

# DBAT — The Damped Bundle Adjustment Toolbox for Matlab v0.8.0.0

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# Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
1.1	Purpose . . . . .	3
1.2	Contents . . . . .	3
1.2.1	Code . . . . .	3
1.2.2	Data . . . . .	5
1.3	Legal . . . . .	5
<b>2</b>	<b>Installation</b>	<b>6</b>
<b>3</b>	<b>Usage</b>	<b>8</b>
3.1	Demos . . . . .	8
3.1.1	Plotting . . . . .	8
3.1.2	Camera calibration . . . . .	8
3.1.3	Lens distortion models . . . . .	13
3.1.4	Bundle adjustment . . . . .	15
3.1.5	Error detection . . . . .	15
3.2	Using your own data . . . . .	18
3.2.1	Photoscan/Metashape . . . . .	18
3.2.2	PhotoModeler . . . . .	18
<b>A</b>	<b>Appendices</b>	<b>21</b>
A.1	Enabling text export from PhotoModeler . . . . .	21
A.2	Camera model . . . . .	21
A.3	Result file with missing observations . . . . .	21
A.4	Result file with single-ray observations . . . . .	21
A.5	Result file with missing datum . . . . .	22
A.6	Successful result file example . . . . .	24

# 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 8.6 (release R2015b). The intention is that at least the computation routines will be Octave-compatible. This has however not been tested yet.

## 1.2 Contents

### 1.2.1 Code

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

- File handling:
  - Reading PhotoModeler-style text export files (`loadpm`), and 2D/3D point table exports files (`loadpm2dtbl` and `loadpm3dtbl`, respectively).
  - Reading PhotoScan native (.psz) files (`loadpsz`).
  - Writing PhotoModeler-style text result files (`bundle_result_file`).
- Post-processing:
  - Post-processing of PhotoScan projects (`ps_postproc`). Includes object point filtering on low ray count and low intersection angles. For self-calibration post-processing, see the help text for `ps_postproc`.
  - As of version 0.7.0.0, DBAT supports both lens distortion models used by Photomodeler and Photoscan.
- Photogrammetric calculations, including:
  - Spatial resection (`resect`).
  - Forward intersection (`forwintersect`).
  - Absolute orientation (`rigidbody`).
  - Relative orientation based on the Nistér 5-point algorithm (Stewénus et al., 2006) will be added in the future.
- Bundle adjustment proper (`bundle`):
  - With or without self-calibration.
  - Works with fixed or weighted prior observations, e.g., control points.
  - Supports check points.

- What parameters that should be estimated are selectable at the parameter level, e.g. down to the coordinate level for 3D points.
  - Estimated parameters can be block-invariant (the same for a whole block), image-variant (individual for each image), or anything inbetween. Parameter sets may be split-variant, e.g., with some IO parameters block-invariant and some IO parameters image-variant.
  - Uses either Classical Gauss-Markov, Gauss-Newton-Armijo, Levenberg-Marquardt, or Levenberg-Marquardt-Powell damping schemes (Börlin and Grussenmeyer, 2013a, 2014, 2016).
  - Posterior covariance calculations (`bundle_cov`) from the bundle result, including correlations and significance levels, point and image quality statistics.
- Analysis of camera networks, including:
    - Detection of structural rank deficiency (Matlab's `dmperm`, `sprank`). Useful as a sanity check on input data. Structural rank deficiency is typically caused by trying to estimate a parameter with too few direct observations.
    - Null-space analysis if the normal matrix is singular using `spnrank` (Foster, 2009). This might, e.g. be caused by insufficient datum specification.

The result of the analysis, including suggestions for what parameters may be impossible to estimate are written to the report file by `bundle_result_file`.

- 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 .psz project (`loadplotpsz`).
  - 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. The available demos are listed by executing the command `help dbatdemos`.

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.

### 1.2.2 Data

The toolbox contains several datasets, including datasets for the Börnin and Grussenmeyer (2016); Murtiyoso et al. (2017) papers.

- PhotoModeler export files or PhotoScan projects.
- Images. To reduce the size of the distribution package, only low resolution images are included in the package<sup>1</sup>. The corresponding high resolution images can be downloaded from [http://www.cs.umu.se/~niclas/dbat\\_images](http://www.cs.umu.se/~niclas/dbat_images). Further instructions are found in `README.txt` files in the respective image directories.

The simplest way to access the data sets is through the demos, described in Section 3.1.

### 1.3 Legal

The licence detail are described in the `LICENSE.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 Börnin and Grussenmeyer (2013a,b, 2014, 2016); Börnin et al. (2018) that the code is based on.
- You may modify and redistribute the code as long as the licensing details are also redistributed.

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<sup>1</sup>No images are included in the StPierre data set.

## 2 Installation (from INSTALL.txt)

```
# == INSTALLATION ==
#
# You can either install DBAT by downloading the source code or (if
# you use a git client) by cloning the repository.
#
# === Download ===
#
# 1) Download the package file dbat-master.zip (from the main page) or
#    dbat-x.y.z.w.zip/dbat-x.y.z.w.tar.gz (from the releases page) of
#    https://github.com/niclasborlin/dbat/
#
# 2) Unpack the file into a directory, e.g. c:\dbat or ~/dbat.
#
# === Clone ===
#
# At the unix/windows command line, write:
#
#   git clone https://github.com/niclasborlin/dbat.git
#
# to clone the repository into the directory 'dbat'. Use
#
#   git clone https://github.com/niclasborlin/dbat.git <dir-name>
#
# to clone the repository to another directory.
#
# If you use a graphical git client, e.g., tortoisegit
# (https://tortoisegit.org), select Git Clone... and enter
# https://github.com/niclasborlin/dbat.git or
# git@github.com:niclasborlin/dbat.git as the URL.
#
#
# ===== Download high-resolution images =====
#
# To reduce the size of the repository and hence download times, only
# low-resolution images are included in the repository. High-resolution
# images can be downloaded from http://www.cs.umu.se/~niclas/dbat_images/.
# For further details, consult the README.txt files in the respective
# image directories.
#
#
# == TESTING THE INSTALLATION ==
#
# 1) Start Matlab. Inside Matlab, do the following initialization:
# 1.1) cd c:\dbat % (change to where you unpacked the files)
# 1.2) dbatSetup % will set the necessary paths, etc.
#
# 2) To test the demos, do 'help dbatdemos' or consult the manual.
#
#
# == UPDATING THE INSTALLATION==
#
# === Git ===
#
# If you cloned the archive, updating to the latest release is a
# simple as (replace ~/dbat and c:\dbat with where you cloned the
```

```
# repository):  
#  
#   cd ~/dbat  
#   git pull  
#  
# at the command line. In TortoiseGit, right-click on the folder  
# c:\dbat, select Git Sync... followed by Pull.  
#  
# === Download ===  
#  
# If you downloaded the code, repeat the download process under  
# INSTALLATION. Most of the time it should be ok to unzip the new  
# version on top of the old. However, we suggest you unzip the new  
# version into a new directory, e.g. dbat-x-y-z-w, where x-y-z-w is  
# the version number.  
#  
#
```

