The Damped Bundle Adjustment Toolbox v0.4.1 for Matlab

Niclas Börlin[1] and Pierre Grussenmeyer[2]

[1]Department of Computing Science, Umeå University, Sweden,
niclas.borlin@cs.umu.se
[2]ICube Laboratory UMR 7357, Photogrammetry and Geomatics Group,
INSA Strasbourg, France

September 3, 2014

Contents

1 Introduction

1.1 Purpose

This purpose of the Damped Bundle Adjustment toolbox is to be a high-level toolbox for photogrammetry in general and bundle adjustment in particular. It is the hope of the authors that the high-level nature of the code will inspire algorithm development. The code is written in Matlab and is verified to work with Matlab version 8 (release R2012B). The intention is that at least the computation routines will be Octave-compatible. This has however not been tested yet.

1.2 Capabilities

The toolbox currently includes routines for (function names in parentheses):

- File handling:
  - Reading Photomodeler-style text export files (`loadpm`).
  - Writing Photomodeler-style text result files (`bundle_result_file`).
- Photogrammetric calculations, including:
  - Spatial resection (`resect`).
  - Forward intersection (`forwintersect`).
  - Relative orientation based on the Nistér 5-point algorithm (Stewénius et al., 2006) will be added in the future.
- Bundle adjustment
  - Bundle adjustment proper (`bundle`) using either Classical, Gauss-Newton-Armijo, Levenberg-Marquardt, or Levenberg-Marquardt-Powell damping schemes (Börlin and Grussenmeyer, 2013a, 2014).
  - Covariance calculations (`bundle_cov`) from the bundle result.
- Various plotting functions, including:
  - Plot image covered by measurements (`plotcoverage`).
  - Plot camera network (`plotnetwork`), either static (as-loaded) or as an illustration of the bundle iterations.
  - Plot of the iteration trace of parameters estimated by bundle (`plotparams`).
  - Plots of quality statistics from the bundle result (`plotimagestats`, `plotopstats`).
- Demo functions using the above functions. The demo functions are detailed in Section 3.1.

This manual does not contain detailed information about how to use each function. More information may be found by typing `help <function name>` at the Matlab prompt, studying the source code of the demo functions, and reading the source code of each file directly.

Things to be added in the near future:

- Testing of all dampings for return parameter consistency.
- Chirality damping.
- Weights on the observations.
- Test octave compatibility.
- Azimuth-tilt-swing camera model.

1.3 Legal

The licence detail are described in the `README.txt` file included in the distribution. In summary:

- You use the code at your own risk.
- You may use the code for any purpose, including commercial, as long as you give due credit. Specifically, if you use the code, or derivatives thereof, for scientific publications, you should refer to on or more of the papers Börlin and Grussenmeyer (2013a,b, 2014) that the code is based on.
- You may modify and redistribute the code as long as the licensing details are also redistributed.

2 Installation

1. Download the package file `dbat_0.4.1.zip`.
2. Unpack the package into a directory *dbat*.
3. Inside Matlab, do the following initialization:
```
cd dbat % the directory where you installed the files.
dbatSetup % set paths, etc.
```
4. Test the installation by executing the supplied demos described in Section 3.1.

3 Usage

3.1 Demos

Hint: You may wish to use the commands `clear` and `close all` between the demos to close all windows and clear all variables.

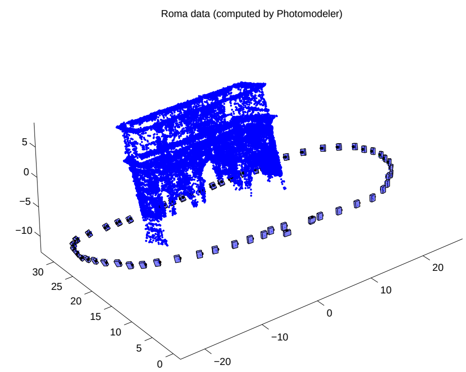


Figure 1: The figure generated by the `loadplotdemo` demo.

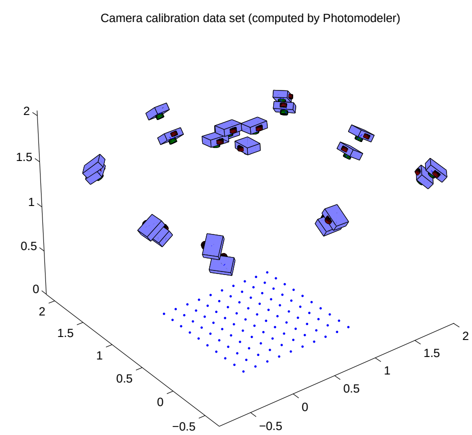


Figure 2: The figure generated by the `loadplotdemo2` demo.

