonal matrix is equal to 0 and a fully-populated covariance matrix has a bandwidth of \( \text{dim-1} \) (**band** maximum possible value is \( \text{dim-1} \)).
- **tag** specifies type of observations in cluster which also implies the table where they are stored in. obs and height-differences stand for obs table, coordinates and vectors stand for coordinates table and vectors table respectively.

Observations, vectors and coordinates are identified by configuration id (**conf_id**), cluster id **ccluster** and theirs index (**indx**). Observation index (**indx**) has to be unique within observations of one cluster (which belongs to one configuration). The same applies for vectors and coordinates.

See also Section 2.8 [Set of observations], page 13.

Example (table contents):

<table>
<thead>
<tr>
<th>conf_id</th>
<th>ccluster</th>
<th>dim</th>
<th>band</th>
<th>tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>obs</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>obs</td>
</tr>
</tbody>
</table>

4.6 Table covmat

Values of cluster covariance matrix are stored in covmat table. Attributes conf_id, ccluster identifies covariance matrix. Value position in matrix is specified by rind and cind fields.

- **conf_id** is id of configuration which cluster belongs to.
- **ccluster** is id of cluster which matrix belongs to.
- **rind** is row number in covariance matrix
• **cind** is column number covariance matrix
• **val** is value itself (variance or covariance).

Values **rind** and **cind** have to respect **dim** and **band** specified in table **clusters**. If value in covariance matrix is not specified (record is missing), it is considered to be zero.

Example (table contents):

```
conf_id|ccluster|rind|cind|val
-------|--------|-----|----|-----
  1   |   1    |  1  |  1  | 400.0
  1   |   1    |  2  |  2  | 400.0
  1   |   1    |  3  |  3  | 400.0
  1   |   4    |  1  |  1  | 400.0
  1   |   4    |  2  |  2  | 400.0
  1   |   4    |  3  |  3  | 400.0
  1   |   4    |  4  |  4  | 400.0
```

### 4.7 Table **obs**

Table **obs** contains simple observations like direction or distance.

• **conf_id** is id of configuration which cluster belongs to.
• **ccluster** is id of cluster which observation belongs to.
• **indx** identifies observation within cluster. It has to be positive integer.
• **tag** specifies a type of an observation. Allowed **tags** follows.
  • **direction** for directions.
  • **distance** for horizontal distances.
  • **angle** for angles.
  • **s-distance** for slope distances (space distances).
  • **z-angle** for zenith angles.
  • **azimuth** for azimuth angles.
  • **dh** for leveling height differences.
• **from_id** is stand point identification. It is mandatory and it must not differ within one cluster for observations with **tag** = 'direction'.
• **to_id** is target identification (mandatory).
• **to_id2** is second target identification. It is valid and mandatory only for angles (**tag** = 'angle').
• **val** is observation value. It is mandatory for all observation types.
• **stdev** is value of standard deviation. It is used when variance in covariance matrix is not specified.
• **from_dh** is value of instrument height (optional).
• **to_dh** is value of reflector/target height (optional).
• **to_dh2** is value of second reflector/target height (optional). It is valid only for angles.
• **dist** is distance of leveling section. It is valid only for height-differences (**tag** = 'dh').
• rejected specifies whether observation is rejected (passive) or not. Value 0 stand for not rejected, value 1 for rejected. It is mandatory. Default value is 0.

Example (table contents without empty columns):

<table>
<thead>
<tr>
<th>conf_id</th>
<th>ccluster</th>
<th>indx</th>
<th>tag</th>
<th>from_id</th>
<th>to_id</th>
<th>val</th>
<th>rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>direction</td>
<td>201</td>
<td>202</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>direction</td>
<td>201</td>
<td>207</td>
<td>0.817750284544</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>direction</td>
<td>201</td>
<td>205</td>
<td>2.020073921388</td>
<td>0</td>
</tr>
</tbody>
</table>

4.8 Table coordinates

Table coordinates contains control (known) coordinates.

• conf_id is id of configuration which cluster belongs to.
• ccluster is id of cluster which coordinates belongs to.
• indx identifies coordinates within cluster. It has to be positive integer.
• id is point identification.
• x, y and z are coordinates.
• rejected specifies whether observation is rejected (passive) or not. Value 0 stand for not rejected, value 1 for rejected. Default value is 0.

See also Section 2.16 [Control coordinates], page 19.

4.9 Table vectors

Table vectors contains coordinate differences (vectors).

• conf_id is id of configuration which cluster belongs to.
• ccluster is id of cluster which vector belongs to.
• indx identifies vector within cluster. It has to be positive integer.
• from_id is point identification. It identifies initial point.
• to_id is point identification. It identifies terminal point.
• dx, dy and dz are coordinate differences.
• from_dh is value of initial point height. It is optional.
• to_dh is value of terminal point height. It is optional.
• rejected integer default 0 not null,

See also Section 2.17 [Coordinate differences], page 19.

4.10 Example of local geodetic network in SQL

Providing complete example would be reasonable because of its extent. However, you can obtain example by following these instructions:

Create a file with XML representation of network by copy and paste example from Section 2.19 [Example], page 20, to a new file. Note that file should start with <?xml version="1.0" ?> (no whitespace). Alternatively you can use existing XML file from collection of sample networks (see Section 1.1 [Download], page 2). Then you can
convert your XML file (here example_network.xml) to SQL statements by program gama-local-xml2sql (the path depends on your Gama installation).

    $ gama-local-xml2sql example_net example_network.xml example_network.sql

Now you have example network (configuration example_net) in the form of SQL INSERT statements in the file example_network.sql.

Another representations you can create and fill SQLite database (for details see Section 4.1 [Working with SQLite database], page 29):

    $ sqlite3 examples.db < gama-local-schema.sql
    $ sqlite3 examples.db < example_network.sql
    $ sqlite3 examples.db

Once you have SQLite database, you can work with it from SQLite command line. You can get nice output by executing following commands.

    sqlite> .mode column
    sqlite> .nullvalue NULL
    sqlite> SELECT * FROM gnu_gama_local_configurations;
    sqlite> SELECT * FROM gnu_gama_local_points;
    sqlite> SELECT * FROM gnu_gama_local_clusters;
    sqlite> SELECT * FROM gnu_gama_local_covmat;
    sqlite> SELECT * FROM gnu_gama_local_obs;

Or you can get database dump (CREATE and INSERT statements) by

    sqlite> .dump

If it is not enough for you, you can try one of GUI tools for SQLite.
5 Network adjustment with gama-local

Adjustment of local geodetic network is a classical case of adjustment of indirect observations. After estimation of approximate values of unknown parameters (coordinates of points) and linearization of functions describing relations between observations and parameters we solve linear system of equations

$$Ax = b + v,$$  \hspace{1cm} (1)

where $A$ is coefficient matrix, $b$ is vector of absolute terms (right hand side) and $v$ is vector of residuals. This system is (generally) overdetermined and we seek the solution $x$ satisfying the basic criterion of Least Squares

$$v^TPv = \min,$$  \hspace{1cm} (2)

where $P$ is weight matrix. This criterion unambiguously defines the shape of adjusted network.