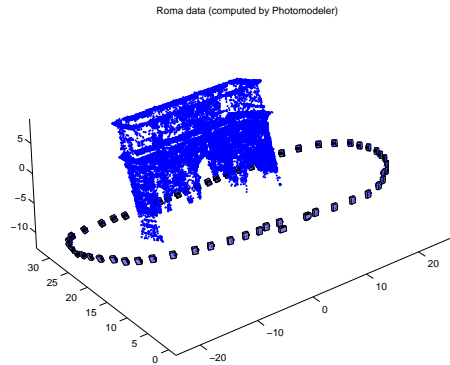


Figure 1: The figure generated by the `loadplotdemo` demo.

## 3 Usage

### 3.1 Demos

**Hint:** You may wish to use the command `close all` between the demos to close all windows.

A summary of the demos is found in Table 1.

#### 3.1.1 Plotting

The `loadplotdemo` function load and plots the content of a PhotoModeler text export file. Two examples are included in the toolbox: ROMA and CAM.

**ROMA** `loadplotdemo('roma')` 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.

**CAM** `loadplotdemo('cam')` 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.

#### 3.1.2 Camera calibration

The `camcaldemo` demo loads the camera calibration export file from Section 3.1.1 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.,



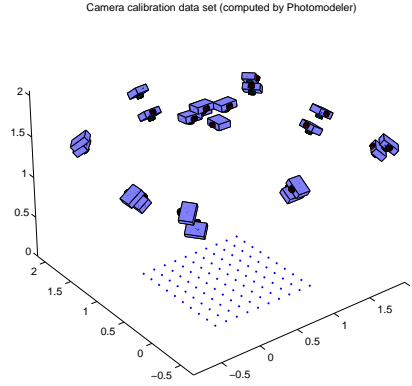


Figure 2: The figure generated by the `loadplotdemo('cam')` demo.

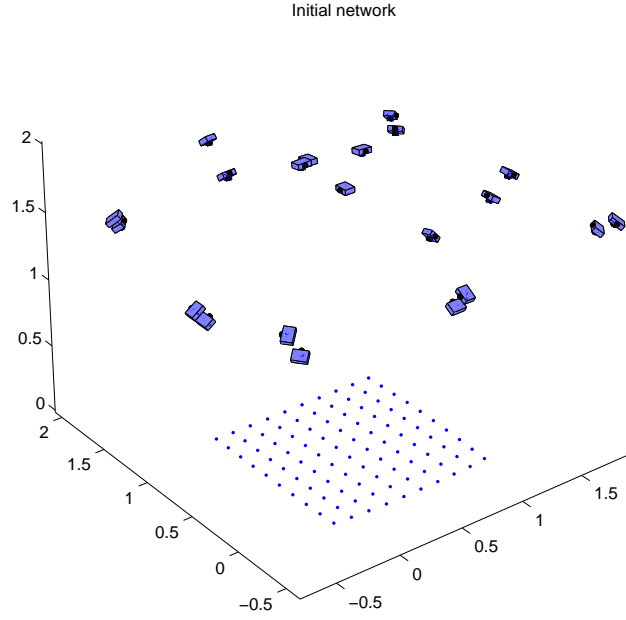
2004, Chap. 11.1.3.4) using the control points defined for the PhotoModeler calibration sheet. The initial OP coordinates are subsequently computed by forward intersection.

The bundle adjustment is run with Gauss-Newton-Armijo damping (Börlin and Grussenmeyer, 2013a). The result is given in a number of plot windows and a Photo-modeler-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.

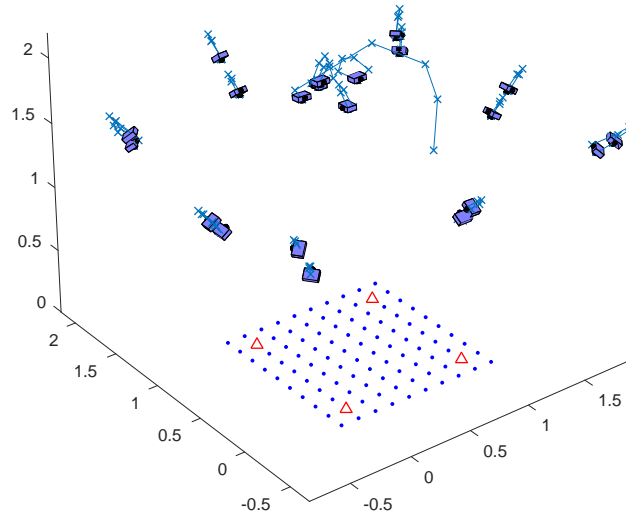
**Evolution plots** The evolution plots are collected in figures 3–7. Figure 3 shows a snapshot of the 3D trace figure at the beginning and end of the iterations. As default, the evolution is presented iteration by iteration with intervening presses of the return key. The figure window is interactive 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  $\omega$ - $\phi$ - $\kappa$  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).



(a) Initial network configuration.  
Damping: gna. Iteration 9 of 9



(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.

