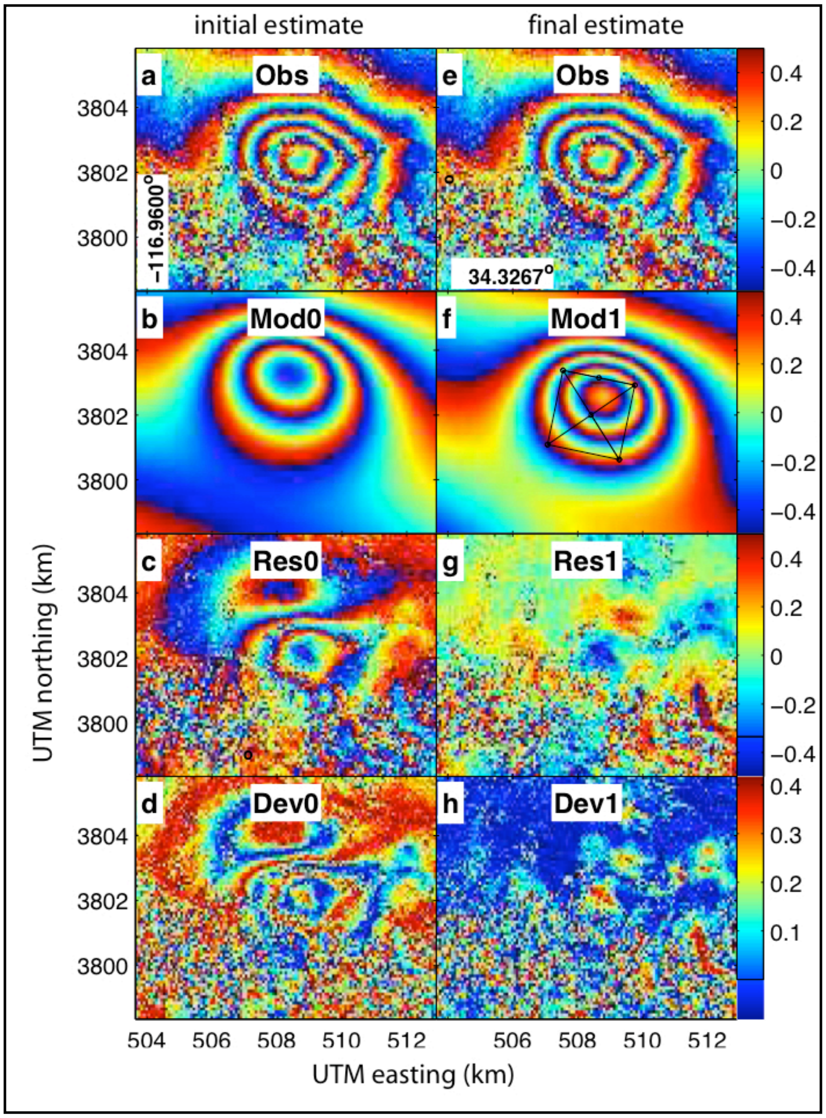
General Inversion for Phase Technique (GIPhT) Demonstration Manual

Kurt L. Feigl, Clifford H. Thurber, and Lee Powell

University of Wisconsin-Madison



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Kurt L. Feigl is an Associate Professor with the University of Wisconsin-Madison, 1215 West Dayton Street, Madison, WI 53706 USA. (phone: +1 608-262-8960; fax +1 262-0693; e-mail: feigl@wisc.edu).

Clifford H. Thurber is a Professor with the University of Wisconsin-Madison.

Lee Powell is an emeritus Senior Instrumentation Innovator with the University of Wisconsin-Madison.

***Abstract*— Interferometric analysis of synthetic aperture radar images (InSAR) measures the phase shifts between two images acquired at two distinct times. These ambiguous 'wrapped' phase values range from -1/2 to +1/2 cycles. The standard approach interprets the phase values in terms of the change in distance between the ground and the radar instrument by resolving the integer ambiguities in a process known as 'unwrapping'. To avoid unwrapping, GIPhT models the wrapped phase data directly. GIPhT defines a cost function in terms of wrapped phase to measure the misfit between the observed and modelled values of phase. By minimizing the cost function with a simulated annealing algorithm, GIPhT estimates parameters in a non-linear model. Since the wrapped phase residuals are compatible with a von Mises distribution, several parametric statistical tests can be used to evaluate the fit of the model to the data. GIPhT can handle noisy, wrapped phase data. The software documented here can be applied to a set of interferograms acquired of the same area under a single imaging geometry. This demonstration includes several example data sets that illustrate simple modeling the deformation associated with subsidence and an earthquake.**

I. Introduction

Synthetic aperture radar (SAR) is an active remote sensing technique used for measuring geophysical activity on the Earth's surface. It records microwaves transmitted by a sensor (usually aboard a satellite) and reflected by features on the Earth's surface (usually on land). The reflected signal contains information in the form of amplitude and phase data, and requires sophisticated post-processing. A technique known as interferometric SAR (InSAR) measures the difference in phase between two images of the same area, which can be used to measure motion and deformation of the ground. In most applications, the interferogram must be "unwrapped" before it can be interpreted. The unwrapped interferogram may be used to monitor geophysical changes on the Earth's surface associated with earthquakes, volcanoes, landslides or glaciers, or with the withdrawal of oil, gas, water or minerals by extractive industries. Unwrapping requires considerable computational power and time, and may lead to significant mistakes in the unwrapped interferogram and thus in its intepretation. These issues can become especially problematic in cases where the data are noisy or the fringes are discontinuous, for example in a fault zone where an earthquake has ruptured the ground surface. To avoid these issues, GIPhT is designed to interpret an interferogram without the need for unwrapping, as described by Feigl and Thurber [1]. To do so, GIPhT estimates parameters in a quantitative model directly from the wrapped phase data. The goal is to produce a modeled interferogram that resembles the observed interferogram. To reach this goal, GIPhT minimizes the angular deviation between the observed and measured values of the interferometric phase.

II. Quick Start

A. Starting computer and terminal

Turn on Macbook computer.

Log in as "gipht". Password is "demo".

A terminal window should appear.

Open a Finder window to list the files in the directory (folder) named **`Documents/demo4`**.

B. Starting GIPHT

The directory called **`demo4`** contains an example of subsidence in Iceland. It is described in more detail below. To start the demonstration, type:

```
giphtdemo demo4
```

The program should begin by writing textual output to the terminal window. Figures, beginning with copyright notice, should appear in separate windows. The demonstration should take about 8 minutes to run to completion. At the end of the run, all the figures should close. The same figures are preserved as output files in various formats, as discussed below.