3.1.1 loadplotdemo

The `loadplotdemo` demo loads a modified Photomodeler text export file of the 60-camera, 26000-point project used in Börlin and Grussenmeyer (2013a). The camera network, as computed by Photomodeler, is plotted with camera 1 aligned to the cardinal axes. The result should look like Figure 1. The figure is a standard Matlab 3D figure and may e.g. be rotated or zoomed using the camera toolbar.

3.1.2 loadplotdemo2

The `loadplotdemo2` demo loads a modified Photomodeler text export file of a 21-camera, 100-point camera calibration project. The camera network, as computed by Photomodeler, is plotted and should look like Figure 2. The figure is a standard Matlab 3D figure and may e.g. be rotated or zoomed using the camera toolbar.

3.1.3 camcaldemo

The `camcaldemo` demo loads the camera calibration export file from Section 3.1.2 and runs a camera calibration. The EXIF focal length is used as the initial value. The other values are set to "default" values, e.g. the principal point at the center of the sensor and all lens distortion parameters equal to zero. The initial value for the EO parameters are computed by spatial resection (Haralick et al., 1994; McGlone et al., 2004, Chap. 11.1.3.4) using the control points defined for the Photomodeler calibration sheet. The initial OP coordinates are subsequently computed by forward intersection.

The bundle adjustment is run with Gauss-Newton-Armijo damping. The result is given in a number of plot windows and a Photomodeler-style result text file. The result plots are of two kinds: Plots that show the evolution of the iterations and plots that show the quality of the input or output data. The former plots may be useful to understand how the bundle adjustment works but also to "debug" a difficult network that has convergence difficulties. The latter plots give information about the quality of the result and may also provide clues on how to improve a network when the bundle did converge.

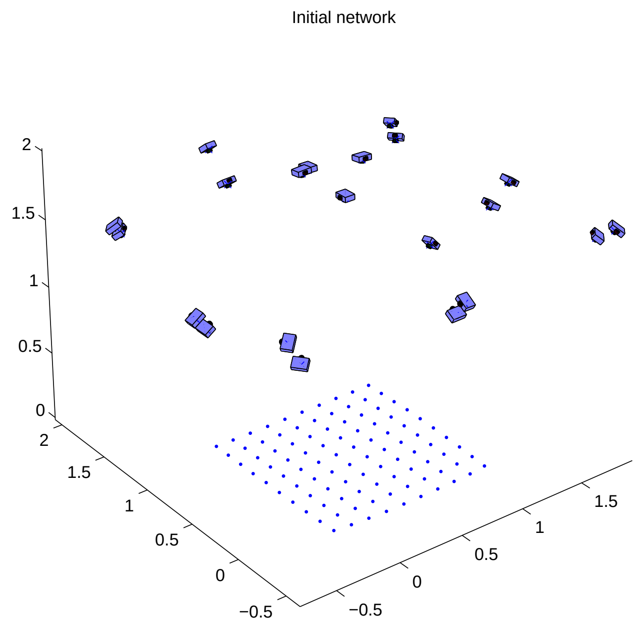
Evolution plots The evolution plots are collected in figures 3–7. Figure 3 shows a snapshot of the 3D trace figure at the beginning and end of the iterations. As default, the evolution is presented iteration by iteration with intervening presses of the return key. The figure window is interactive and may be rotated, zoomed, etc. In this example, it is clear in Figure 3b that one camera station had poorer initial values than the rest.

Figures 4–6 contain three plots showing the evolution of the internal orientation (IO), external orientation (EO), and object point (OP), respectively, during the iterations. The IO plot is split into a focal/principal point panel and a radial and tangential distortion panel, where the radial distortion parameters are scaled to provide more information. The EO plot contains a camera center panel and an ω-ϕ-κ Euler angle panel. The EO and OP plots are interactive. Lines in the plots or legends may be selected and all corresponding lines will be highlighted. In the top panel of Figure 5, the motion of one camera stands out. Clicking that line reveals that it belongs to camera station 21, which can be further investigated to decide if it should be excluded from the calibration.

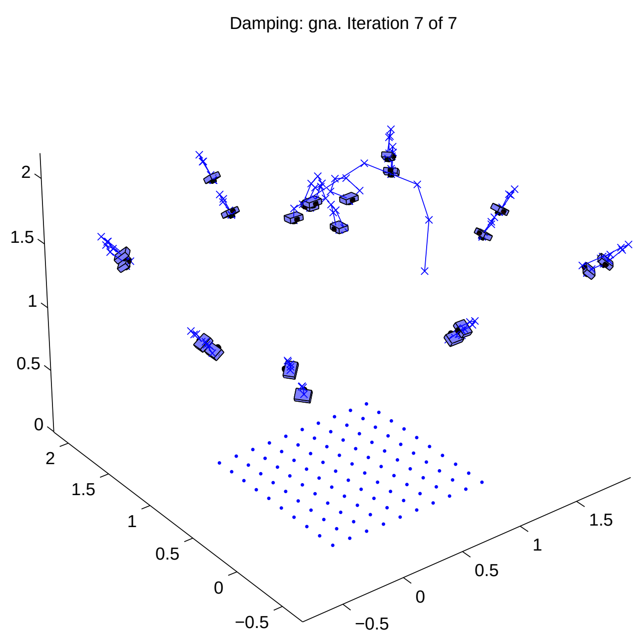
The final evolution plot, shown in Figure 7, illustrates the evolution of the norm of the total residual and the damping behaviour, if any, during the bundle iterations. In this example, the Gauss-Newton-Armijo linesearch damping is active during the first two iterations. For further details on the damping, see Börlin and Grussenmeyer (2013a).