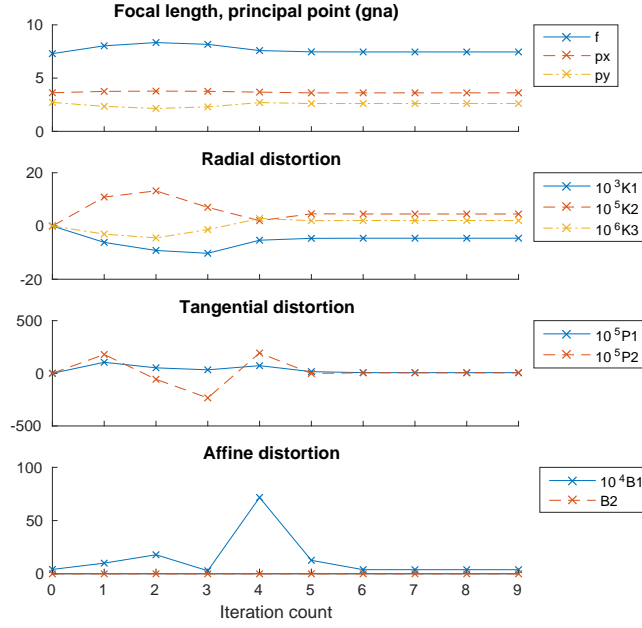


Figure 4: Evolution of IO parameters during the iteration sequence.

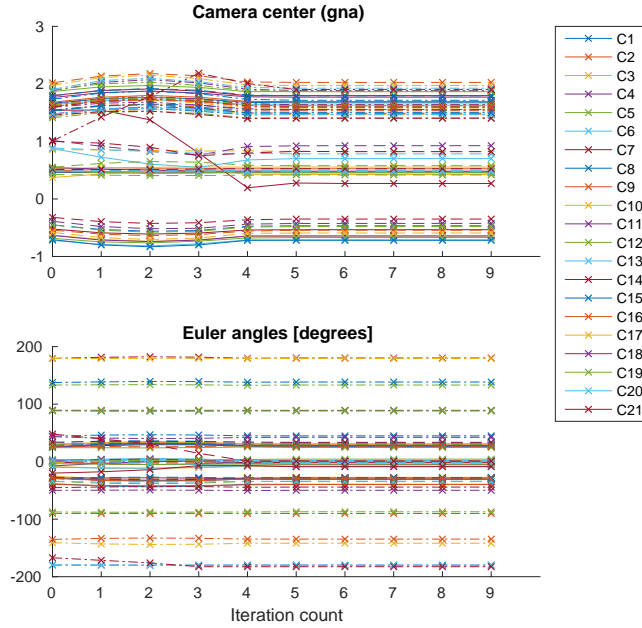


Figure 5: Evolution of EO parameters during the iteration sequence.

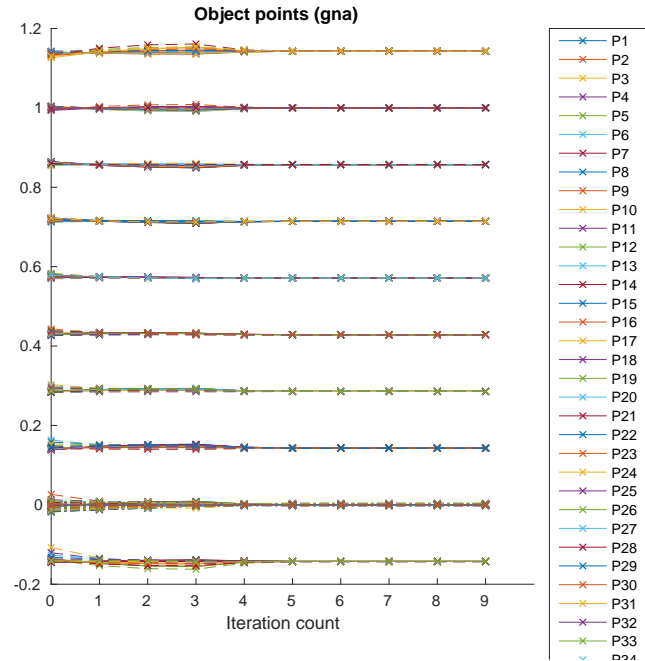


Figure 6: Evolution of OP coordinates during the iteration sequence.

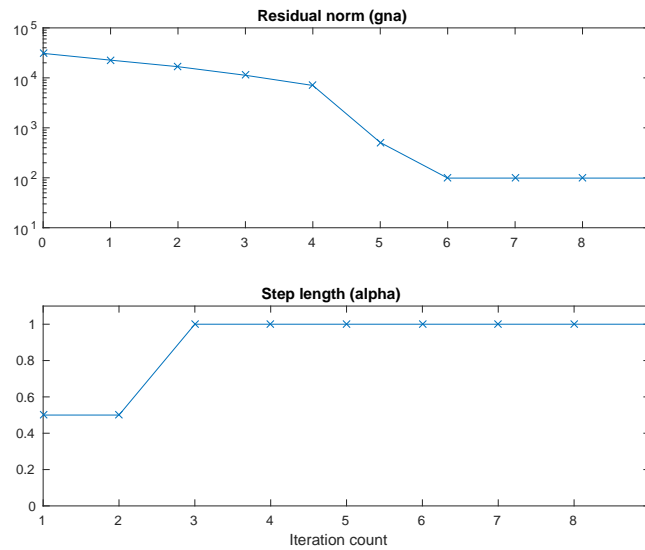


Figure 7: Residual evolution and damping behaviour during the iterations.