Alternatively, the directory named **`demoF`** contains files for the Fawnskin earthquake as described by Feigl and Thurber [1]. In the terminal window, start the Fawnskin earthquake demonstration by typing:

```
giphtdemo demoF
```

C. Evaluating Output

GIPhT creates output of five different types, as described in detail below. All five types are placed in a directory named after the date and time of the run, e.g. `x_20090413_100015` for 15 seconds past 10:00 AM on 13 April 2009. The several subdirectories in the directory called **`examples`** each include all the output for a successful run, as executed before the demonstration was shipped.

1) Log file

The log file, named **`x.log,`** records all pertinent information regarding the run.

2) Output parameters file

The output parameters file, named **`x_parameters.out,`** records the values of the model parameters used and estimated in the run. It also contains the statistical values used to evaluate its quality. One line of this file pertains to one parameter, in the same format as the input parameters file.

3) Graphics in JPG format

Most figures are in JPEG format. These files have names ending in **`.jpg`**. They may be visualized directly by clicking on them in the Finder window. Specific examples are shown below.

4) Graphics in PostScript format

A few figures, notably the 8-panel figures in UTM projections are stored as PostScript files to preserve their aspect ratios. These files have names ending in **.ps**. They may also be visualized clicking on them in the Finder window. After translating the file from PostScript format into PDF format, the Preview.app program will display the graphic on the screen. Specific examples are shown below.

5) Phase values in binary RAW format

These binary files have names ending in **.pha**. They cannot be visualized directly.

III. Subsidence Example (demo4)

A. Description

This example shows subsidence in Iceland, using four interferometric pairs. The subsidence signal is caused by the withdrawal of fluids at the Svartsengi geothermal field, near the Blue Lagoon on the Reykanes Peninsula (

Figure 1). A map is shown in Figure 2 .The geothermal resourced has been described by Bjornsson [2]. A copy of this paper is provided in the file called

doc/Bjornsson.pdf.

The subsidence was observed by InSAR [3]. A copy of this paper is provided in the file called

doc/VadonAndSigmundsson1997Science.pdf.

The model for the subsidence is an infinitesimal sphere that decreases its volume at constant rate, also called a "point sink". This sphere is embedded in an elastic half-space with a known Poisson's ratio. This model was developed by Mogi [4]. It includes four free parameters: easting coordinate, northing coordinate, depth, and volume change (rate) as sketched in

Figure 3. ***In this example, the volume change is assumed to vary linearly with the time spanned by the interferograms. In other words, the rate of volume change rate is assumed to be constant. In theory, the Poisson's ratio can also be adjusted.*** In practice, however, it tends to trade off with the depth parameter.

Although the Mogi model fits the InSAR data in this example, it leads to an estimate of the depth that is deeper than that inferred from other geophysical data. One possible explanation may be that some of the assumptions in the Mogi model are inappropriate. These issues have been explored by Akarvardar et al. [5]. This paper also applies a Mogi model to a subsidence signal recorded by InSAR. A copy of the corrected proofs of this paper is provided in the file called

doc/gji_4126_corrections20090403.pdf.

B. Input files

1) dem_descriptor.dat

The file named **dem_descriptor.dat** is used to define the region covered by the interferograms recorded in the phase file(s). Each line contains a keyword followed by a numerical value or another keyword. The numerical values control how GIPhT reads the phase files. Note that the region must be the same in all the phase files. The various areal subsets are sketched in Figure 4. The file used for the example in the demo4 example appears in Figure 5.

2) dem.i2

The binary file named **dem.i2** contains the digital elevation model (DEM). Topographic elevation is specified in meters as two (2) signed bytes per pixel, as described in the file named **dem_descriptor.dat**. The binary file named **dem.i2** is rectangular and flat. It contains no headers. Accordingly, the number of lines and columns should be identical to those of **<u>all</u>** the phase files. Since the DEM is coded as two bytes per pixel, the number of bytes in **dem.i2** should be exactly twice the number of bytes in each (and every) phase file if a subset of the DEM is defined (by setting the EXTRACTION keyword to NON in the file named **dem_descriptor.dat)**. The coordinates are implied. They may be specified in geographic (latitude and longitude in degrees) or cartographic (easting and northing in meters), as described in the file named **dem_descriptor.dat**.

3) sub_region.dat

The file named **sub_region.dat** is used to define the sub_region of interferograms to be analyzed with GIPhT. It contains a keyword followed by a numerical value. The numerical value controls how GIPhT operates. The file used for the example in the demo4 example appears in Figure 6. Note that the sub-region is a subset of the "extract" region specified in the file called **dem_descriptor.dat,** as sketched in Figure 4.

The file named **sub_region.dat** also includes the unit vector $\hat{\mathbf{s}}$ pointing from the pixel on the ground to the satellite, such that the range change *Δρ* is the scalar ("dot") product

$$\Delta\rho = -\hat{\mathbf{s}} \bullet \mathbf{u}$$

where u is the displacement vector as sketched in Figure 7.

The file named **sub_region.dat** also includes the keyword **pselect** that controls how GIPhT selects the pixels for inversion from the rectangular sub-region. If keyword **pselect == 1**, then GIPhT selects the pixels randomly, as described by Feigl and Thurber [1]. If keyword **pselect == 2**, then GIPhT re-uses the same pixels as in the previous run and stored in the binary files **ikeep.mat** and **jkeep.mat.** For examples, see **demo2**, **demo4**, and **demoF**. if keyword **pselect == 3**, then GIPhT selects the pixels using "quad-tree resampling", as described by Jonsson et al. [6]. For example, see **demo6.**

The file named **sub_region.dat** also includes the keyword **anneal** that controls how GIPhT performs the inversion. If keyword **anneal == 0**, then GIPhT simply copies the initial estimate of the parameters to the final estimate, without performing any inversion. This option is useful for forward modeling by trial and error, as described in the section on troubleshooting (VI.B.1). If keyword **anneal == 1**, then GIPhT uses simulated annealing, without recording all the trial values. If keyword **anneal == 2**, then GIPhT uses simulated annealing, but (slowly) records all the trial values.

4) file_names.dat

The file named **file_names.dat** defines the names of the phase files as well as the corresponding master epochs and slave epochs in decimal years. There is one line per interferometric pair. An example from **demo4** is shown in Figure 8. If **file_names.dat** is present, then **interferograms.lst** is ignored. GIPhT reads **file_names.dat** until the end or an incorrect format is found.

5) interferograms.lst (optional)

The file named **interferograms.lst** contains the meta-data (e.g., dates and orbit numbers) of the interferometric pairs to analyzed. Interferometric pairs to be used should be flagged by including a lower-case letter 'a' at the end of the corresponding line. Note that the files are implied to have names of the form:

psp_10575_20438_ort.pha

where **10575** is the orbit number for the (older) master epoch and **20438** is the orbit number of the (younger) slave epoch. GIPhT reads **interferograms.lst** until the end or an incorrect format is found. This file also contains additional meta-data, e.g., calendar dates for the master and slave epochs, altitude of ambiguity, temporal separation, etc., for each interferometric pair. The file named **interferograms.lst** is ignored if **file_names.dat** is present.