Quality plots The quality plots a gathered in figures 8–10. Per-image quality statistics is shown in Figure 9. The statistics presented for each image are the image coverage (rectangular coverage, convex hull coverage, and radial coverage); the number of measured points; the average (RMS) point residual; and the standard deviations for the EO parameters for the camera stations. In this example, the data does not give any obvious support to exclude the suspected image 21 from the calibration.

The image coverage is detailed in a separate Figure 8. The plotted data is selectable. All observations from a specific image, including their convex hull, will be highlighted when a point or line is selected.



(a) Initial network configuration.



(b) Network configuration after convergence, with camera center trace lines.

Figure 3: 3D network evolution during the iterations. Only the EO and OP parameters are illustrated. In this example, the variation of the OP coordinates is barely visible.

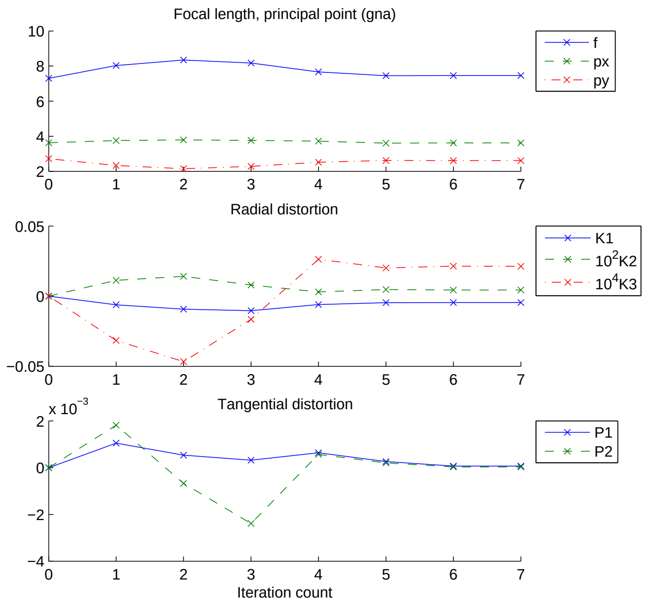


Figure 4: Evolution of network parameters during the iteration sequence: IO parameters.

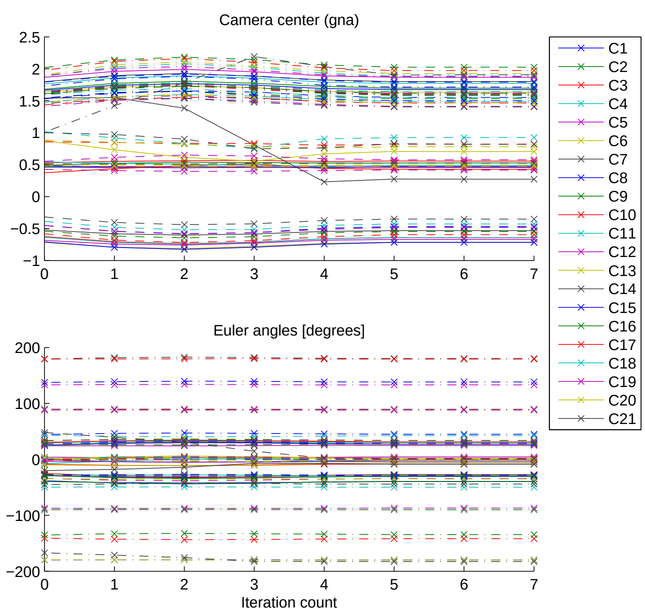


Figure 5: Evolution of network parameters during the iteration sequence: EO parameters.