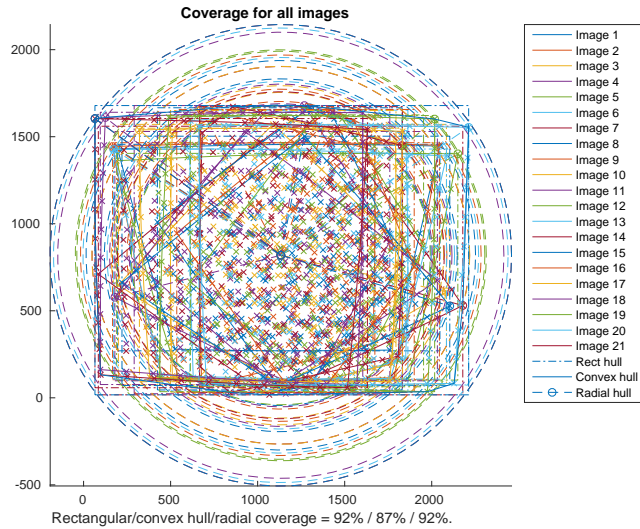


Figure 8: Plots of input/output statistics: Image coverage.

**Quality plots** The quality plots are 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.

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 A.6.

### 3.1.3 Lens distortion models

The `camcaldemo_allmodels` demo calibrates the camera using each of the available lens distortion models. A result file is generated for each model.

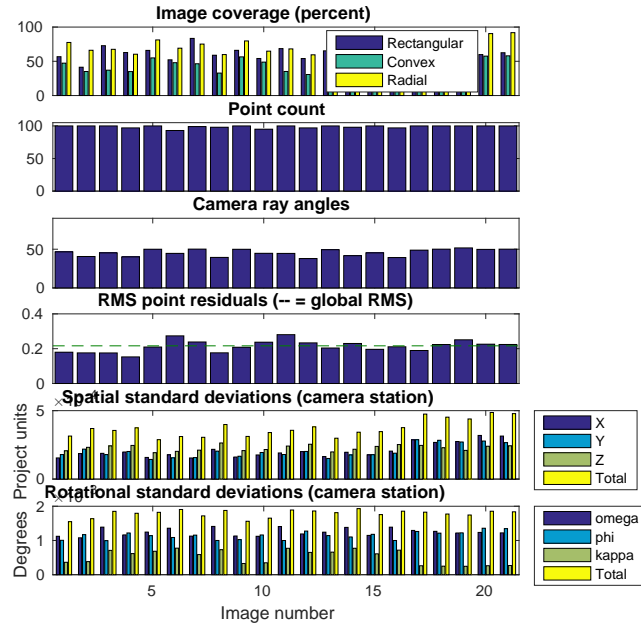


Figure 9: Plots of input/output statistics: Image statistics.

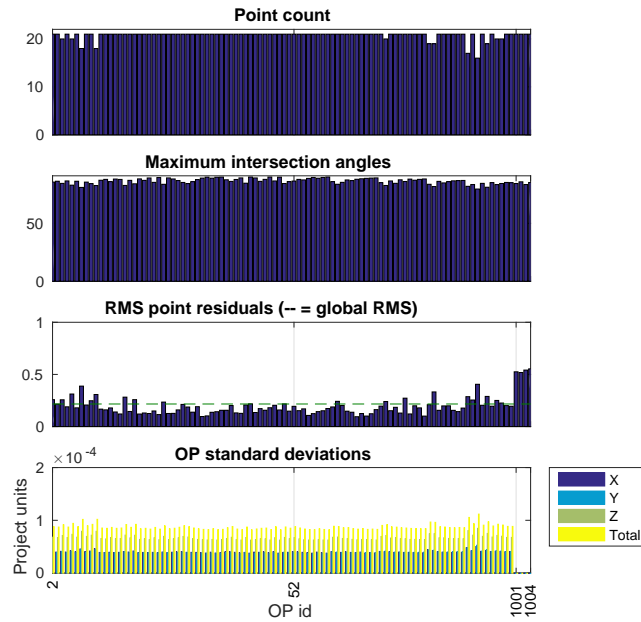


Figure 10: Plots of input/output statistics: Object point statistics.

### 3.1.4 Bundle adjustment

**ROMA** 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). Two variants with self-calibration (`romabundledemo_selfcal`) and image-variant self-calibration (`romabundledemo_imagevariant`) are also included. In the latter, the principal point is image-variant whereas the other IO parameters are block-invariant.

**PRAGUE'16** The `prague2016_pm` function displays six projects that compare the result of the bundle adjustment procedure in DBAT and the results of PhotoModeler (Börlin and Grussenmeyer, 2016). Similarly, the `prague2016_ps` function displays the results of a comparison between DBAT and PhotoScan.

The v0.5.1.6 release includes a fix to a bug the distributed the image observation weights incorrectly. The result is slightly different estimation results than in Börlin and Grussenmeyer (2016). However, the conclusions remain valid.

**HAMBURG'17** The `stpierrebundledemo_ps` function runs a self-calibration bundle on a Photoscan project included in the StPierre data set.

### 3.1.5 Error detection

Three demos are included to illustrate the error detection capabilities of `sprank` (`dmperm`) and `spnrank`. All are modelled from `=camcaldemo=`.

**Missing observations** The `camcaldemo_missing_obs` demo contains a data file where the image observations of two object points (id 13 and 60, respectively) have been deleted. With no observations of either point, the rank deficiency detected by `sprank` is six. In the generated result file (Section A.3), the X/Y/Z coordinates of both points number 12 and 59 (with id 13 and 60, respectively) are indeed listed as suspicious.

**Single-ray observations** The `camcaldemo_1ray` demo contains a data file that contains only one observation of object point with id 88. Since two observations (one 2D point) is present but three parameter (one 3D point) is to be estimated, the rank deficiency is one, the rank deficiency detected by `sprank` is one. The generated result file (Section A.4) lists one coordinate of point 87 (with id 88) as suspicious.

**Missing datum** The `camcaldemo_no_datum` demo contains a demo where no datum has been specified. As in the previous problems, the result is a numerical problem with a singular (rank deficient) normal matrix. However, in this case the problem is manifested by that many or all parameters are linearly dependent of each other. This will not be detected by `sprank`. In such a case, the null-space of the normal matrix will carry information about what parameters are linearly dependent, i.e. what parameters are part of the problem. However, when the normal matrix is large, computing the null-space of the normal matrix in the conventional way using the Matlab function `null` will be intractable. Instead, the `spnrank` (Foster, 2009) function is used to estimate the rank deficiency of the normal matrix, i.e. the dimension of the null-space. Given the dimension of the null-space, a basis for the null-space is found using Matlab's `eigs` function. For this demo, the generated result file (Section A.5) lists many EO parameters as suspicious. The cause of the problem is less straight-forward to determine from the list. However, the listed rank deficiency of seven should be a strong hint of a datum problem.