Geodetic adjustment is traditionally computed as the solution of normal equations

$$Nx = n, \hspace{0.5cm} N = A'PA, \hspace{0.5cm} n = A'Pb.$$  \hspace{1cm} (a)

In the case of free network, i.e. network with no fixed coordinates (or network without sufficient number of fixed coordinates), the system (1) is singular, matrix $A$ has linearly dependent columns, and there is infinite number of solutions $x$.

To define a unique solution $x$ we need to define a set of constraint equations (inner constraints)

$$Cx = c$$  \hspace{1cm} (b)

to minimize

$$v^TPv - 2k'(Cx - c) = \min$$  \hspace{1cm} (c)

where $r$ is the vector of residuals, $r = Ax - b$, $k$ is a vector of so called Lagrange multipliers and adjusted vector $x$ is obtained from solution of

$$\begin{pmatrix} A'PA & C' \\ C & 0 \end{pmatrix} \begin{pmatrix} x \\ k \end{pmatrix} = \begin{pmatrix} A'Pb \\ c \end{pmatrix}$$  \hspace{1cm} (d)

In gama-local a slightly different approach is used, we define a second regularization criterion as

$$\sum_{i \in \Omega} x_i^2 = \min,$$  \hspace{1cm} (3)

stating that at the same time with (2) we demand that the sum of squares corrections of selected parameters is minimal (corrections of unknown parameters with indexes from the set $\Omega$). Geometrically this criterion is equivalent to adjustment of the network according to (2) with simultaneous transformation to the selected set of fiducial points. This transformation does not change the shape of adjusted network.

---

1 gama-local can solve the project equations (1) directly using algorithms Gram-Schmidt orthogonalisation or Singular Value Decomposition, which generally yield numerically more stable solution.
Often it is advantageous to work with a homogenized system, ie. with the system of project equations in which coefficient of each row and absolute term are multiplied by square root of the weight of corresponding observation.

\[ \tilde{\mathbf{A}} \mathbf{x} = \tilde{\mathbf{b}}, \]

(4)

where \( \tilde{\mathbf{A}} = \mathbf{P}^{1/2} \mathbf{A}, \tilde{\mathbf{b}} = \mathbf{P}^{1/2} \mathbf{b} \). Symbol \( \mathbf{P}^{1/2} \) denotes diagonal matrix of square roots of observation weights (or Cholesky decomposition of covariance matrix in the case of correlated observations). To criterion (2) corresponds in the case of homogenized system criterion

\[ \tilde{\mathbf{v}}' \tilde{\mathbf{v}} = \min. \]

(5)

Normal equations are clearly equivalent for both systems.

\[ (\mathbf{A}' \mathbf{P} \mathbf{A}) \mathbf{x} = (\mathbf{A}' \mathbf{P} \mathbf{b}) \quad \equiv \quad (\tilde{\mathbf{A}}' \tilde{\mathbf{A}}) \mathbf{x} = (\tilde{\mathbf{A}} \tilde{\mathbf{b}}). \]

Between weight coefficients of the original system (1) and homogenized system (4) are the following relations

\[ q_{x_i} = \tilde{q}_{x_i}, \quad i = 1, \ldots, n, \]
\[ q_{L_j} = \tilde{q}_{L_j}/p_j, \quad j = 1, \ldots, m, \]
\[ q_{v_k} = \tilde{q}_{v_k}/p_k = (1 - \tilde{q}_{L_k})/p_k = 1/p_k - q_{L_k}, \quad k = 1, \ldots, m. \]

5.1 Approximate coordinates

For computation of coefficients in system (1) (ie. during linearization) we need, first of all, an estimate of approximate coordinates of points and approximate values of orientations of observed directions sets.

Approximate values of unknown parameters are usually not known and we have to compute them from the available observations. For approximate value of orientation program \texttt{gama-local} uses median of all estimates from the given set of directions to the points with known coordinates. Median is less sensitive to outliers than arithmetic mean which is normally used for approximate estimate of orientations.

During the phase of computation of approximate coordinate of points, program \texttt{gama-local} walks through the list of computed points and for each point gathers all determining elements pointing to points with known or previously computed coordinates. Determining elements are

- outer bearing (oriented half-line) starting from the point with known coordinates and pointing to the computed point
- distance between given and computed points
- inner angle with vertex in the computed point and arms intersecting given points

For all combinations of determining elements program \texttt{gama-local} computes intersections and estimates approximate coordinates as the median of all available solutions.

If at least one point was resolved while iterating through the list, the whole cycle is repeated. If no more coordinates can be solved using intersections and points with unknown coordinates are remaining, program tries to compute coordinates of unresolved points in a local
coordinates system and obtain their coordinates using similarity transformation. If a transformation succeeds to resolve coordinates at least one computed point and there are still some points without coordinates left, the whole process is repeated. Classes for computation of approximate coordinates have been written by Jiri Vesely.

If program gama-local fails to compute approximate coordinates of some of the network points, they are eliminated from the adjustment and they are listed in the output listing.

With the outlined strategy, program gama-local is able to estimate approximate coordinates in most of the cases we normally meet in surveying profession. Still there are cases in which the solution fails. One example is an inserted horizontal traverse with sets of observed direction on both ends but without a connecting observed distance. The solution of approximate coordinates can fail when there is a number of gross error for example resulting from confusion of point identifications but in normal situations, leaving computation of approximate coordinates on program gama-local is recommended.

Example

Computation of approximate coordinates of points
**************************************************************************
Number of points with given coordinates: 2
Number of solved points : 2
Number of observations : 4
----------------------------------------------------------------------------
Successfully solved points : 0
Remaining unsolved points : 2

List of unresolved points
*************************
422
424

5.2 Gross absolute terms

One of parameters in XML input of program gama-local is tolerance tol-abs for detecting of gross absolute terms in project equations. Observations with outlying absolute terms are always excluded from adjustment.

For measured distances program tests difference between observed value $d_i$ and distance computed from approximate coordinates $d_0$

$$|d_i - d_0| > \text{tol} - \text{abs},$$

for observed directions program gama-local tests transverse deviation corresponding to absolute term $b_i$ from project equations (1)

$$|b_i|d_0 > \text{tol} - \text{abs}$$
and similarly for angles, program tests the greater of two deviations corresponding to left and right distances (left and right arm of the angle)

$$|b_i| \max\{d_{0i}, d_{0r}\} > t_{\text{ol-abs}}.$$

Default value of parameter $t_{\text{ol-abs}}$ is 1000 mm.