6) Input phase files

These binary files contain the InSAR phase change data for the region specified in dem_descriptor.dat. The phase values are coded as one (1) signed byte per pixel, such that

$$-128 \text{ DN} = -0.5 \text{ cycle}$$

$$0 \text{ DN} = 0 \text{ cycle (or missing data)}$$

$$+127 \text{ DN} = +0.5 \text{ cycle}$$

$$256 \text{ DN} = 1 \text{ cycle of wrapped phase}$$

Filenames are built by parsing interferograms.lst or listed in **file_names.dat.** For example, the following four phase files are expected in **demo4**:

psp_10575_20438_ort.pha

psp_10575_21941_ort.pha

psp_5565_10575_ort.pha

psp_7278_17298_ort.pha

7) parameters.in

The file named **parameters.in** contains the initial and bounding values of the parameters. These values are used to calculate the modeled phase values. An example of **parameters.in** appears in Figure 9. The simulated annealing algorithm in GIPhT tries many sets of values for the model parameters. It selects the set of parameter values that leads to the minimal value of the "cost function" as defined by Feigl and Thurber [1] in their equation (17). Adjusting the width of these bounds (the difference between the upper and lower bounding values) controls how GIPhT explores the parameter space. Widely spaced bounds leads to a more exhaustive search. An example for the fault depth parameter in the Fawnskin earthquake example appears in Figure 7 of Feigl and Thurber [1].

8) startup.m

This file sets the search path to the Matlab m-files required by GIPhT when starting MATLAB. It should not be modified by the user.

9) coh.byt

This file contains coherence values, coded as one (1) unsigned byte per pixel, such that 255 = perfect coherence. This optional file is not yet used.

C. Output files

All the output files produced by one run of GIPhT are placed in a directory named after the date and time of the run with a name of the form **x_YYYYMMDD_HHMMSS.** For example, **x_20090413_100015** denotes 15 seconds past 10:00 AM on 13 April 2009. Most of the output files also include a number indicating the interferometric pair, e.g., **x_001…, x_002…,** etc

1) x.log

The file named **x.log** records all the intermediate steps taken by GIPhT. There is one such file per run.

2) x_parameters.out

The file named **x_parameters.out** contains the values of the parameters as estimated by GIPhT. There is one such file per run. An example appears in Figure 10. The values in the column labeled "initial" are those provided by the user as input before running GIPhT. The values in the column labeled "final" and highlighted in magenta are those estimated by GIPhT after running simulated annealing. The values in the column labeled "adjust" are the difference between the initial and final estimates of the model parameters. The values in the column labeled "sigma" are the uncertainties calculated by varying the parameters one parameter at a time, as described in section 5.2 of Feigl and Thurber [1]. One line indicates the "cost" (misfit) of the final estimate of the parameters. The "cost function" is defined by Feigl and Thurber [1] in their equation (17). ***This statistic is the best single number for assessing the quality of a solution.*** In particular, the cost of the final estimate should be lower than the cost of the initial estimate. If not, reconsider the bounding values, as described in the section below on troubleshooting (VI.B.1)

3) x_001_8PAN.ps

This 8-panel plot that summarizes the results from GIPhT succintly. There is one such file for each pair. For the Iceland example in the demo4 directory, the 8-panel plot appears in Figure 11. For the Fawnskin earthquake example, these plots appear as Figures 2 and 3 of Feigl and Thurber [1]. The panels in the left column include:

(a) observed phase values;

(b) modeled phase values calculated from the initial estimate;

(c) initial residual phase values formed by subtracting the initial modeled phase values from the observed phase values;

(d) angular deviations for the initial estimate;

The panels in the right column include:

(e) observed phase values, repeated for convenience;

(f) modeled phase values calculated from the final estimate;

(g) final residual phase values formed by subtracting the final modeled values from the observed phase values;

(h) angular deviations for the final estimate.

In the upper three rows, one colored fringe corresponds to one cycle of phase change, or 28 mm of range change. In the lowermost (fourth) row, the colors denote the angular deviation in phase between 0 and ½ cycle. Coordinates are Universal Transverse Mercator easting and northing in km outside the frames.

4) Phase values plotted on maps with coordinates

These maps are recorded in the JPEG format. They may be visualized directly by clicking on them directly in the Finder window. There is one such file for each pair.

a) x_001_OBS1.jpg

Map of observed phase values. Circles denote pixels selected for the inversion.

b) x_001_MOD1.jpg

Map of modeled phase values calculated using the final estimates of the model parameters.

c) x_001_RES1.jpg

Wrapped residual phase calculated by subtracting the modeled phase values from the observed phase values and wrapping the difference (modulo 1 cycle). This figure should show a small number of fringes.

d) x_001_COST.jpg

Values of the angular deviation (also called "cost"), ranging from a minimum of 0.0 cycles, shown as blue, (modeled and observed phase values agree perfectly) to a maximum of 0.5 cycles, shown as red, (modeled and observed phase values disagree extremely badly). In other words a model that fits the observations well will show more blue pixels than red.

5) Phase files

All the files with names ending in **`.pha`** contain phase data coded as described above. The following output phase files are 2-dimensional arrays covering the selected sub-region. In general, the output phase files are smaller than the input phase files. For each interferometric pair, there are four output files.

a) x_001_OBSV.pha

Observed wrapped phase values as read by GIPhT. The values range from -0.5 to +0.5 cycles.

b) x_001_MODL.pha

Modeled wrapped phase values calculated from the final estimate of the modeled phase parameters. The values range from -0.5 to +0.5 cycles.

c) x_001_RESD.pha

Wrapped residual phase calculated by subtracting the modeled phase values from the observed phase values and wrapping the difference (modulo 1 cycle). The values range from -0.5 to +0.5 cycles.

d) x_001_COST.pha

Values of the angular deviation (also called "cost"), ranging from 0.0 cycles (modeled and observed phase values agree perfectly) to 0.5 cycles (modeled and observed phase values disagree completely).

6) ikeep.mat and jkeep.mat

The binary files named **`ikeep.mat`** and **`jkeep.mat`** contain the indices to the pixels selected by GIPhT for analysis. To re-use the same pixels in subsequent inversions, set the **`pselect`** keyword to 2 in the file called **`sub_region.dat`**. To randomly select a new set of pixels in subsequent inversions, set the **`pselect`** keyword to 1 in the file called **`sub_region.dat`**. In this case, the binary files named **`ikeep.mat`** and **`jkeep.mat`** will be ignored.

7) matlab.mat

Used by GIPhT to pass data from one processing step to another. For the demonstration, this file should be deleted to avoid filling the hard disk space.

8) unitv.mat

Used by GIPhT to pass data from one processing step to another. For the demonstration, this file should be deleted to avoid filling the hard disk space.