Demo	Description	Datum	Self-calibration
loadplotdemo	Load and plot	-	-
romabundledemo	Bundle adjustment	Relative dependent orientation	no
romabundledemo_selfcal	Bundle adjustment	Relative dependent orientation	yes
romabundledemo_imagevariant	Bundle adjustment	Relative dependent orientation	yes, split-variant
camcaldemo	Camera calibration	Hard-coded control pts	yes
camcaldemo_allmodels	Camera calibration, varying distortion models	Hard-coded control pts	yes
camcaldemo_missing_obs	Exact singular normal matrix	Hard-coded control pts	yes
camcaldemo_1ray	Exact singular normal matrix	Hard-coded control pts	yes
camcaldemo_no_datum	Numerically singular normal matrix	Missing	yes
prague2016_pm('c1')	Camera calibration	Hard-coded fixed control points	yes
prague2016_pm('c2')	Camera calibration	Hard-coded weighted control points	yes
prague2016_pm('s1')	Bundle adjustment	Fixed ctrl pts from text file	no
prague2016_pm('s2')	Bundle adjustment	Weighted ctrl pts from text file	no
prague2016_pm('s4')	Bundle adjustment	Weighted ctrl pts from text file	no
prague2016_ps('s5')	Photoscan post-processing	Weighted ctrl pts from psz file	no
ps_postproc("")	Photoscan post-processing	Weighted ctrl pts from psz file	no
stpierrebundledemo_ps	Photoscan post-processing	Weighted ctrl pts from psz file	yes

Table 1: Summary of demos.

## 3.2 Using your own data

### 3.2.1 Photoscan/Metashape

DBAT can read native Photoscan Archive (.psz) files. DBAT cannot read Photoscan Project (.psx) files. If you have a .psx project, use the *Save as...* menu in Photoscan and save the project as a Photoscan Archive (.psz). DBAT has been tested with Photoscan file versions up to v1.4.0, Photoscan program version v1.4.4 as well as a pre-release v1.5.0 of Metashape.

The `ps_postproc` function can be used to post-process a Photoscan project. `loadplotpsz` may be useful to visualize the project, as computed by Photoscan.

**Known limitations** DBAT cannot handle all Photoscan coordinate systems. If you get strange results, you may have to convert to Local Coordinates. `loadplotpsz` may be useful for debugging the input.

### 3.2.2 PhotoModeler

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 toolbox authors and request an import function. Although we cannot guarantee anything, we may adhere to the request, time permitting.

**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.1.
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.
```

### Loading into Matlab

1. In Matlab, run step 2 from Section 2 if not already done.
2. Call `loadplotdemo` with the name of your text export file as first parameter. A figure with your camera network, aligned with the first camera and rotated to have +Z 'up', should now have been generated.

**Using the bundle adjustment of DBAT** Modify either of the demo functions to match what you want to do. If you run into any problems, send us an email. The interesting results may either be in the plots or in the result file.

## References

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

## A Appendices

### A.1 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.

### A.2 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).

### A.3 Result file with missing observations

```
Damped Bundle Adjustment Toolbox result file
Project Name: Bundle Soln PhotoModeler Calibration Project
Problems and suggestions:
Project Problems:
  Structural rank: 417 (deficiency: 6)
  DMPERM suggests the following parameters have problems:
    OX-12/13
    OY-12/13
    OZ-12/13
    OX-59/60
    OY-59/60
    OZ-59/60
  Numerical rank: not tested.
Problems related to the processing: (1)
  Bundle failed with code -4 (see below for details).
.
.
.
```

### A.4 Result file with single-ray observations

```
Damped Bundle Adjustment Toolbox result file
Project Name: Bundle Soln PhotoModeler Calibration Project
Problems and suggestions:
Project Problems:
  Structural rank: 422 (deficiency: 1)
  DMPERM suggests the following parameters have problems:
    OZ-87/88
  Numerical rank: not tested.
Problems related to the processing: (1)
  Bundle failed with code -4 (see below for details).
.
.
.
```

## A.5 Result file with missing datum

```
Damped Bundle Adjustment Toolbox result file
Project Name: Bundle Soln PhotoModeler Calibration Project
Problems and suggestions:
Project Problems:
  Structural rank: ok.
  Numerical rank: 428 (deficiency: 7)
  Null-space suggest the following parameters are part of the problem:
    Vector 1 (eigenvalue 1.36254e-18):
      (EX-21, -0.156)
      (EX-9, -0.13)
      (EX-13, -0.12)
      (EX-10, -0.119)
      (EX-11, -0.115)
      (EX-12, -0.108)
      (EX-14, -0.104)
    Vector 2 (eigenvalue -1.60532e-17):
      (EX-21, 0.207)
      (EY-21, 0.195)
      (EY-1, 0.192)
      (EY-2, 0.178)
      (EX-13, 0.167)
      (EY-15, 0.166)
      (EY-3, 0.166)
      (EY-4, 0.163)
      (EY-16, 0.161)
      (EX-14, 0.157)
      (EX-15, 0.151)
      (EX-11, 0.149)
      (EY-18, 0.147)
      (EX-12, 0.146)
      (EX-16, 0.145)
      (EY-20, 0.133)
      (EY-17, 0.128)
    Vector 3 (eigenvalue 5.21745e-17):
      (om-21, -0.16)
      (EX-3, -0.155)
      (EX-4, -0.151)
      (EX-5, -0.147)
      (EX-6, -0.136)
      (EZ-7, 0.132)
      (om-13, -0.129)
      (EX-1, -0.129)
      (om-15, -0.127)
      (om-16, -0.125)
      (EZ-8, 0.125)
      (om-14, -0.125)
      (EZ-9, 0.122)
      (EX-2, -0.117)
      (om-11, -0.116)
      (EZ-10, 0.116)
      (om-12, -0.114)
      (om-18, -0.113)
      (om-20, -0.113)
      (EZ-11, 0.111)
      (EX-7, -0.111)
      (EZ-12, 0.11)
      (om-19, -0.109)
      (om-9, -0.108)
      (EZ-5, 0.107)
      (om-1, -0.106)
      (om-17, -0.106)
      (om-2, -0.105)
      (om-10, -0.105)
    Vector 4 (eigenvalue -5.5516e-17):
      (EZ-21, -0.174)
      (EX-5, -0.13)
```