**Example**

Outlying absolute terms in project equations

<table>
<thead>
<tr>
<th>i</th>
<th>standpoint</th>
<th>target</th>
<th>observed</th>
<th>absolute term</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>103</td>
<td>104 dir.</td>
<td>301.087900</td>
<td>-9989.1</td>
</tr>
</tbody>
</table>

Observations with outlying absolute terms removed

### 5.3 Parameters of statistical analysis

Program `gama-local` uses two basic statistical parameters

- confidence probability $P$ (default value is 95%, see input XML parameter `conf-pr`) and
- actual type of reference standard deviation $m_{0a}$ (parameter `sigma-act`).

Confidence probability determines significance level on which statistical tests of adjusted quantities are carried. Actual type of reference standard deviation $m_{0a}$ specifies whether during statistical analysis we use an a priori reference standard deviation $m_0$ or an a posteriori estimate $m'_0$. On the type of actual reference standard deviation depends the choice of density functions of stochastic quantities in statistical analysis of the adjustment.

**A priori reference standard deviation** $m_0$ is an estimate of the standard deviation of an observation with the unit weight. Numerically it is a scaling factor used in calculation of the weights. If we change $m_0$, only the sum of weighted residuals squares is changed and all adjustment results remain the same (there is just one least squares solution). $m_0$ can be selected in cases when we know its value in advance and with sufficient reliability. Another situation when $m_0$ is used are networks with low number of degrees of freedom (poorly overdetermined systems) or when veen degrees of freedom is zero. Examples may be analysis of network models etc.

**A posteri estimate of reference standard deviation** $m'_0$ is used in cases when a priori value of reference standard deviation $m_0$ is not known and when degrees of freedom is sufficiently high and reliable for empirical estimate of $m'_0$.

The standard deviation of an adjusted quantity $\theta$ is computed in dependece on the choice of actual type of reference standard deviation $m_{0a}$ according to formula

$$m_{\theta_i} = m_{0a}\sqrt{\hat{\theta}_{i}}.$$
where \( q_{\theta_i} \) is weight coefficient (cofactor) of the \( i \)-th adjusted unknown parameter (coordinate or orientation, \( \theta = x_i \)) or \( i \)-th adjusted observation (distance, direction, \ldots, \( \theta = L_i \)).

Apart from standard deviation \( m_0 \), program \texttt{gama-local} computes for adjusted quantity \( \theta \) its confidence interval \( (\Theta_1, \Theta_2) \) in which the real value \( \Theta \) is located with probability \( P \)

\[
P(\Theta_1 < \Theta < \Theta_2) = P,
\]

\[
\Theta_1 = \theta - k_p m_{\theta}, \quad \Theta_2 = \theta + k_p m_{\theta},
\]

where coefficient \( k_p \) depends on confidence probability \( P \) and in the case of low number of degrees of freedom on the choice of actual type of reference standard deviation \( m_{0\alpha} \).

Coefficient \( k_p \) is computed for \( m_{0\alpha} = m_0 \) as critical value of normal distribution for probability \( \alpha/2 \), for the case of choice \( m_{0\alpha} = m'_0 \) as critical value of Student distribution on confidence level \( \alpha/2 \) with \( \tau \) degrees of freedom

\[
k_p = \begin{cases} 
  u_{\alpha/2} & \text{if } m_{0\alpha} = m_0, \\
  t_{\alpha/2,\tau} & \text{if } m_{0\alpha} = m'_0.
\end{cases}
\]

Similarly confidence ellipses for adjusted points are defined in the following text.

### 5.4 Test on the reference standard deviation

Null hypothesis \( H_0 : m_0 = m'_0 \) is tested versus alternative hypothesis \( H_1 : m_0 \neq m'_0 \).

Test criterion is ratio of a posteriori estimate of reference standard deviation

\[
m'_0 = \sqrt{\mathbf{v}' \mathbf{P} \mathbf{v} / \tau}
\]

and a priori reference standard deviation \( m_0 \) (input data parameter \texttt{m0-apr}). For given significance level \( \alpha \) lower and upper bounds of interval \( (L,U) \) are computed so, that if hypothesis \( H_0 \) is true, probabilities \( P(m'_0/m_0 \leq D) \) and \( P(m'_0/m_0 \geq H) \) are equal to \( \alpha/2 \).

Lower and upper bounds of the interval are computed as

\[
L = \sqrt{\chi^2_{1-\alpha/2,\tau} / \tau}, \quad U = \sqrt{\chi^2_{\alpha/2,\tau} / \tau}.
\]

Probability

\[
P(L < m'_0/m_0 < U) = \text{conf} - \text{pr}
\]

is by default 95\%, this corresponds to 5\% confidence level test.

Exceeding the upper limit \( H \) of the confidence interval can be caused even by a single gross error (one outlying observation). Method of Least Squares is generally very sensitive to presence of outliers. Safely can be detected only one observation whose elimination leads to maximal decrease of a posteriori estimate of reference standard deviation

\[
m''_0 = \sqrt{(\mathbf{v}' \mathbf{P} \mathbf{v} - \delta) / (\tau - 1)}, \quad \delta = \max(v_i^2/q_{v_i}),
\]

where

\[
q_{v_i} = 1/p_i - q_L,
\]

is weight coefficient of \( i \)-th residual. If the set of observations contains only one gross error, the outlying observation is likely to be detected, but this can not be guaranteed.

In addition, program \texttt{gama-local} computes a posteriori estimate of reference standard deviation separately for horizontal distances and directions and/or angles after formula from

\[
m'_{0t} = \sqrt{\sum \hat{v}_{it}^2 / \sum \hat{q}_{v_i}}, \quad t = d, s,
\]

where symbol \( t \) denotes observed distances, directions and/or angles.
Example

\( m_0 \) apriori : 10.00
\( m_0' \) empirical: 9.64 \[pvv\] : 3.43560e+03

During statistical analysis we work

- with empirical standard deviation 9.64
- with confidence level 95 %

Ratio \( m_0' \) empirical / \( m_0 \) apriori: 0.964
95 % interval (0.773, 1.227) contains value \( m_0'/m_0 \)
\( m_0'/m_0 \) (distances): 0.997 \( m_0'/m_0 \) (directions): 0.943

Maximal decrease of \( m_0''/m_0 \) on elimination of one observation: 0.892

Maximal studentized residual 2.48 exceeds critical value 1.95
on significance level 5 % for observation #35

<distance from="407" to="422" val="346.415" stdev="5.0" />

5.5 Information on points

Program \texttt{gama-local} lists separately review of coordinates of fixed and adjusted points; adjusted constrained coordinates are marked with *; see equation (3). Adjusted coordinate standard deviations \( m_x \) and \( m_y \), and values for computing confidence intervals are given in the listing of adjusted coordinates (Section 5.3 [Statistical analysis], page 40). In the review index \( i \) is the index of unknown \( x_i \) from the system of project equations (1) corresponding to the point coordinates \( x \) and \( y \).