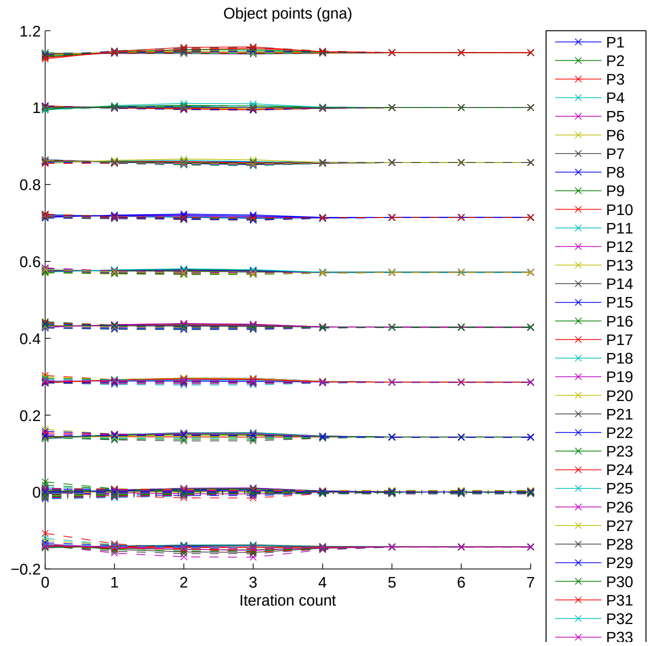


Figure 6: Evolution of network parameters during the iteration sequence: OP coordinates.

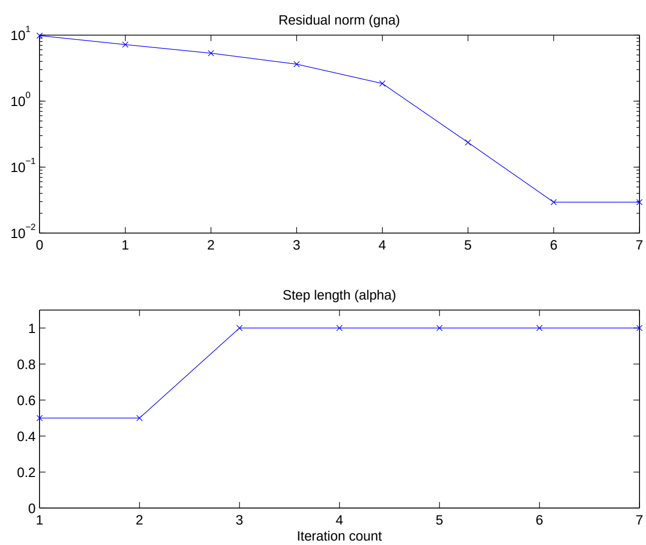


Figure 7: Residual evolution and damping behaviour during the iterations.

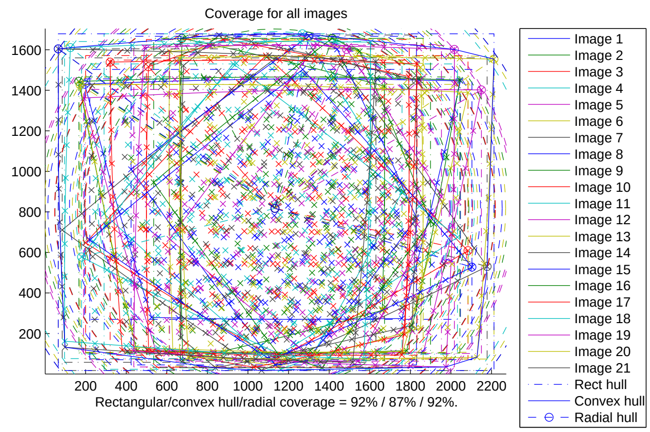


Figure 8: Plots of input/output statistics: Image coverage.

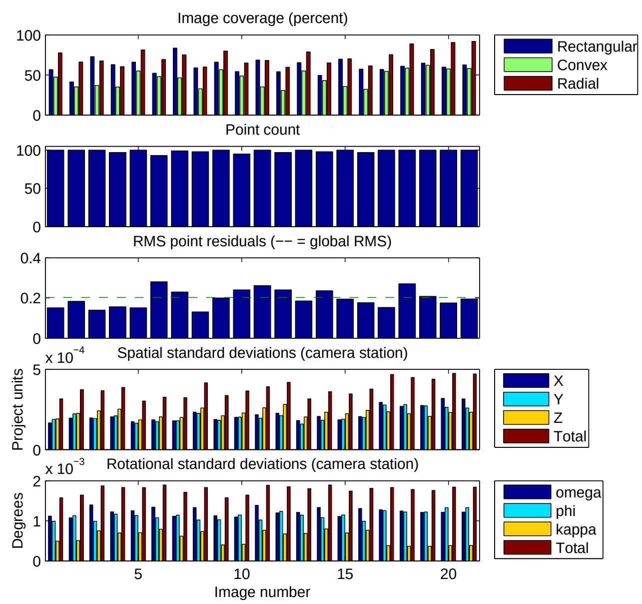


Figure 9: Plots of input/output statistics: Image statistics.