```

(EX-7, -0.129)
(EX-8, -0.12)
(EX-6, -0.119)
(EY-9, -0.114)
(EY-11, -0.111)
Vector 5 (eigenvalue -1.45759e-16):
(EY-7, 0.158)
(EY-5, 0.154)
(EY-8, 0.153)
(EY-9, 0.151)
(om-4, -0.147)
(EY-19, 0.147)
(om-3, -0.144)
(EY-6, 0.143)
(EY-10, 0.143)
(EY-17, 0.133)
(EZ-3, -0.132)
(EZ-4, -0.129)
(om-17, -0.126)
(om-19, -0.126)
(om-18, -0.125)
(om-1, -0.124)
(om-9, -0.124)
(om-2, -0.124)
(EY-18, 0.121)
(om-10, -0.121)
(EY-20, 0.12)
(om-20, -0.12)
(om-5, -0.12)
(EZ-2, -0.118)
(EZ-1, -0.118)
(om-6, -0.116)
(ph-9, -0.114)
(ph-7, -0.113)
(ph-11, -0.112)
(EY-11, 0.112)
(ph-12, -0.111)
(ph-8, -0.11)
(ph-10, -0.109)
(ph-5, -0.108)
(om-11, -0.108)
(EY-12, 0.107)
(EZ-5, -0.106)
(ph-13, -0.106)
(om-7, -0.104)
(ph-19, -0.104)
(om-12, -0.104)
(ph-14, -0.104)
Vector 6 (eigenvalue -1.54875e-16):
(om-21, 0.185)
(ph-9, -0.174)
(EZ-21, 0.174)
(ph-10, -0.169)
(ph-11, -0.167)
(ph-7, -0.167)
(ph-8, -0.165)
(ph-12, -0.164)
(EX-9, -0.152)
(EX-7, -0.151)
(EX-8, -0.151)
(EY-11, -0.148)
(EY-12, -0.146)
(EX-10, -0.146)
(EZ-15, 0.142)
(EZ-16, 0.137)
(EY-13, -0.136)
(ph-5, -0.135)
(EY-14, -0.133)

```

```

(EZ-13, 0.127)
(ph-13, -0.127)
(EZ-14, 0.126)
(ph-14, -0.124)
(ph-6, -0.123)
(ph-19, -0.12)
(EY-21, -0.117)
Vector 7 (eigenvalue 1.9046e-16):
(ph-1, 0.194)
(ph-2, 0.194)
(ph-15, 0.173)
(EX-2, 0.173)
(om-5, -0.173)
(ph-16, 0.169)
(ph-4, 0.169)
(EX-1, 0.168)
(ph-3, 0.164)
(om-8, -0.163)
(om-7, -0.16)
(om-6, -0.16)
(ph-21, 0.157)
(EY-21, -0.138)
(EY-5, 0.138)
(EY-6, 0.132)
(om-3, -0.127)
(ph-20, 0.126)
(om-4, -0.125)
Problems related to the processing: (1)
  Bundle failed with code -2 (see below for details).
.
.
.

```

## A.6 Successful result file example