9) unitv2.mat

Used by GIPhT to pass data from one processing step to another. For the demonstration, this file should be deleted to avoid filling the hard disk space.

10) x.jpg

Splash screen showing version number of GIPhT and legal messages.

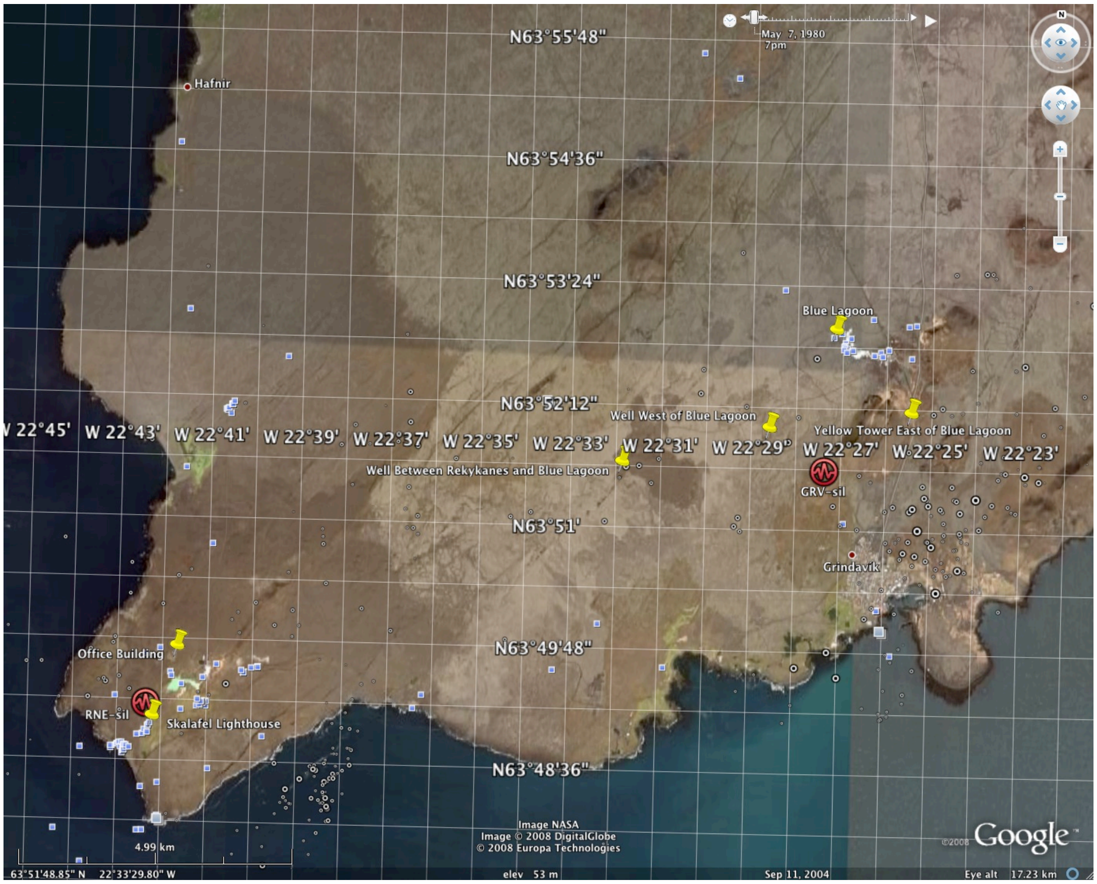

Figure 1. Optical image of the Reykanes Peninsula in southwest Iceland showing the study area for demonstration data set **`demo4`** for monitoring subsidence produced by withdrawal of geothermal fluids near the Blue Lagoon. Figure from Google Earth.

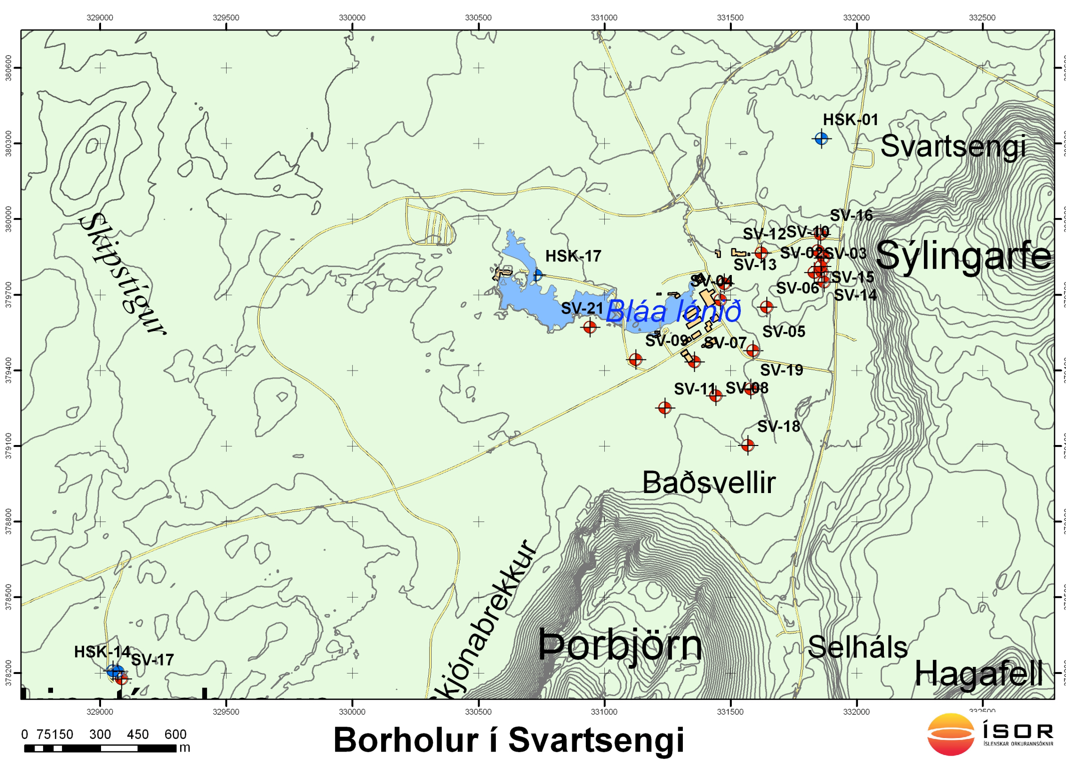

Figure 2. Map of the geothermal fields near the Blue Lagoon. Figure courtesy of ISOR.

Figure 3. Cartoon of a Mogi model showing the parameters of 3-dimensional position (X = easting, Y = northing, out of page, Z, depth) and volume change *ΔV* (red shell). The spherical source changes its volume from the dashed line to the solid line.