Example

Fixed points
*************

<table>
<thead>
<tr>
<th>point</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1054980.484</td>
<td>644498.590</td>
</tr>
<tr>
<td></td>
<td>1054933.801</td>
<td>643654.101</td>
</tr>
</tbody>
</table>

Adjusted coordinates
***************

<table>
<thead>
<tr>
<th>i</th>
<th>point</th>
<th>approximate correction</th>
<th>adjusted std.dev</th>
<th>conf.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>value</td>
<td>value</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[m]</td>
<td>[mm]</td>
<td></td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>point</th>
<th>mp</th>
<th>mxy</th>
<th>mean error ellipse</th>
<th>conf.err. ellipse</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>422</td>
<td>3.6</td>
<td>2.6</td>
<td>2.7</td>
<td>2.5</td>
<td>187.0</td>
</tr>
<tr>
<td>424</td>
<td>4.7</td>
<td>3.4</td>
<td>3.7</td>
<td>2.9</td>
<td>131.8</td>
</tr>
<tr>
<td>403</td>
<td>5.7</td>
<td>4.0</td>
<td>4.3</td>
<td>3.6</td>
<td>78.9</td>
</tr>
</tbody>
</table>

Mean square positional error \( m_p \) and mean coordinate error \( m_{xy} \) are computed as

\[
m_p = \sqrt{m_y^2 + m_x^2}, \quad m_{xy} = m_p / \sqrt{2},
\]

where \( m_y^2 \) and \( m_x^2 \) are squares of standard deviations (variances) of adjusted points coordinates.

Semimajor and semiminor axes of standard ellipse are denoted as \( a \) and \( b \) in the listing, bearing of semimajor axis is denoted as \( \alpha \) and they are computed from covariances of adjusted coordinates

\[
a = \sqrt{\frac{1}{2}(\text{cov} \, yy + \text{cov} \, xx + c)} \quad b = \sqrt{\frac{1}{2}(\text{cov} \, yy + \text{cov} \, xx - c)},
\]

\[
c = \sqrt{(\text{cov} \, xx - \text{cov} \, yy)^2 + 4(\text{cov} \, xy)^2},
\]

\[
\tan 2\alpha = 2(\text{cov} \, xy)/(\text{cov} \, xx - \text{cov} \, yy).
\]

The angle \( \alpha \) (the bearing of semimajor axis) is measured clockwise from X axis.

Probability that standard ellipse covers real position of a point is relatively low. For this reason program *gama-local* computes extra confidence ellipse for which the probability of covering real point position is equal to the given confidence probability. Both ellipses are located in the same center, they share the same bearing of semimajor axes and they are similar. For lengths of their semi-axis holds

\[
a' = k_p a, \quad b' = k_p b,
\]

For adjusted points, program summarizes information on standard ellipses, confidence ellipses, mean square positional errors \( (m_p) \), mean coordinate errors \( (m_{xy}) \) and coefficients \( g \) characterizing position of approximate coordinates with regard to the confidence ellipse.

**Example**

Mean errors and parameters of error ellipses

<table>
<thead>
<tr>
<th>point</th>
<th>mp</th>
<th>mxy</th>
<th>mean error ellipse</th>
<th>conf.err. ellipse</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For adjusted points, program summarizes information on standard ellipses, confidence ellipses, mean square positional errors \( (m_p) \), mean coordinate errors \( (m_{xy}) \) and coefficients \( g \) characterizing position of approximate coordinates with regard to the confidence ellipse.
where \( k_p \) is a coefficient computed for the given probability \( P \) as defined in Section 5.3 [Statistical analysis], page 40.

Position of approximate coordinates of an adjusted point with respect to its confidence ellipse is described by two points \( P \) and \( V \) where point \( P \) depicts approximate coordinates and \( V \) adjusted coordinates. Point \( E \) is the intersection of oriented half-line \( VP \) and the confidence ellipse. Coefficient \( g \) is defined as the ration of abscissae

\[
g = \frac{VP}{VE}.\]

Three cases are possible

- \( g < 1 \) approximate coordinates of adjusted point are located inside the confidence ellipse
- \( g = 1 \) approximate coordinates of adjusted point are located on the confidence ellipse
- \( g > 1 \) approximate coordinates of adjusted point are outside the confidence ellipse

The coefficient \( g \) is calculated from formula

\[
g = \sqrt{(a_0/a')^2 + (b_0/b')^2}
\]

where

\[
b_0 = \delta_y \cos \alpha - \delta_x \sin \alpha, \quad a_0 = \delta_y \sin \alpha - \delta_x \cos \alpha
\]

symbol \( \delta \) is used for correction of approximate coordinates and \( \alpha \) is bearing of confidence ellipse semimajor axis.

If network contains sets of observed directions, program writes information on corresponding adjusted orientations, standard deviations and confidence intervals. Index \( i \) is the same as in the case of adjusted coordinates the index of \( i \)-th adjusted unknown in the project equations.
Example

**Adjusted bearings**

<table>
<thead>
<tr>
<th>i</th>
<th>standpoint</th>
<th>approximate correction</th>
<th>adjusted</th>
<th>std.dev</th>
<th>conf.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>value [g]</td>
<td>value [g]</td>
<td></td>
<td>[cc]</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>296.484371</td>
<td>-0.000917</td>
<td>296.483454</td>
<td>5.1</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>96.484371</td>
<td>0.000708</td>
<td>96.485079</td>
<td>5.1</td>
</tr>
<tr>
<td>21</td>
<td>403</td>
<td>20.850571</td>
<td>-0.001953</td>
<td>20.848618</td>
<td>8.8</td>
</tr>
</tbody>
</table>

5.6 Adjusted observations and residuals

In the review of adjusted observations program **gama-local** prints index of the observation, index of the row in matrix $A$ in the system (1), identifications of standpoint and target point, type of the observation, its approximate and adjusted value, standard deviation and confidence interval.