```

Damped Bundle Adjustment Toolbox result file
Project Name: Bundle Soln PhotoModeler Calibration Project
Problems and suggestions:
Project Problems:
  Structural rank: ok.
  Numerical rank: ok.
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-Oct-2018 20:55:37
DBAT version: 0.7.6.1 (2018-10-25)
MATLAB version: 8.6.0.267246 (R2015b)
Host system: GLNXA64
Host name: slartibartfast
Status: OK
Sigma0: 1.6148
Sigma0 (pixels): 0.16148
Processing options:
  Orientation: on
  Global optimization: on
  Calibration: on
  Constraints: off
  Maximum # of iterations: 20
  Convergence tolerance: 1e-06
  Termination criteria: relative
  Singular test: on
  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:  9
First error:          30882.3
Last error:           98.556
Execution time (s):    0.78
Lens distortion models:
  Backward (Photogrammetry) model 3
Cameras:
  Calibration: yes (Xp Yp f K1 K2 K3 P1 P2 aspect)
  Camera1
    Lens distortion model:
      Backward (Photogrammetry) model 3
    Focal Length:
      Value:      7.457 mm
      Deviation:  0.00105 mm
    Xp - principal point x:
      Value:      3.61546 mm
      Deviation:  0.00082 mm
    Yp - principal point y:
      Value:      2.61329 mm
      Deviation:  0.00098 mm
    Fw - format width:
      Value:      7.25301 mm
    Fh - format height:
      Value:      5.43764 mm
    K1 - radial distortion 1:
      Value:      0.00458861 mm-3
      Deviation:  2.21e-05 mm-3
      Significance: p=1.00
    K2 - radial distortion 2:
      Value:      -4.51351e-05 mm-5
      Deviation:  2.65e-06 mm-5
      Significance: p=1.00
      Correlations over 95%: K3:-97.9%.
    K3 - radial distortion 3:
      Value:      -2.05253e-06 mm-7
      Deviation:  1.01e-07 mm-7
      Significance: p=1.00
      Correlations over 95%: K2:-97.9%.
    P1 - decentering distortion 1:
      Value:      -6.12803e-05 mm-3
      Deviation:  3.52e-06 mm-3
      Significance: p=1.00
    P2 - decentering distortion 2:
      Value:      -4.41172e-05 mm-3
      Deviation:  3.94e-06 mm-3
      Significance: p=1.00
    B1 - aspect ratio:
      Value:      0.000389598
      Deviation:  2.08e-05
      Significance: p=1.00
    B2 - skew:
      Value:      0
    Iw - image width:
      Value:      2272 px
    Ih - image height:
      Value:      1704 px
    Xr - X resolution:
      Value:      313.371 px/mm
    Yr - Y resolution:
      Value:      313.371 px/mm
    Pw - pixel width:
      Value:      0.00319235 mm
    Ph - pixel height:
      Value:      0.0031911 mm
    Rated angle of view (h,v,d): (52, 40, 63) deg
    Largest distortion: 0.37 mm (116.4 px, 8.2% of half-diagonal)
  Precisions / Standard Deviations:

```

Photograph Standard Deviations:

Photo 1: P8250021.JPG

Omega:  
Value: -39.413082 deg  
Deviation: 0.0085 deg

Phi:  
Value: -1.183179 deg  
Deviation: 0.00761 deg

Kappa:  
Value: -179.838467 deg  
Deviation: 0.00275 deg

Xc:  
Value: 0.454947 ou  
Deviation: 0.000155 ou

Yc:  
Value: 1.793849 ou  
Deviation: 0.000179 ou

Zc:  
Value: 1.468066 ou  
Deviation: 0.000207 ou

Photo 2: P8250022.JPG

Omega:  
Value: -39.734523 deg  
Deviation: 0.00816 deg

Phi:  
Value: -1.813688 deg  
Deviation: 0.00886 deg

Kappa:  
Value: -90.123062 deg  
Deviation: 0.00289 deg

Xc:  
Value: 0.470305 ou  
Deviation: 0.000186 ou

Yc:  
Value: 2.026401 ou  
Deviation: 0.000219 ou

Zc:  
Value: 1.639148 ou  
Deviation: 0.000232 ou

Photo 3: P8250023.JPG

Omega:  
Value: -27.227000 deg  
Deviation: 0.0105 deg

Phi:  
Value: -28.559177 deg  
Deviation: 0.00753 deg

Kappa:  
Value: -141.839170 deg  
Deviation: 0.00538 deg

Xc:  
Value: -0.644442 ou  
Deviation: 0.000188 ou

Yc:  
Value: 1.466578 ou  
Deviation: 0.000179 ou

Zc:  
Value: 1.580187 ou  
Deviation: 0.000243 ou

Photo 4: P8250024.JPG

Omega:  
Value: -28.556794 deg  
Deviation: 0.00881 deg

Phi:  
Value: -30.289704 deg  
Deviation: 0.00923 deg

Kappa:  
Value: -49.786720 deg  
Deviation: 0.00467 deg

Xc:  
   Value:       -0.643144 ou  
   Deviation: 0.000198 ou  
 Yc:  
   Value:       1.490295 ou  
   Deviation: 0.000202 ou  
 Zc:  
   Value:       1.637492 ou  
   Deviation: 0.000246 ou  
 Photo 5: P8250025.JPG  
   Omega:  
     Value:       4.385418 deg  
     Deviation: 0.00943 deg  
   Phi:  
     Value:       -34.659929 deg  
     Deviation: 0.00863 deg  
   Kappa:  
     Value:       -87.134063 deg  
     Deviation: 0.00519 deg  
 Xc:  
   Value:       -0.671014 ou  
   Deviation: 0.000158 ou  
 Yc:  
   Value:       0.417412 ou  
   Deviation: 0.000144 ou  
 Zc:  
   Value:       1.409244 ou  
   Deviation: 0.000193 ou  
 Photo 6: P8250026.JPG  
   Omega:  
     Value:       2.063986 deg  
     Deviation: 0.0103 deg  
   Phi:  
     Value:       -33.988460 deg  
     Deviation: 0.00823 deg  
   Kappa:  
     Value:       1.485869 deg  
     Deviation: 0.00587 deg  
 Xc:  
   Value:       -0.712797 ou  
   Deviation: 0.000177 ou  
 Yc:  
   Value:       0.476083 ou  
   Deviation: 0.000155 ou  
 Zc:  
   Value:       1.465130 ou  
   Deviation: 0.000203 ou  
 Photo 7: P8250027.JPG  
   Omega:  
     Value:       27.342174 deg  
     Deviation: 0.00854 deg  
   Phi:  
     Value:       -28.292503 deg  
     Deviation: 0.00875 deg  
   Kappa:  