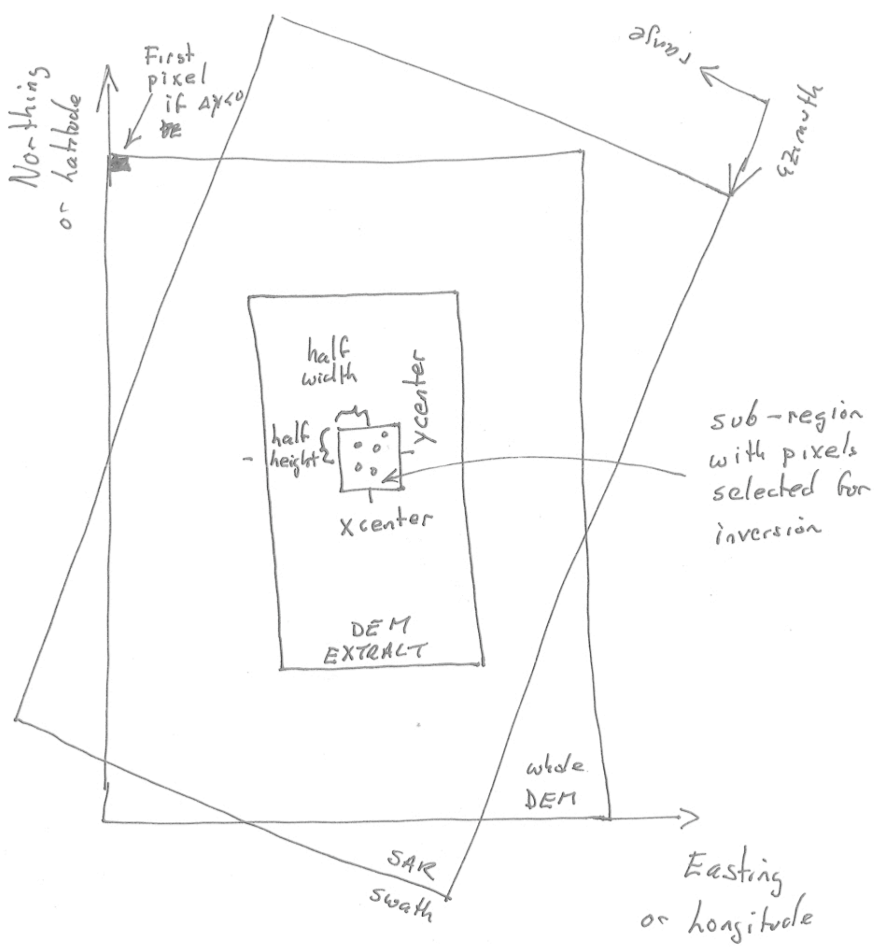

Figure 4. Sketch showing three subsets of the digital elevation model (DEM), namely: the entire area (largest rectangle), the extracted area (medium-sized rectangle), and the sub_region (smallest rectangle) used to select pixels for analysis with GIPhT. The phase files should cover exactly the same area as the

extracted area. If no extraction is performed, then the extracted area covers the entire area of the DEM. In this case, the EXTRACTION keyword in the file named **dem_descriptor.dat** should be set to NON.

```
FICHIER BINAIRE                    dem.i2
(BINARY FILE)
NOMBRE DE LIGNES          3777
(NUMBER OF ROWS)
NOMBRE DE COLONNES             5204
(NUMBER OF COLUMNS)
EXTRACTION                  OUI
(OUI ou NON)
PREMIERE LIGNE EXTRAITE         2700
(FIRST EXTRACTED ROW)
PREMIERE COLONNE EXTRAITE       630
(FIRST EXTRACTED COLUMN)
LIGNES EXTRAITES                 420
(EXTRACTED ROWS)
COLONNES EXTRAITES              800
(EXTRACTED COLUMN)
NATURE DES COORDONNEES               CARTOGRAPHIQUES
(SYSTEM OF COORDINATES : GEOGRAPHIQUES ou CARTOGRAPHIQUES)
COORDONNEE X POINT 0                     244241.939052   (en metres)
(COORDINATE IN X FOR POINT 0 in meters)
PAS X                                    100.000000      (en metres)
(GRID IN X in meters)
COORDONNEE Y POINT 0                     683033.000000   (en metres)
(COORDINATE IN Y FOR POINT 0 in meters)
PAS Y                                    -100.000000     (en metres)
(GRID IN Y in meters)
REPRESENTATION                  LAMBERT
(UTM ou LAMBERT)
LATITUDE ORIGINE EN DEGRES                  65.00352701
(ORIGIN OF THE LATITUDE IN DEGREES)
LONGITUDE ORIGINE EN DEGRES                 341.0
(ORIGIN OF THE LONGITUDE IN DEGREES)
COORDONNEES EN X DE L'ORIGINE               500000.000
(COORDINATE IN X OF THE ORIGIN)
COORDONNEES EN Y DE L'ORIGINE               500000.000
(COORDINATE IN Y OF THE ORIGIN)
FACTEUR D'ECHELLE LAMBERT                   0.9999144231
(SCALE FACTOR FOR THE LAMBERT REPRESENTATION)
```

Figure 5 Example of **dem_descriptor.dat** file used to define the region to be analyzed with GIPhT.

```
% sub_region.dat
% Variables to control how GIPhT selects pixels
% This file is for subsidence study in Iceland
% parameter name must start in column 1 with the parameter
% value as the second word
% parameter names must be lower case
%
% COORDINATES
xcenter 329970      % X coordinate of center of sampled region
                    %   UTM easting in meters, OR
                    %   Geographic Longitude in decimal degrees (positive East)
ycenter 378560      % Y coordinate of center of sampled region
                    %   UTM northing in meters, OR
                    %   Geographic Latitude in decimal degrees (positive North)
                    % Note on coordinates:
                    %  These values should be specified in the same system
                    %   as the DEM,
                    %   as described in the dem_descriptor.dat file
% DIMENSIONS            %
halfwidth 150        % half the east-west width of the sampled region in pixels
halfheight 75        % half the north-south height of sampled region in pixels
                     %
npix 200              % number of pixels to include in inversion
                        %   Value is ignored if PSELECT = 3
pselect 3            % Approach for selecting pixels from subregion
                        % 1=random from subregion
                        % 2=reuse previous pixels
                        % 3=quadtree sampling
                        % Note on PSELECT=2:
                        %      If ikeep.mat or jkeep.mat are not present,
                        %       or if they don't match npix
                        %      the first run will select pixels randomly
                        % Note on PSELECT=3:
                        %     NPIX will be ignored
                        %     elevations will be set to zero
                        %     Vertical gradients cannot be estimated.
tolerance 0.05          % threshold for circular mean deviation misfit
                        % for quad-tree sampling in cycles
                        %
% UNIT VECTOR FROM TARGET TO SATELLITE
                        % assumed constant over scene
unitv_east      0.3611  % Eastward component
unitv_north    -0.1022  % Northward component
unitv_up        0.9269  % Upward component (must be positive)
                        %
tquake 0                % Date of earthquake in decimal years.
                        % Not needed for subsidence
```

Figure 6 Example of **`sub_region.dat`** file used to define sub-region of interferograms to be analyzed with GIPhT. An additional keyword **`anneal`** controls how GIPhT handles the inversion. If **`anneal`** is set to 0, then simulated annealing is not performed and the final estimate equals the initial estimate. If **`anneal`** is set to 1, then simulated annealing is performed, but only the optimal estimate is recorded (default case). If **`anneal`** is set to 2, then simulated annealing is performed, but all the trial values of the parameters are recorded (slow).