Example

**Adjusted observations**

<table>
<thead>
<tr>
<th>i</th>
<th>standpoint</th>
<th>target</th>
<th>observed</th>
<th>adjusted</th>
<th>std.dev</th>
<th>conf.i.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>value [m]</td>
<td>value [cm]</td>
<td>[mm]</td>
<td>[mm]</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2 dis.</td>
<td>845.77700</td>
<td>845.77907</td>
<td>3.0</td>
<td>6.1</td>
</tr>
<tr>
<td>2</td>
<td>422</td>
<td>dir.</td>
<td>28.205700</td>
<td>28.205613</td>
<td>5.1</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>424</td>
<td>dir.</td>
<td>60.490600</td>
<td>60.491359</td>
<td>6.7</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Review of residuals serves for analysis of observations and contains values of normalized or studentized residuals (depending on type of $m_0a$ used) and three characteristics. These are coefficient $f$ identifying weak network elements and estimates of real error of observation $e$-obs and real error of its adjusted value $e$-adj, see definition in the following text.

If normalized or studentized residual exceeds critical value for the given confidence probability, it is marked in the review with symbol $c$ (critical) and maximal normalized or studentized residual is marked with symbol $m$.

Example

**Residuals and analysis of observations**

<table>
<thead>
<tr>
<th>i</th>
<th>standpoint</th>
<th>target</th>
<th>$f[%]$</th>
<th>$v$</th>
<th>$v'$</th>
<th>e-obs.</th>
<th>e-adj.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>value [mm]</td>
<td>[mm]</td>
<td>[cc]</td>
<td>[mm]</td>
<td>[cc]</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2 dir.</td>
<td>47.4</td>
<td>9.170</td>
<td>1.1</td>
<td>12.7</td>
<td>3.5</td>
</tr>
</tbody>
</table>
5.7 Identification of weak network elements

When planning observations in a geodetic network we always try to guarantee that all observed elements are checked by other measurements. Only with redundant measurements it is possible to adjust observations and possibly remove blunders that might otherwise totally corrupt the whole set of measurements. Apart from sufficient number of redundant observations the degree of control of single observed elements is given by the network configuration, i.e. its geometry.

Less controlled observations represent weak network elements and they can in extreme cases even disable detection of gross observational errors as it is in the case of uncontrolled observations. There are two limit cases of observation control

- **fully controlled observation** as is for example an observed distance between two fixed points (standard deviation of the adjusted element is zero; standard deviation of the residual equals to the standard deviation if the observation) and
- **uncontrolled observations** as is a free polar bar for example (standard deviation of adjusted value is equal to standard deviation of observed quantity; residual and standard deviation of the residual are zero).

Weakly controlled or uncontrolled observations can result even from elimination of certain suspisios observations during analysis of adjustment.

Standard deviation of adjusted observations is less than standard deviation of the measurement. Degree of observation control in network is defined as coefficient

\[ f = 100 \frac{m_L - m_L}{m_L}, \]  

where \( m_L \) is standard deviation of observed quantity and \( m_L \) is standard deviation computed from a posteriori reference standard deviation \( m_0 \). We consider observed network element to be

- **uncontrolled** if \( f < 0.1 \) (in listing marked with letter u),
- **weakly controlled** if \( 0.1 \leq f < 5 \) (in listing marked with letter w).

5.8 Estimation of real errors

According to previous section we can consider an observation to be controlled if its coefficient \( f > 0.1 \). Any controlled observation can be eliminated from the network without corrupting the network consistency—network reduced by one controlled observation can be adjusted and all unknown parameters can be compute without the eliminated observation.

Estimate of real error of \( i \)-th observation is defined as

\[ \varepsilon_{\ell_i} = L_i^{red} - \ell_i, \]  

where \( \ell_i \) is value of \( i \)-th observation and \( L_i^{red} \) is value of \( i \)-th network element computed from adjusted coordinates and/or orientations of the reduced network. Similarly is defined
the estimate of real error of a residual
\[ \varepsilon_{v_i} = L_i^{\text{red}} - L_i. \]  

Adjustment results are the best statistical estimate of unknown parameters that we have. This holds true even for adjustment of reduced network which is not influenced by real error of \( i \)-th observation. On favourable occasions differences (9) and (10) can help to detect blunders but to interpret these estimates as real errors is possible only with substantial exaggeration. These estimates fail when there are more than one significant observational error. Generally holds that the weaker the element is controlled in network the less reliable these estimates are.

Estimate of real error of an observation computes program \texttt{gama-local} as
\[ \varepsilon_{l_i} = v_i/(p_i q_{v_i}) \]
and estimate of real error of a residual as
\[ \varepsilon_{v_i} = \varepsilon_{l_i} - v_i. \]

5.9 Test on linearization
Mathematical model of geodetic network adjustment in \texttt{gama-local} is defined as a set of known real-valued differentiable functions
\[ L^* = \varphi(X^*), \]  
where \( L^* \) is a vector of theoretical correct observations and \( X^* \) is a vector of correct values of parameters. For the given sample set of observations \( L \) and the unknown vector of residuals \( v \) we can express the estimate of parameters \( X \) as a nonlinear set of equations
\[ L + v = \varphi(X). \]  
With approximate values \( X_0 \) of unknown parameters
\[ X = X_0 + x \]
we can linearize the equations (12)
\[ L + v = \varphi(X_0) + \left. \frac{\partial \varphi}{\partial X} \right|_{X=X_0} x \]
yielding the linear set of equations (1) where
\[ A = \left. \frac{\partial \varphi}{\partial X} \right|_{X=X_0} \quad \text{and} \quad b = L - \varphi(X_0). \]

Unknown parameters in \texttt{gama-local} mathematical model are points coordinates and orientation angles (transforming observed directions to bearings). The observables described by functions (12) belong into two classes

- **linear observables**: horizontal and slope distances, height differences, control coordinates and vectors (coordinate differences),
angular observables: directions, horizontal and zenith angles.

Internally in `gama-local` unknown corrections to linear observables are computed in millimeters and corrections to angular observables in centigrade seconds. To reflect the internal units in used all partial derivatives of angular observables by coordinates are scaled by factor $2000/\pi = 10^{-3} \times (200 \times 10^4/\pi)$.

When computing coefficients of project equations (1) we expect that approximate coordinates of points are known with sufficient accuracy needed for linearization of generally nonlinear relations between observations and unknown parameters. Most often this is true but not always and generally we have to check how close our approximation is to adjusted parameters.

Generally we check linearization in adjustment by double calculation of residuals

$$v^i = Ax - b,$$
$$v^{ii} = \bar{\ell}(\bar{x}) - \ell,$$

where in our notation $x$ is vector of corrections of approximate unknown parameters $x_0$, $b$ vector of reduced observations, $\ell$ vector of observations and $\bar{\ell}(\bar{x})$ is vector of adjusted observations computed from adjusted coordinates $\bar{x} = x_0 + x$. Disagreement $v^i \neq v^{ii}$ signals discrepancies in linearization.

Program `gama-local` similarly computes and tests differences in values of adjusted observations once computed from residuals and once from adjusted coordinates. For measured directions and angles `gama-local` computes in addition transverse deviation corresponding to computed angle difference in the distance of target point (or the farther of two targets for angle). As a criterion of bad linearization is supposed positional deviation greater or equal to 0.0005 millimetres.