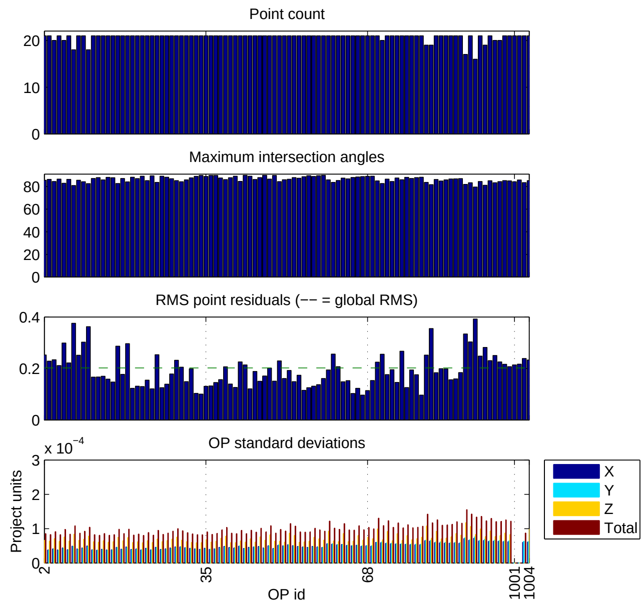


Figure 10: Plots of input/output statistics: Object point statistics.

Finally, the per-OP quality statistics in Figure 10 show the number of observations per OP; the maximum ray intersection angle; the average (RMS) point residual; and the OP coordinate standard deviation. The presentation may be zoomed to show only a subset of the OPs by activating the "zoom" function of the figure window.

Result file The result file is modelled after the Photomodeler result file. The result file is listed in Appendix C.

3.1.4 romabundledemo

The `romabundledemo` function loads the project from Section 3.1.1 and present essentially the same plots and the `camcaldemo`. This demo uses the Photomodeler file as input to the bundle adjustment that runs a few iterations until convergence. The same result file and result plots as `camcaldemo` are essentially generated. Since the project is larger (60 cams/26 000 points) than the previous example (20 cams/100 points), the computation will take a bit longer. Computation time was around one minute running on a HP compaq dc7800 with an Intel Core2 Quad CPU Q9300 @ 2.50GHz under 64-bit Ubuntu 12.04 (kernel 3.5.0-45).

3.1.5 Camera calibration demos

The camera calibration demos from Börlin and Grussenmeyer (2014) will be added to the next version of the toolbox.

3.2 Using your own data

This section describes how to import you own data using Photomodeler text export files. If you have another type of input file, you may be able to write your own loader. Otherwise, if you have a text file you wish to import, feel free to mail the file to the the toolbox authors and request an import function. Althought we cannot guarantee anything, we may adhere to the request, time permitting.

3.2.1 Export from Photomodeler

To import a Photomodeler project into the toolbox, the following steps are valid in Photomodeler Scanner 2012:

1. Export the project using the *Export Text File* menu command. If the command is not available, follow the instructions in Appendix A.

2. After export, open the *Project/Cameras...* dialog and select the camera that was used in your project.

3. Open the generated text file in a text editor.

   (a) On the 2nd line (usually reading `0.00005 20`), append the width and height in pixels of your images, e.g. to `0.000500 20 5616 3744`.

   (b) Inspect the 4th line. For instance, the original data in `roma.txt` was (some trailing zeros removed):
   `24.3581 18.1143 12.0 35.96404 24.0 0.00022 -0.0 0.0 0.0 0.0`
   The values correspond to the following camera parameters:
   `focal pp_x pp_y format_w format_h K1 K2 K3 P1 P2`.
   Notice that most of the significant digits of K1–K3 were lost in the text export.

   (c) Update the parameter values on the 4th line with values from the camera dialog *for each parameter with a larger number of significant digits in the dialog*. This usually means all parameters except `format_w`. In the `roma.txt` test case, the 4th line was modified to:
   `24.3581 18.1143 12 35.96404 24 2.174e-4 -1.518e-7 0 0 0`.

3.2.2 Loading into Matlab

1. In matlab, run step 3 from Section 2 if not already done.

2. Set the variable `fName` to the text export file name `fName='c:/path/to/exported/file.txt';`, or select it using `[f,p]=uigetfile('*.txt'); fName=[f,p];`

3. Run the `loadplotdemo` script. A figure with your camera network, aligned with the first camera and rotated to have +Z 'up', should now have been generated.

References

N. Börlin and P. Grussenmeyer. Bundle adjustment with and without damping. *Photogrammetric Record*, 28(144):396–415, Dec. 2013a. doi: 10.1111/phor.12037.

N. Börlin and P. Grussenmeyer. Experiments with metadata-derived initial values and linesearch bundle adjustment in architectural photogrammetry. *ISPRS Annals of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, II-5/W1:43–48, Sept. 2013b.

N. Börlin and P. Grussenmeyer. Camera calibration using the damped bundle adjustment toolbox. *ISPRS Annals of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, II(5):89–96, June 2014.

D. C. Brown. Close-range camera calibration. *Photogrammetric Engineering*, 37(8): 855–866, 1971.

R. M. Haralick, C.-N. Lee, K. Ottenberg, and M. Nölle. Review and analysis of solutions of the three point perspective pose estimation problem. *Int J Comp Vis*, 13(3): 331–356, 1994.