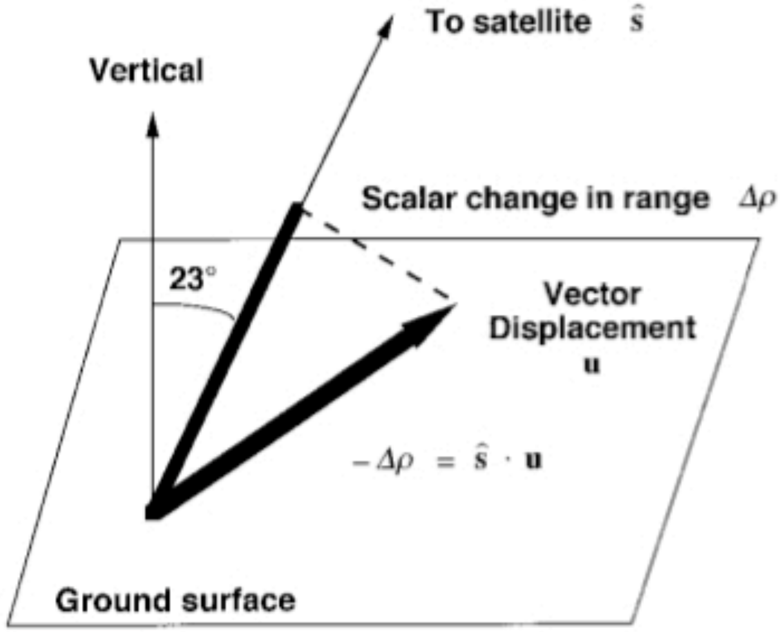

Figure 7. Relation between unit vector $\hat{\mathbf{s}}$ and the ground displacement vector **u**. The unit vector points from the pixel on the ground toward the satellite. The three components (easting, northing, and upward) are specified in the file named **`sub_region.dat`** and read by GIPhT. Figure from Feigl and Dupre [7].

```
%  decimal.year_master  decimal.year_slave  phase_file_name  % comments
1992.6011  1993.5589  psp_5565_10575_ort.pha          % 1992 AUG 08 1993 JUL 24
1993.5589  1995.4438  psp_10575_20438_ort.pha         % 1993 JUL 24 1995 JUN 12
1993.5589  1995.7315  psp_10575_21941_ort.pha         % 1993 JUL 24 1995 SEP 25
1996.6913  1998.6082  psp_7278_17298_ort.pha          % 1996 SEP 10 1998 AUG 11
end of file
```

Figure 8. Example of file named **`file_names.dat`** used to define the master epochs, slave epochs, and phase files to be analyzed by GIPhT.

```
I      Name                                 initial    final      adjust      Sigma    Signif LowerBound UpperBound
F#  31 Mogi1_Easting_in_m_____________      330.0e3    0.00e+00   0.00e+00   0.00e+00    NaN    329.0e3    331.0e3
F#  32 Mogi1_Northing_in_m____________      378.5e3    0.00e+00   0.00e+00   0.00e+00    NaN    377.0e3    381.0e3
F#  33 Mogi1_Depth_in_m_______________      4.6e3      0.00e+00   0.00e+00   0.00e+00    NaN      4.0e3      5.0e3
F#  34 Mogi1_Volume_Increase_in_m^3___    -2.0e+06     0.00e+00   0.00e+00   0.00e+00     0    -5.0e+06   -1.0e+05
```

Figure 9 Example of file named **`parameters.in`** used to define the initial values, lower bounds, and upper bounds of the model parameters to be estimated by GIPhT. If the upper bound equals the lower bound, then the corresponding parameter is not adjusted. The values in the columns labeled “final”, “adjust”, “sigma”, and “Signif” are output, not input, by GIPhT. The format of one line is the same as that output by GIPhT in the file named **`parameters.out`**.

```
x_20090416_175555/x_parameters.out x_20090416_175555/x
I          Name                            initial     final      Adjustment Sigma      Signif.  LowerBound UpperBound
E#  37 Mogi1_Easting_in_m_____________   3.30e+05   3.31e+05   9.44e+02   7.00e+02    1.35   3.29e+05   3.31e+05
E#  38 Mogi1_Northing_in_m____________   3.78e+05   3.80e+05   1.32e+03   9.40e+02    1.40   3.77e+05   3.81e+05
E#  39 Mogi1_Depth_in_m_______________   4.60e+03   4.99e+03   3.88e+02   5.25e+02    0.74   4.00e+03   5.00e+03
E#  40 Mogi1_Volume_Increase_in_m^3___  -2.00e+06  -1.07e+06   9.30e+05   1.47e+05    6.33  -5.00e+06  -1.00e+05
F#  65 Poisson_Ratio_(dimless)________   2.50e-01   2.50e-01   0.00e+00   0.00e+00     NaN   2.50e-01   2.50e-01
F#  66 Shear_Modulus_in_Pa____________   3.00e+10   3.00e+10   0.00e+00   0.00e+00     NaN   3.00e+10   3.00e+10
F#  67 Poisson_Ratio_in_drained_cond._   2.50e-01   2.50e-01   0.00e+00   0.00e+00     NaN   2.50e-01   2.50e-01


Total Average Cost of null  model = 0.2743 cycles per datum for   3352 observations in inverted data set
Total Average Cost of initl model = 0.2451 cycles per datum for   3352 observations in inverted data set
Total Average Cost of final model = 0.1781 cycles per datum for   3352 observations in inverted data set
Circular Mean Dev  of initl model = 0.2433 cycles per datum for   3352 observations in inverted data set
Circular Mean Dev  of final model = 0.1781 cycles per datum for   3352 observations in inverted data set
Circular Mean Dev0 of initl model = 0.2451 cycles per datum for   3352 observations in inverted data set
Circular Mean Dev0 of final model = 0.1781 cycles per datum for   3352 observations in inverted data set
Mean direction of residuals from null     model             = 0.5557 cycles
Mean direction of residuals from initial  model             = -0.1163 cycles
Mean direction of residuals from final    model             = -0.0012 cycles
Circular standard deviation of residuals from final    model = 0.2303 cycles
Mean Resultant Length for residuals for NULL  model Rbar00   =     0.1249
Mean Resultant Length for residuals for initl model Rbar0    =     0.0345
Mean Resultant Length for residuals for final model Rbar1    =     0.3509
Test Statistic distributed as N(0,1) eta00             =   -13.7326
Test Statistic distributed as N(0,1) eta0              =   -18.9886
Test Statistic for mean direction of residuals En00         =    -3.2492
Test Statistic for mean direction of residuals En0          =    -0.9432
Test Statistic for mean direction of residuals En1          =     0.8575
```