**Example**

Test of linearization error

***************************

Diffs in adj. obs from residuals and from adjusted coordinates

************************************************************

<table>
<thead>
<tr>
<th>i</th>
<th>standpoint</th>
<th>target</th>
<th>observed</th>
<th>$r$</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3022184030</td>
<td>3022724008</td>
<td>dist. 28.39200</td>
<td>-7.070</td>
<td>-0.003</td>
</tr>
<tr>
<td>3</td>
<td>3022724002</td>
<td>72.30700</td>
<td>-18.815</td>
<td>-0.001</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3000001063</td>
<td>dir. 286.305200</td>
<td>11.272</td>
<td>-0.002</td>
<td>-0.001</td>
</tr>
<tr>
<td>8</td>
<td>3022724008</td>
<td>dir. 357.800600</td>
<td>-23.947</td>
<td>0.037</td>
<td>0.002</td>
</tr>
</tbody>
</table>

From the practical point of view it might seem that the tolerance 0.0005 mm for detecting poor linearization is too strict. Its exceeding in program `gama-local` results in repeated adjustment with substitute adjusted coordinates for approximate. Given tolerance was
chosen so strict to guarantee that listed output results would never be influenced by linearization and could serve for verification and testing of numerical solutions produced by other programs.

Iterated adjustment with successive improvement of approximate unknown coordinates converges usually even for gross errors in initial estimates of unknown coordinates. If the influence of linearization is detected after adjustment, typically only one iteration is sufficient for recovering.

For any automatically controlled iteration we have to set up certain stopping criterion independent on the convergence and results obtained. Program gama-local computes iterated adjustment three times at maximum. If the bad linearization is detected even after three readjustments it signals that given network configuration is somehow suspicious.

5.10 Glossary
Symbols and names used in adjustment statistics.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v, V)</td>
<td>residual, vector of residuals</td>
</tr>
<tr>
<td>(p, P)</td>
<td>observation weight, matrix of weights</td>
</tr>
<tr>
<td>([pvv])</td>
<td>sum of weighted residuals (v'Pv).</td>
</tr>
<tr>
<td>(Ax = b, P)</td>
<td>design matrix, right-hand side (rhs) and weight matrix (P)</td>
</tr>
<tr>
<td>(r)</td>
<td>redundancy, typically number of columns minus rows of (A)</td>
</tr>
<tr>
<td>(Nx = n)</td>
<td>normal equations, (N = A'PA), (n = A'Pb).</td>
</tr>
<tr>
<td>(Q = N^{-1})</td>
<td>cofactor matrix for adjusted unknowns (matrix of weight coefficients, cofactors, of adjusted unknowns)</td>
</tr>
<tr>
<td>(Q_L = AQA')</td>
<td>cofactor matrix for adjusted observations</td>
</tr>
<tr>
<td>(f[%])</td>
<td>degree of control of an observation in the network, spans from 0% (uncontrolled, e.g. observed direction and distance to an isolated adjustment point) to 100% (fully controled, e.g. measured distance between two fixed points)</td>
</tr>
<tr>
<td>(m_0)</td>
<td>a priori reference standard deviation.</td>
</tr>
<tr>
<td>(m'_0)</td>
<td>a posteriori estimate of reference standard deviation</td>
</tr>
<tr>
<td>(m''_0)</td>
<td>minimal a posteriori estimate of reference standard deviation after removal one observation (removal of the observation leading to minimal value of (m0''))</td>
</tr>
</tbody>
</table>
position of approximate coordinates xy of the adjusted point with respect to its confidence ellipse ($g < 1$ approximate coordinates are located inside the ellipse; $g = 1$ on the ellipse; $g > 1$ outside the ellipse).

Zero value of $g$ indicates that approximate and adjusted coordinates are identical. This situation typically happens when iterative adjustment is needed due to poor initial linearization (initial approximate coordinates are too far from the adjusted) and the iterative process ends up with identical approximate and adjusted coordinates.
6 Data structures and algorithms

6.1 Observation data and points

The Gama observation data structures are designed to enable adjustment of any combination of possibly correlated observations. At its very early stage Gama was limited to adjustment of uncorrelated observations. Only directions and distances were available and observable's weight was stored together with the observed value in a single object. A single array of pointers to observation objects was sufficient for handling all observations. So called orientation shifts corresponding to directions measured form a point were stored together with coordinations in point objects.

To enable adjustment of possibly correlated observations (like angles derived from observed directions or already adjusted coordinates from a previous adjustment) Gama has come with the concept of clusters. Cluster is an object with a common variance-covariance matrix and a list of pointers to observation objects (distances, directions, angles, etc.). Weights were removed from observation objects and replaced with a pointer to the cluster to which the observation belong. All clusters are joined in a common object ObservationData; similarly to observations, each cluster contains a pointer to its parent Observation Data object. Orientation shifts were separated from coordinates and are stored in the cluster containing the bunch of directions and thus number of orientations is not limited to one for a point.

This organisation of observational information has proved to be effective. Template classes ObservationData and Cluster are used as base classes both in gama-local and gama-g3.

template <typename Observation>
    class ObservationData
The following template class `PointBase` for handling point information is used in `gama-g3`. The template class `PointBase` relies internally on `std::map` container but comes with its own interface (in `gama-local std::map` was used directly for storing points).

```cpp
template <typename Point>
class PointBase
{
    typedef std::map<typename Point::Name, Point*> Points;

    public:
        PointBase();
        PointBase(const PointBase& cod);
        ~PointBase();

        PointBase& operator=(const PointBase& cod);
        void put(const Point&);

        double stdDev(int i) const;
        int size() const;
        void update();
        int activeCount() const;
        typename Observation::CovarianceMatrix activeCov() const;
};
```
void put(Point*);
Point* find(const typename Point::Name&);
const Point* find(const typename Point::Name&) const;
void erase(const typename Point::Name&);
void erase();

class const_iterator;
const_iterator begin();
const_iterator end();

class iterator;
iterator begin();
iterator end();
}

Template classes ObservationData and PointBase are defined in namespace GNU_gama and are located in the source directory gnu_gama.