C. McGlone, E. Mikhail, and J. Bethel, editors. *Manual of Photogrammetry*. ASPRS, 5th edition, July 2004. ISBN 1-57083-071-1.

H. Stewénius, C. Engels, and D. Nistér. Recent developments on direct relative orientation. *ISPRS J Photogramm*, 60(4):284–294, June 2006.

A Enabling text export from Photomodeler

.

Some versions of Photomodeler do not have the text file export option enabled by default. In that case, the following steps worked in Photomodeler Scanner 2012:

1. Right-click on the main window toolbar, select *Customize toolbar...*.
2. In the *Commands* tab, select the *File* category.
3. Drag the *Export Text File...* command to a toolbar of your choice.
4. Now you should be able to export your project as a text file by clicking on the *Export Text File* button.

B Camera model

Currently, the only supported camera model is the omega-phi-kappa Euler angle camera model (McGlone et al., 2004, Ch. 2.1.2.3) with the Brown (1971) lens distortion model.

C Result file example

```
Damped Bundle Adjustment Toolbox result file
   Project Name: Bundle Soln PhotoModeler Calibration Project
   Problems and suggestions:
      Project Problems: Not evaluated
      Problems related to the processing: (1)
         One or more of the camera parameter has a high correlation (see below).
   Information from last bundle
      Last Bundle Run: 25-Jun-2014 15:33:03
      DBAT version:    0.4.0.203 (2014-02-12 16:27:27)
      Status:          OK (0)
      Sigma0 (pixels): 0.168901
      Sigma0 (mm):     0.000539091
      Processing options:
         Orientation:             on
         Global optimization:     on
         Calibration:             on
         Constraints:             off
         Maximum # of iterations: 20
         Convergence tolerance:   0.001
         Singular test:           off
         Chirality veto:          off
         Damping:                 gna
         Camera unit (cu):        mm
         Object space unit (ou):  m
         Initial value comment:   Camera calibration from EXIF value
      Total error:
         Number of stages:     1
         Number of iterations: 7
         First error:          9.85752
         Last error:           0.0329067
      Precisions / Standard Deviations:
         Camera Calibration Standard Deviations:
            Camera1 (camera unit cu=mm)
               Focal Length:
```

```
            Value:        7.45895 cu
            Deviation:    0.001 cu
       Xp - principal point x:
            Value:        3.61664 cu
            Deviation:    0.0009 cu
       Yp - principal point y:
            Value:        2.60895 cu
            Deviation:    0.001 cu
       Fw - format width:
            Value:        7.25319 cu
       Fh - format height:
            Value:        5.43764 cu
       K1 - radial distortion 1:
            Value:        0.00457036 cu^(-3)
            Deviation:    2e-05 cu^(-3)
            Significance: p=1.00
       K2 - radial distortion 2:
            Value:        -4.25953e-05 cu^(-5)
            Deviation:    3e-06 cu^(-5)
            Significance: p=1.00
            Correlations over 95%: K3:-97.9%.
       K3 - radial distortion 3:
            Value:        -2.15839e-06 cu^(-7)
            Deviation:    1e-07 cu^(-7)
            Significance: p=1.00
            Correlations over 95%: K2:-97.9%.
       P1 - decentering distortion 1:
            Value:        -6.56858e-05 cu^(-3)
            Deviation:    4e-06 cu^(-3)
            Significance: p=1.00
       P2 - decentering distortion 2:
            Value:        -2.97019e-05 cu^(-3)
            Deviation:    4e-06 cu^(-3)
            Significance: p=1.00
       Iw - image width:
            Value:        2272 px
       Ih - image height:
            Value:        1704 px
       Xr - X resolution:
            Value:        313.306 px/cu
       Yr - Y resolution:
            Value:        313.306 px/cu
       Pw - pixel width:
            Value:        0.00319176 cu
       Ph - pixel height:
            Value:        0.00319176 cu
    Rated angle of view: (88, 72) deg
    Largest distortion: 0.37 cu (116.4 px, 8.2% of half-diagonal)
 Photograph Standard Deviations:
    Photo 1: P8250021.JPG
       Omega:
          Value:     -39.425843 deg
          Deviation: 0.009 deg
       Phi:
          Value:     -1.180802 deg
          Deviation: 0.008 deg
       Kappa:
          Value:     -179.839285 deg
          Deviation: 0.003 deg
       Xc:
          Value:     0.454890 ou
          Deviation: 0.0002 ou
       Yc:
          Value:     1.793761 ou
          Deviation: 0.0002 ou
       Zc:
          Value:     1.469288 ou
          Deviation: 0.0002 ou
```

```
Photo 2: P8250022.JPG
   Omega:
      Value:     -39.761293 deg
      Deviation: 0.008 deg
   Phi:
      Value:     -1.846860 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     -90.121386 deg
      Deviation: 0.003 deg
   Xc:
      Value:     0.470426 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     2.027244 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.638798 ou
      Deviation: 0.0002 ou
Photo 3: P8250023.JPG
   Omega:
      Value:     -27.239614 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -28.565376 deg
      Deviation: 0.008 deg
   Kappa:
      Value:     -141.846643 deg
      Deviation: 0.006 deg
   Xc:
      Value:     -0.644455 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     1.466419 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.581500 ou
      Deviation: 0.0002 ou
Photo 4: P8250024.JPG
   Omega:
      Value:     -28.558154 deg
      Deviation: 0.009 deg
   Phi:
      Value:     -30.331823 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     -49.784434 deg
      Deviation: 0.005 deg
   Xc:
      Value:     -0.643656 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     1.491034 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.637067 ou
      Deviation: 0.0003 ou
Photo 5: P8250025.JPG
   Omega:
      Value:     4.382465 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -34.669530 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     -87.136963 deg
      Deviation: 0.005 deg
   Xc:
```

```
      Value:     -0.670769 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     0.417346 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.410400 ou
      Deviation: 0.0002 ou
Photo 6: P8250026.JPG
   Omega:
      Value:     2.097667 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -34.017559 deg
      Deviation: 0.008 deg
   Kappa:
      Value:     1.509495 deg
      Deviation: 0.006 deg
   Xc:
      Value:     -0.713593 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     0.476373 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.464831 ou
      Deviation: 0.0002 ou
Photo 7: P8250027.JPG
   Omega:
      Value:     27.348313 deg
      Deviation: 0.009 deg
   Phi:
      Value:     -28.303040 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     -44.207883 deg
      Deviation: 0.005 deg
   Xc:
      Value:     -0.534727 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.349536 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.403703 ou
      Deviation: 0.0002 ou
Photo 8: P8250028.JPG
   Omega:
      Value:     26.923373 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -28.127910 deg
      Deviation: 0.008 deg
   Kappa:
      Value:     44.866709 deg
      Deviation: 0.006 deg
   Xc:
      Value:     -0.718941 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.466478 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.715076 ou
      Deviation: 0.0003 ou
Photo 9: P8250029.JPG
   Omega:
      Value:     30.389367 deg
```

```
      Deviation: 0.009 deg
   Phi:
      Value:     0.190622 deg
      Deviation: 0.008 deg
   Kappa:
      Value:     0.084680 deg
      Deviation: 0.003 deg
   Xc:
      Value:     0.524910 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.543280 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.534217 ou
      Deviation: 0.0002 ou
Photo 10: P8250030.JPG
   Omega:
      Value:     31.007671 deg
      Deviation: 0.009 deg
   Phi:
      Value:     1.729947 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     89.539852 deg
      Deviation: 0.003 deg
   Xc:
      Value:     0.554112 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.593288 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.617126 ou
      Deviation: 0.0002 ou
Photo 11: P8250031.JPG
   Omega:
      Value:     27.634325 deg
      Deviation: 0.01 deg
   Phi:
      Value:     30.750264 deg
      Deviation: 0.008 deg
   Kappa:
      Value:     42.335672 deg
      Deviation: 0.006 deg
   Xc:
      Value:     1.770072 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     -0.425193 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.552593 ou
      Deviation: 0.0002 ou
Photo 12: P8250032.JPG
   Omega:
      Value:     24.650099 deg
      Deviation: 0.009 deg
   Phi:
      Value:     30.239562 deg
      Deviation: 0.01 deg
   Kappa:
      Value:     133.204262 deg
      Deviation: 0.005 deg
   Xc:
      Value:     1.864900 ou
      Deviation: 0.0002 ou
   Yc:
```

```
      Value:     -0.480971 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.614059 ou
      Deviation: 0.0003 ou
Photo 13: P8250033.JPG
   Omega:
      Value:     0.525577 deg
      Deviation: 0.01 deg
   Phi:
      Value:     33.149904 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     88.705093 deg
      Deviation: 0.005 deg
   Xc:
      Value:     1.630632 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     0.497602 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.471594 ou
      Deviation: 0.0002 ou
Photo 14: P8250034.JPG
   Omega:
      Value:     -1.739778 deg
      Deviation: 0.01 deg
   Phi:
      Value:     33.635687 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     180.202160 deg