Figure 10 Excerpts from file named **parameters.out** listing the model parameters estimated by GIPhT. The values in the column labeled "initial" are those provided by the user as input before running GIPhT. The values in the column labeled "final" and highlighted in magenta are those estimated by GIPhT after running simulated annealing. The values in the column labeled "adjust" are the difference between the initial and final estimates of the model parameters. The values in the column labeled "sigma" are the uncertainties calculated by varying the parameters one parameter at a time, as described in section 5.2 of [1]. The values in the column labeled "Signif" are the ratio of the adjustment to the uncertainty. The term "NaN" denotes "not a number", or an undefined value, e.g., the result of dividing by zero. The line highlighted in yellow indicates the cost of the final estimate of the parameters. This statistic is the best single number for assessing the quality of a solution.

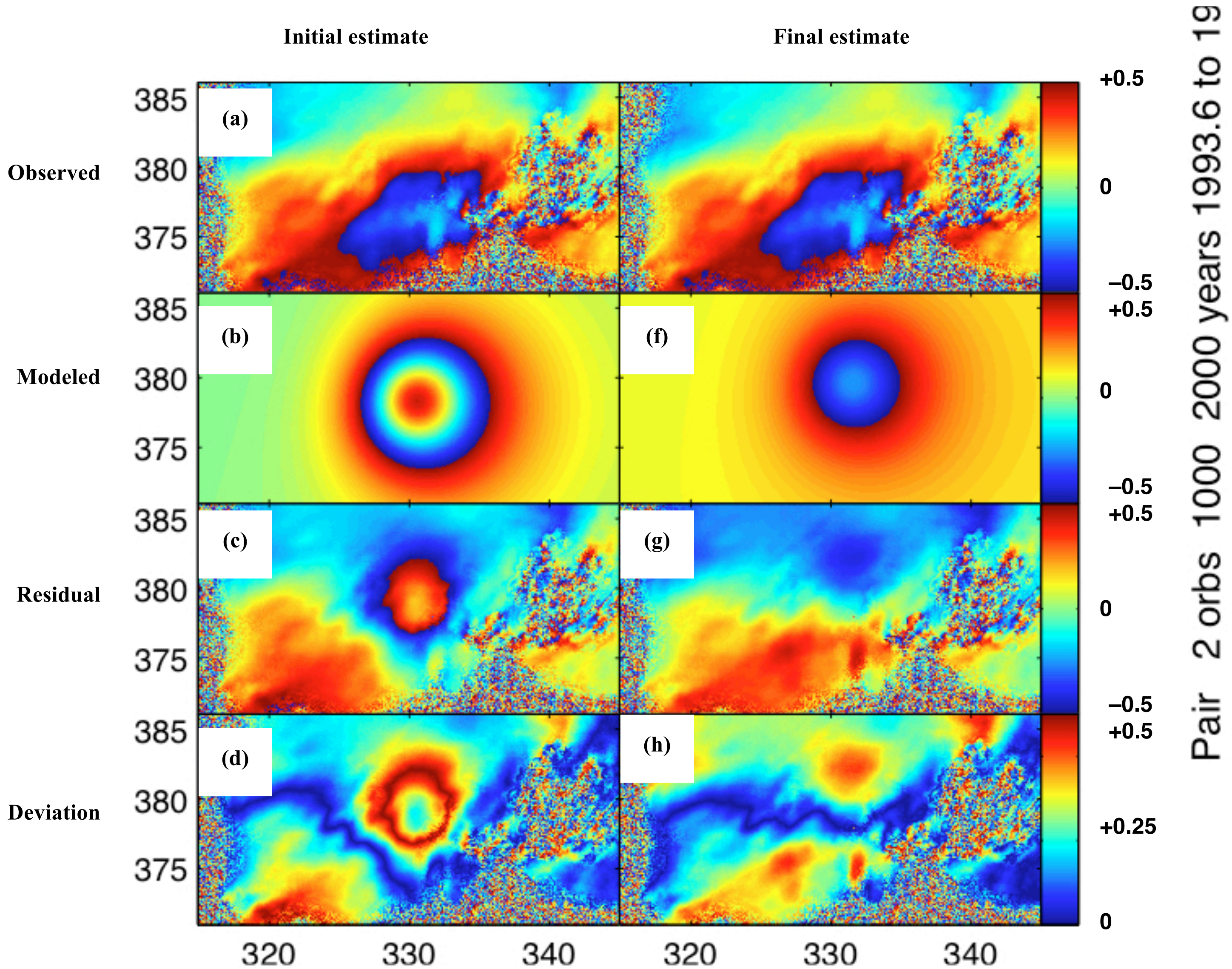

Figure 11. An example of an 8-panel plot for pair 2 of **demo4**. The left panel pertains to the initial estimate of the model parameters, before GIPhT attempts to optimize the fit of model to data. The panels in the left column include, from top to bottom: (a) observed phase values; (b) modeled phase values calculated from the initial estimate; (c) initial residual phase values formed by subtracting the initial modeled phase values from the observed phase values; (d) angular deviations for the initial estimate;

The right panel pertains to the final estimate of the model parameters, as determined by the simulated annealing algorithm within GIPhT. The panels in the right column include: (e) observed phase values, repeated for convenience; (f) modeled phase values calculated from the final estimate; (g) final residual phase values formed by subtracting the final modeled values from the observed phase values; (h) angular deviations for the final estimate.

In the upper three rows, one colored fringe corresponds to one cycle of phase change, or 28 mm of range change. In the lowermost (fourth) row, the colors denote the angular deviation in phase between 0 and ½ cycle. Coordinates are Universal Transverse Mercator easting and northing in km outside the frames. Metadata describing the interferometric pair are written along the right edge of the page.

IV. Fawnskin Earthquake

A. Description

The directory called **demoF** contains files for the Fawnskin earthquake as described by Feigl and Thurber [1]. A copy of this paper is provided in the file called

doc/ FeiglThurber2009GJIpreprint.pdf.