### 6.2 Supported ellipsoids

<table>
<thead>
<tr>
<th>id</th>
<th>a</th>
<th>b, 1/f, f</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>airy</td>
<td>6377563.396</td>
<td>6356256.910</td>
<td>Airy ellipsoid 1830 [4]</td>
</tr>
<tr>
<td>airy_mod</td>
<td>6377340.189</td>
<td>6356034.446</td>
<td>Modified Airy</td>
</tr>
<tr>
<td>andrae1876</td>
<td>6377104.43</td>
<td>300.0</td>
<td>Andrae 1876 (Denmark, Iceland)</td>
</tr>
<tr>
<td>australian</td>
<td>6378160</td>
<td>298.25</td>
<td>Australian National 1965</td>
</tr>
<tr>
<td>bessel</td>
<td>6377397.155</td>
<td>6356078.962890</td>
<td>Bessel ellipsoid 1841 [1]</td>
</tr>
<tr>
<td>bessel_nam</td>
<td>6377483.865</td>
<td>299.1528128</td>
<td>Bessel 1841 (Namibia) [4]</td>
</tr>
<tr>
<td>clarke1858a</td>
<td>6378361</td>
<td>6356685</td>
<td>Clarke ellipsoid 1858 1st [3]</td>
</tr>
<tr>
<td>clarke1858b</td>
<td>6378558</td>
<td>6355810</td>
<td>Clarke ellipsoid 1858 2nd [3]</td>
</tr>
<tr>
<td>clarke1866</td>
<td>6378206.4</td>
<td>6356583.8</td>
<td>Clarke ellipsoid 1866 [3]</td>
</tr>
<tr>
<td>clarke1880</td>
<td>6378316</td>
<td>6356582</td>
<td>Clarke ellipsoid 1880 [3]</td>
</tr>
<tr>
<td>clarke1880m</td>
<td>6378249.145</td>
<td>293.4663</td>
<td>Clarke ellipsoid 1880 (modified) [4]</td>
</tr>
<tr>
<td>cpm1799</td>
<td>6375738.7</td>
<td>334.29</td>
<td>Comm. des Poids et Mesures 1799 [4]</td>
</tr>
<tr>
<td>delambre</td>
<td>6376428</td>
<td>311.5</td>
<td>Delambre 1810 (Belgium) [4]</td>
</tr>
<tr>
<td>engelis</td>
<td>6378136.05</td>
<td>298.2566</td>
<td>Engelis 1985 [4]</td>
</tr>
<tr>
<td>everest1830</td>
<td>6377276.345</td>
<td>300.8017</td>
<td>Everest 1830 [4]</td>
</tr>
<tr>
<td>everest1848</td>
<td>6377304.063</td>
<td>300.8017</td>
<td>Everest 1848 [4]</td>
</tr>
<tr>
<td>everest1856</td>
<td>6377301.243</td>
<td>300.8017</td>
<td>Everest 1856 [4]</td>
</tr>
<tr>
<td>everest1869</td>
<td>6377295.664</td>
<td>300.8017</td>
<td>Everest 1869 [4]</td>
</tr>
<tr>
<td>Ellipsoid Name</td>
<td>Semi-major Axis (a)</td>
<td>Eccentricity (e)</td>
<td>Notes</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------------</td>
<td>-----------------</td>
<td>-------</td>
</tr>
<tr>
<td>everest_ss</td>
<td>6377298.556</td>
<td>0.003017</td>
<td>Everest (Sabah and Sarawak)</td>
</tr>
<tr>
<td>fisher1960</td>
<td>6378166</td>
<td>0.003065</td>
<td>Fisher 1960 (Mercury Datum)</td>
</tr>
<tr>
<td>fisher1960m</td>
<td>6378155</td>
<td>0.003065</td>
<td>Modified Fisher 1960</td>
</tr>
<tr>
<td>fischer1968</td>
<td>6378150</td>
<td>0.003065</td>
<td>Fischer 1968</td>
</tr>
<tr>
<td>grs67</td>
<td>6378160</td>
<td>0.002997</td>
<td>GRS 67 (IUGG 1967)</td>
</tr>
<tr>
<td>grs80</td>
<td>6378137</td>
<td>0.002977</td>
<td>Geodetic Reference System 1980</td>
</tr>
<tr>
<td>hayford</td>
<td>6378388</td>
<td>0.002977</td>
<td>Hayford 1909 (International)</td>
</tr>
<tr>
<td>helmert</td>
<td>6378200</td>
<td>0.002977</td>
<td>Helmert ellipsoid 1906</td>
</tr>
<tr>
<td>hough</td>
<td>6378270</td>
<td>0.002977</td>
<td>Hough</td>
</tr>
<tr>
<td>iau76</td>
<td>6378140</td>
<td>0.002977</td>
<td>IAU 1976</td>
</tr>
<tr>
<td>international</td>
<td>6378388</td>
<td>0.002977</td>
<td>International 1924 (Hayford 1909)</td>
</tr>
<tr>
<td>kaula</td>
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6.3 Transformation from spatial to geographical coordinates

Spatial coordinates \((X, Y, Z)\) can be easily computed from geographical ellipsoidal coordinates \((B, L, H)\), where \(B\) is geographical latitude, \(L\) geographical longitude and \(H\) is ellipsoidal height, as

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
(N + H) \cos B \cos L \\
(N + H) \cos B \sin L \\
(N(1 - e^2) + H) \sin B
\end{pmatrix}
\]

where \(N = a/\sqrt{1 - e^2 \sin^2 B}\) is the radius of curvature in the prime vertical, \(e^2 = (a^2 - b^2)/a^2\) is the first eccentricity for the given rotational ellipsoid (spheroid) with semi-major axis \(a\) and semi-minor axis \(b\).

In the case of coordinate transformation from \((X, Y, Z)\) to \((B, L, H)\), the longitude is given by the formula

\[
\tan L = Y/X.
\]

Now we can introduce \(D = \sqrt{X^2 + Y^2}\), so that the cartesian system become \((D, Z)\). Coordinates \(B\) and \(H\) are then usually computed by iteration with some starting value of \(B_0\), for example \(\tan B_0 = Z/D/(1 - e^2)\),

\[
\tan B_i = Z/D + \frac{N_{i-1}}{(N_{i-1} + H_{i-1})} e^2 \tan B_{i-1}, \quad H_i = D/ \cos B_{i-1} = Z/ \sin B_{i-1} - N(1 - e^2)
\]
B. R. Bowring described a closed formula\(^1\) that is more effective and sufficiently accurate and that is used in GNU Gama.