      Deviation: 0.006 deg
   Xc:
      Value:     1.796838 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     0.525347 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.598322 ou
      Deviation: 0.0002 ou
Photo 15: P8250035.JPG
   Omega:
      Value:     -30.765541 deg
      Deviation: 0.009 deg
   Phi:
      Value:     28.173152 deg
      Deviation: 0.009 deg
   Kappa:
      Value:     138.430069 deg
      Deviation: 0.005 deg
   Xc:
      Value:     1.671658 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     1.554521 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.501366 ou
      Deviation: 0.0002 ou
Photo 16: P8250036.JPG
   Omega:
      Value:     -29.886032 deg
      Deviation: 0.01 deg
   Phi:
      Value:     26.975324 deg
```

```
      Deviation: 0.008 deg
   Kappa:
      Value:     -134.632200 deg
      Deviation: 0.006 deg
   Xc:
      Value:     1.694046 ou
      Deviation: 0.0002 ou
   Yc:
      Value:     1.619403 ou
      Deviation: 0.0002 ou
   Zc:
      Value:     1.590017 ou
      Deviation: 0.0003 ou
Photo 17: P8250037.JPG
   Omega:
      Value:     -8.525031 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -0.515992 deg
      Deviation: 0.01 deg
   Kappa:
      Value:     179.396297 deg
      Deviation: 0.002 deg
   Xc:
      Value:     0.424528 ou
      Deviation: 0.0003 ou
   Yc:
      Value:     0.823029 ou
      Deviation: 0.0003 ou
   Zc:
      Value:     1.972158 ou
      Deviation: 0.0003 ou
Photo 18: P8250038.JPG
   Omega:
      Value:     -4.780071 deg
      Deviation: 0.01 deg
   Phi:
      Value:     0.666412 deg
      Deviation: 0.01 deg
   Kappa:
      Value:     88.786570 deg
      Deviation: 0.002 deg
   Xc:
      Value:     0.481967 ou
      Deviation: 0.0003 ou
   Yc:
      Value:     0.926767 ou
      Deviation: 0.0003 ou
   Zc:
      Value:     1.885336 ou
      Deviation: 0.0002 ou
Photo 19: P8250039.JPG
   Omega:
      Value:     -4.413682 deg
      Deviation: 0.01 deg
   Phi:
      Value:     -0.411819 deg
      Deviation: 0.01 deg
   Kappa:
      Value:     88.244392 deg
      Deviation: 0.002 deg
   Xc:
      Value:     0.461866 ou
      Deviation: 0.0003 ou
   Yc:
      Value:     0.578854 ou
      Deviation: 0.0003 ou
   Zc:
```

```
            Value:     1.875379 ou
            Deviation: 0.0002 ou
      Photo 20: P8250040.JPG
         Omega:
            Value:     -7.605746 deg
            Deviation: 0.01 deg
         Phi:
            Value:     -1.556271 deg
            Deviation: 0.01 deg
         Kappa:
            Value:     -180.050870 deg
            Deviation: 0.002 deg
         Xc:
            Value:     0.701783 ou
            Deviation: 0.0003 ou
         Yc:
            Value:     0.782358 ou
            Deviation: 0.0003 ou
         Zc:
            Value:     1.926168 ou
            Deviation: 0.0002 ou
      Photo 21: P8250041.JPG
         Omega:
            Value:     -8.697313 deg
            Deviation: 0.01 deg
         Phi:
            Value:     1.049908 deg
            Deviation: 0.01 deg
         Kappa:
            Value:     -182.614506 deg
            Deviation: 0.002 deg
         Xc:
            Value:     0.268717 ou
            Deviation: 0.0003 ou
         Yc:
            Value:     0.821199 ou
            Deviation: 0.0003 ou
         Zc:
            Value:     1.905691 ou
            Deviation: 0.0002 ou
Quality
   Photographs
      Total number: 21
      Numbers used: 21
   Cameras
      Total number: 1
      Camera1:
         Calibration:                   yes
         Number of photos using camera: 21
         Photo point coverage:
            Rectangular: 41%-83% (61% average, 92% union)
            Convex hull: 31%-62% (46% average, 87% union)
            Radial:      60%-92% (73% average, 92% union)
   Photo Coverage
      References points outside calibrated region:
         none
   Point Measurements
      Ray count: 16-21 (20.7 avg)
      Number of control pts: 4
      Number of object pts: 96
   Point Marking Residuals
      Overall point RMS: 0.226 pixels
      Mark point residuals:
         Maximum: 0.952 pixels (OP 1003 on photo 5)
      Object point residuals (RMS over all images of a point):
         Minimum: 0.101 pixels (OP 67 over 21 images)
         Maximum: 0.569 pixels (OP 1004 over 21 images)
      Photo residuals (RMS over all points in an image):
```

```
      Minimum: 0.178 pixels (photo 4 over 97 points)
      Maximum: 0.318 pixels (photo 6 over 93 points)
Point Precision
   Total standard deviation (RMS of X/Y/Z std):
      Minimum: 8.6e-05 (OP 49)
      Maximum: 0.00012 (OP 90)
   Maximum X standard deviation: 5.2e-05 (OP 90)
   Maximum Y standard deviation: 5.5e-05 (OP 90)
   Maximum Z standard deviation: 8.9e-05 (OP 90)
Point Angles
   Minimum: 79.6 degrees (OP 90)
   Maximum: 90.0 degrees (OP 47)
   Average: 86.4 degrees
```