B. Running the demonstration

In the terminal window, start the Fawnskin earthquake demonstration by typing:

```
giphtdemo demoF
```

The program should begin by writing textual output to the terminal window. Figures, beginning with copyright notice, should appear in separate windows. Output files for a successful run appear in the directory called **examples/x_demoF**. Note that the keyword **tquake** has been set to 1999.9, the epoch of the earthquake on 4 December 1992, in the file named **sub_region.dat.**

V. Applying GIPhT to other Data Sets

A. Make and populate a directory

GIPhT operates in a directory (folder) that is later named in on the command line. For example, to consider a data set called **my_data**, make a directory by typing:

```
mkdir my_data
```

It should be at the same hierarchical level as the other demonstration directories, so that when you type **ls**, you see:

```
demo2
demo4
demoF
my_data
```

You will need all the input files with the names and contents that are described in Section III.B above. We suggest copying them from **demo2** and then modifying them with a text editor such as **TextEdit.app**.

1) reduce the number of pairs

Decrease the number of phase files listed in **files_list.dat** or **interferograms.lst.** For example, the data set included in the directory named **demo2** is the fastest example because it includes only a single pair. To start the quickest demonstration, type:

```
giphtdemo demo2
```

VI. Troubleshooting

A. Calculation takes too long

The simulated annealing algorithm employed in GIPhT evaluates many (~10^4) possible sets of values for the model parameters by calculating the modeled range change value for every pixel in every interferometric pair. To improve performance by reducing the calculating time, try one of the following:

1) Reduce the number of pairs

Decrease the number of phase files listed in **files_list.dat** or **interferograms.lst.** For example, the data set included in the directory named **demo2** is the fastest example because it includes only a single pair. To start the quickest demonstration, type:

```
giphtdemo demo2
```

2) Reduce the number of pixels

Decrease the numerical value following the **npix** keyword in **subregion.dat.**

3) Avoid quadtree sampling of the data set

Set the **pselect** keyword in **subregion.dat** to 1 or 2 (not 3).

B. Final estimate does not look like the data

The goal of using GIPhT is to make a modeled interferogram that resembles the observed interferogram. In the second column of the 8-panel plot, the model (second row, panel f) should have fringes that look like the observations (first row, panel e). In this case, the residual (third row, panel g) should show less than one fringe. Equivalently, the angular deviations (fourth row, panel h) should be less than 0.1 or 0.2 cycle over most of the sub-region. In other words, most pixels in the final panel of an 8-panel plot should be blue, rather than red in color. If this is not the case, consider the following:

1) Improve the initial estimate

Trial and error using human intuition can be more efficient than simulated annealing, especially when starting with a new data set. To modify the parameter values manually, set the anneal keyword to 0 in the file named **subregion.dat.** This will turn “off” simulated annealing. Then “play” with the parameters defined in the second column of the file named **parameters.in.** Then look at the output residuals and angular deviations. When you are satisfied, adjust the upper and lower bounds to be “close to” (within 10 or 20%) these values in the file named **parameters.in.** Then set the **anneal** keyword back to 1 in the file named **subregion.dat.**

2) Check the sign of the phase values

As an observer’s eye scans a path across an interferogram, phase can either increase (colors going from blue to green to yellow to red) or decrease (colors going from red to yellow to green to blue). The fringe gradient should have the same sense in both the observed and modeled interferograms. If not, consider changing the sign of the **volume_change** (rate) parameter in **parameters.in.** Alternatively, there may issues with the file format. In this case, consider multiplying all the phase values in the input phase files by negative one to change their sign. GIPhT assumes that positive phase values correspond to increases in range.

3) Shrink the sub-region

The information in an interferogram is contained in the gradient of the phase values. Accordingly, it is best to analyze pixels where this gradient is large. To do so, set the values of **xcenter** and **ycenter** to the coordinates of the center of the fringe pattern of interest, and decrease the values of the keywords **half_width** and **half_height** in the file named **sub_region.dat**.

C. The residual interferogram shows twice as many fringes as either the observed or the modeled interferogram.

The phase gradient in the modeled interferogram is opposite that in the observed interferogram. Check the sign of the phase values, as described above.

D. The model is all green.

If the modeled phase values are all zero, then they will appear as a uniform green field in panel f of an 8-panel plot. Usually this issue is caused by a mismatch of coordinates of the source defined in the **parameters.in** file compared to the image coordinates specified in the file named **dem_descriptor.dat.** We find it helpful to sketch the different subsets of the study area as in Figure 4.

E. There are crenulated fringes in some of the interferograms.

Tropospheric artefacts are challenging to model. If they occur only in a small subset of the interferometric pairs, then we recommend removing these pairs from the analysis. Alternatively, GIPhT can estimate the vertical component of the phase gradient. To do so, use the parameter labeled **vertical_gradient** in the file named **parameters.in**. Estimate this parameter only for those epochs that form the pair(s) showing the crenulated interferometric fringes in the observed interferogram(s). Given enough pairs, one can usually determine if the tropospheric perturbation occurred at the master epoch or the slave epoch, using pair-wise discrimination, as described by Massonnet and Feigl [8, 9].

F. I do not have a DEM.

To make a flat digital elevation model with a topographic height of zero everywhere, try:

```
dd if=/dev/zero of=dem.i2 \
bs=1600 count=420
```

where 1600 is twice the number of columns and 420 is the number of rows. In this case, however, GIPhT will not be able to estimate the vertical component of the phase gradient.

G. The format of the parameters.in file is wrong

If GIPhT generates error messages when reading the values of the parameters in the file named **parameters.in**, you can generate a new file with the proper format, but null values by following the following steps:

Rename or delete the existing file

```
mv parameters.in params0.in
```

Run GIPhT on your data again:

```
giphtdemo my_data
```

Copy the output file

```
cp x_*/x.log parameters.in
```

Using the **TextEdit.app** program, edit the file named **parameters.in** so that it has only one header line, as shown in Figure 9. Edit the values for the initial estimate, as well as the lower and upper bounds for each parameter.

Run GIPhT on your data again:

```
giphtdemo my_data
```

H. The program crashes

1) Remain calm

Remember, this version of GIPhT is still just a prototype for the purposes of evaluation. With your constructive criticism, the software can be improved.

2) Look for hints in the output

Please check the following issues:

Are all the phase files available for reading? Missing files will leave an error message.

Are the input files properly formatted? A letter in place of a number will cause a problem.

Are the parameter values in the initial estimate and bounds physically reasonable? The following are examples of unreasonable values: negative values for depth, source dimensions larger than Earth or smaller than a pixel, or a negative value for the upward component of the look vector from ground to satellite.

3) Send the output to Madison

If you wish to report an issue, please send an email to feigl@wisc.edu with the word "GIPhT" in the subject field. Be sure to include the following:

The output left from the terminal window. Please copy the last 100 lines and paste it into the email text. Alternatively, you can capture the screen with **Grab.app** or the keystroke combination CMD-SHIFT-3 which creates a file called **Picture001.png** file on the desktop.

The most recent log file, called **x.log**. In the event of a crash, it will not be moved to the corresponding directory.

VII. Conclusion

To be written by you, the user. Thanks for your interest!

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