The centre of curvature \(C\) of the spheroid corresponding to \(P'\) is the point

\[
(e^2 a \cos^2 u, -e'^2 b \sin^3 u),
\]

where \(e'^2 = (a^2 - b^2)/b^2\) is second eccentricity and \(u\) is the parametric latitude of the point \(P',\) \((1 - e^2)N \sin B = b \sin u.\) Therefore

\[
\tan B = \frac{Z + e'^2 b \sin^3 u}{D - e^2 a \cos^3 u}.
\]

This is clearly an iterative solution; but it has been found that this formula is extremely accurate using the single first approximation for \(u\) for the \(\tan u = (Z/D)(a/b).\) Maximum error in earth bound region is 3e-8 of sexagesimal arc seconds (5e-7 millimetres); maximum is 0.0018” (0.1 millimetres) at height \(H = 2a.\)

### 6.4 Class g3::Model

g3::model documentation shall come here ...

```cpp
namespace GNU_gama {
namespace g3 {

    class Model {

    
```

\(^1\) B. R. Bowring: Transformation from spatial to geographical coordinates, Survey Review XXIII, 181, July 1976
public:

typedef GNU_gama::PointBase<g3::Point> PointBase;
typedef GNU_gama::ObservationData<g3::Observation> ObservationData;

PointBase *points;
ObservationData *obs;

GNU_gama::Ellipsoid ellipsoid;

Model();
~Model();

Point* get_point(const Point::Name&);
void write_xml(std::ostream& out) const;
void pre_linearization();
}}
7 Gama-local companion tools

With gama-local come several companion command line tools, most of them being conversion programs for various data formats.

7.1 gama-local-deformation

Program gama-local-deformation reads XML adjustment results files from two dates (epochs), compute differences for adjusted points common in both epochs, calculate the covariance matrix of the differences and optionally renders the deformation diagram in SVG output file.

Usage: gama-local-deformation epoch1.xml epoch2.xml [--text file] [--svg file]
gama-local-deformation --version
  gama-local-deformation --help

Options:

epoch1 and epoch2 are adjustment results in XML format of the surveying network.
The program computes the shift vectors of common adjusted points and their corresponding covariance matrix.

--text deformation analyses in textual format. If missing, standard output device is used (i.e. screen).
--svg if defined, the program writes SVG image of the second epoch adjustment with standard deviation ellipses and points' shifts.
The network schema is available only in 2D (xy coordinates only).
--version
--help

Report bugs to: <bug-gama@gnu.org>
GNU gama home page: <https://www.gnu.org/software/gama/>
General help using GNU software: <https://www.gnu.org/gethelp/>
7.2 gama-local-gkf2yaml

Program gama-local-gkf2yaml converts input XML format of gama-local (in Gama project usually denoted with extension gkf) to yaml format.

    gama-local-gkf2yaml input.gkf [output.yaml]

7.3 gama-local-yaml2gkf

Program gama-local-yaml2gkf converts YAML input to XML input format.

    gama-local-yaml2gkf input.yaml [output.gkf]

7.4 gama-local-xml2sql

Program gama-local-xml2sql converts gama-local XML input format (aka gkf) to SQL script.

Usage: gama-local-xml2sql configuration (xml_input|-) [sql_output|-

    Convert XML adjustment input of gama-local to SQL

7.5 gama-local-xml2txt

Conversion from adjustment XML output to text format.

Usage: gama-local-xml2txt [options] < std_input > std_output

    Convert XML adjustment output of gama-local to text format

Options:

    --angles 400 | 360
    --language en | ca | cz | du | fi | fr | hu | ru | ua
    --encoding utf-8 | iso-8859-2 | iso-8859-2-flat | cp-1250 | cp-1251
    --help

7.6 krumm2gama-local

GNU Gama sources come with an extensive set of testing data examples in the directory tests where subdirectory tests/krumm contains examples from the book by Friedhelm Krumm, Geodetic Network Adjustment Examples, Geodätisches Institut Universität Stuttgart, https://www.gis.uni-stuttgart.de, Rev. 3.5 January 20, 2020. All these examples are distributed with GNU Gama with permission from the author.

Conversion program krumm2gama-local converts the examples data format defined in the book to the gama-local XML input format. For more details read the file tests/krumm/input.README.md.

Conversion from data format used in Geodetic Network Adjustment Examples by Friedhelm Krumm to XML input format of gama-local (GNU Gama)
https://www.gis.uni-stuttgart.de/lehre/campus-docs/adjustment_examples.pdf

    krumm2gama-local input_file [output_file]
    krumm2gama-local < std_input [ > std_output ]
Options:
-h, --help  this text
-v, --version  print program version
-e, --examples  add the following comment to the generated XML file

This example is based on published material Geodetic Network Adjustment Examples by Friedhelm Krumm, Geodätisches Institut Universität Stuttgart, Rev. 3.5, January 20, 2020
8 Gama-local test suite

GNU Gama comes with a set of tests that provides `gama-local` test suite. To run the test suite, go to the top-level Gama directory and type

```
$ make check
```

You should see the names of the test suite files as they are processed, any other output indicates some problem. The output might be for example this

```
Entering directory 'gama/tests/gama-local'
PAS: gama-local-version.sh
PAS: gama-local-adjustment.sh
PAS: gama-local-algorithms.sh
PAS: gama-local-xml-xml.sh
PAS: gama-local-html.sh
PAS: gama-local-equivalents.sh
PAS: gama-local-xml-results.sh
PAS: gama-local-parameters.sh
PAS: gama-local-import.sh
PAS: gama-local-sqlite-reader.sh
PAS: xmllint-gama-local-xsd.sh
PAS: xmllint-gama-local-adjustment-xsd.sh
```

```
Testsuite summary for gama 2.29
```

```
# TOTAL: 12
# PASS: 12
# SKIP: 0
# XFAIL: 0
# FAIL: 0
# XPASS: 0
# ERROR: 0
```

Number of tests vary according to the configuration of your system. Tests that are always present are

- `gama-local-version`
- `gama-local-adjustment`
- `gama-local-algorithms`
- `gama-local-xml-xml`
- `gama-local-html`
- `gama-local-equivalents`
- `gama-local-xml-results`
- `gama-local-parameters`
- `gama-local-export`

Optional tests are

- `gama-local-sqlite-reader`
- `xmllint-gama-local-xsd`
xmlint-gama-local-adjustment-xsd
which are included only if sqlite3 database support libraries and/or xmlint program are installed.
You can also request more extra test configuring the project as

    ./configure --enable-extra-tests

but be prepared that these extra test might take some time to finish.

8.1 Internal organisation

Gama-local tests are implemented as shell scripts that are stored in gama/tests/gama-local directory. The scripts are generated from corresponding .in files which are stored in gama/tests/gama-local/script directory where are also stored helper C++ programs called by the testing suite scripts. Generating scripts and the build of helper programs is controlled from gama/tests/gama-local/Makefile.am, where a list of testing data files is also defined.

In gama/tests/gama-local directory are also stored detail .log files for all tests together with corresponding .trs (as in Test ReSults) files.

All files generated by the test suite are stored in gama/tests/gama-local/script/2.29 (thus generated files from different versions are not overwritten).

To run selected test individually, go to the directory gama/tests/gama-local and start the test manually

    $ cd gama/tests/gama-local
    $ ./test-name
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Version 1.1, March 2000

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