     Value:       -44.210389 deg  
     Deviation: 0.00445 deg  
 Xc:  
   Value:       -0.534821 ou  
   Deviation: 0.000154 ou  
 Yc:  
   Value:       -0.349595 ou  
   Deviation: 0.000157 ou  
 Zc:  
   Value:       1.402489 ou  
   Deviation: 0.000212 ou  
 Photo 8: P8250028.JPG  
   Omega:

Value: 26.875970 deg  
 Deviation: 0.0107 deg  
 Phi:  
 Value: -28.129516 deg  
 Deviation: 0.00757 deg  
 Kappa:  
 Value: 44.840805 deg  
 Deviation: 0.00553 deg  
 Xc:  
 Value: -0.718081 ou  
 Deviation: 0.000218 ou  
 Yc:  
 Value: -0.466107 ou  
 Deviation: 0.000204 ou  
 Zc:  
 Value: 1.715475 ou  
 Deviation: 0.000264 ou  
 Photo 9: P8250029.JPG  
 Omega:  
 Value: 30.383673 deg  
 Deviation: 0.00856 deg  
 Phi:  
 Value: 0.193844 deg  
 Deviation: 0.00776 deg  
 Kappa:  
 Value: 0.084838 deg  
 Deviation: 0.00248 deg  
 Xc:  
 Value: 0.524897 ou  
 Deviation: 0.000161 ou  
 Yc:  
 Value: -0.543737 ou  
 Deviation: 0.000167 ou  
 Zc:  
 Value: 1.533003 ou  
 Deviation: 0.000208 ou  
 Photo 10: P8250030.JPG  
 Omega:  
 Value: 30.975069 deg  
 Deviation: 0.0085 deg  
 Phi:  
 Value: 1.702984 deg  
 Deviation: 0.00879 deg  
 Kappa:  
 Value: 89.537060 deg  
 Deviation: 0.00264 deg  
 Xc:  
 Value: 0.554430 ou  
 Deviation: 0.000176 ou  
 Yc:  
 Value: -0.592328 ou  
 Deviation: 0.000194 ou  
 Zc:  
 Value: 1.617413 ou  
 Deviation: 0.000216 ou  
 Photo 11: P8250031.JPG  
 Omega:  
 Value: 27.620051 deg  
 Deviation: 0.0106 deg  
 Phi:  
 Value: 30.742857 deg  
 Deviation: 0.00756 deg  
 Kappa:  
 Value: 42.343765 deg  
 Deviation: 0.00584 deg  
 Xc:  
 Value: 1.770052 ou  
 Deviation: 0.000191 ou

Yc:  
   Value:       -0.425243 ou  
   Deviation: 0.00018 ou  
 Zc:  
   Value:       1.551302 ou  
   Deviation: 0.000241 ou  
 Photo 12: P8250032.JPG  
   Omega:  
     Value:       24.647784 deg  
     Deviation: 0.00901 deg  
   Phi:  
     Value:       30.199261 deg  
     Deviation: 0.00965 deg  
   Kappa:  
     Value:       133.199858 deg  
     Deviation: 0.00493 deg  
   Xc:  
     Value:       1.864503 ou  
     Deviation: 0.000201 ou  
   Yc:  
     Value:       -0.480191 ou  
     Deviation: 0.000202 ou  
   Zc:  
     Value:       1.614517 ou  
     Deviation: 0.000255 ou  
 Photo 13: P8250033.JPG  
   Omega:  
     Value:       0.519301 deg  
     Deviation: 0.00941 deg  
   Phi:  
     Value:       33.141786 deg  
     Deviation: 0.00865 deg  
   Kappa:  
     Value:       88.708362 deg  
     Deviation: 0.00499 deg  
   Xc:  
     Value:       1.630951 ou  
     Deviation: 0.000165 ou  
   Yc:  
     Value:       0.497645 ou  
     Deviation: 0.000151 ou  
   Zc:  
     Value:       1.470402 ou  
     Deviation: 0.000199 ou  
 Photo 14: P8250034.JPG  
   Omega:  
     Value:       -1.707201 deg  
     Deviation: 0.0105 deg  
   Phi:  
     Value:       33.605390 deg  
     Deviation: 0.00835 deg  
   Kappa:  
     Value:       180.179674 deg  
     Deviation: 0.00585 deg  
   Xc:  
     Value:       1.795963 ou  
     Deviation: 0.000196 ou  
   Yc:  
     Value:       0.525690 ou  
     Deviation: 0.000177 ou  
   Zc:  
     Value:       1.598647 ou  
     Deviation: 0.000218 ou  
 Photo 15: P8250035.JPG  
   Omega:  
     Value:       -30.757132 deg  
     Deviation: 0.00869 deg  
   Phi:

Value: 28.161929 deg  
 Deviation: 0.00893 deg  
 Kappa:  
 Value: 138.427120 deg  
 Deviation: 0.00462 deg  
 Xc:  
 Value: 1.671692 ou  
 Deviation: 0.000177 ou  
 Yc:  
 Value: 1.554494 ou  
 Deviation: 0.000178 ou  
 Zc:  
 Value: 1.500046 ou  
 Deviation: 0.000239 ou  
 Photo 16: P8250036.JPG  
 Omega:  
 Value: -29.841912 deg  
 Deviation: 0.0105 deg  
 Phi:  
 Value: 26.976407 deg  
 Deviation: 0.00757 deg  
 Kappa:  
 Value: -134.657860 deg  
 Deviation: 0.00543 deg  
 Xc:  
 Value: 1.693214 ou  
 Deviation: 0.000204 ou  
 Yc:  
 Value: 1.619159 ou  
 Deviation: 0.000189 ou  
 Zc:  
 Value: 1.590375 ou  
 Deviation: 0.000252 ou  
 Photo 17: P8250037.JPG  
 Omega:  
 Value: -8.536369 deg  
 Deviation: 0.00979 deg  
 Phi:  
 Value: -0.515819 deg  
 Deviation: 0.00956 deg  
 Kappa:  
 Value: 179.396590 deg  
 Deviation: 0.00198 deg  
 Xc:  
 Value: 0.424677 ou  
 Deviation: 0.000287 ou  
 Yc:  
 Value: 0.824641 ou  
 Deviation: 0.000288 ou  
 Zc:  
 Value: 1.971217 ou  
 Deviation: 0.000246 ou  
 Photo 18: P8250038.JPG  
 Omega:  
 Value: -4.760952 deg  
 Deviation: 0.00959 deg  
 Phi:  
 Value: 0.661695 deg  
 Deviation: 0.00919 deg  
 Kappa:  
 Value: 88.788380 deg  
 Deviation: 0.00189 deg  
 Xc:  
 Value: 0.483059 ou  
 Deviation: 0.000268 ou  
 Yc:  
 Value: 0.925982 ou  
 Deviation: 0.000284 ou

```

Zc:
  Value:      1.885017 ou
  Deviation:  0.000229 ou
Photo 19: P8250039.JPG
Omega:
  Value:      -4.415305 deg
  Deviation:  0.00923 deg
Phi:
  Value:      -0.416632 deg
  Deviation:  0.00926 deg
Kappa:
  Value:      88.245577 deg
  Deviation:  0.00186 deg
Xc:
  Value:      0.462946 ou
  Deviation:  0.000275 ou
Yc:
  Value:      0.578695 ou
  Deviation:  0.000271 ou
Zc:
  Value:      1.874858 ou
  Deviation:  0.00021 ou
Photo 20: P8250040.JPG
Omega:
  Value:      -7.619745 deg
  Deviation:  0.00935 deg
Phi:
  Value:      -1.571494 deg
  Deviation:  0.0103 deg
Kappa:
  Value:      -180.050126 deg
  Deviation:  0.00199 deg
Xc:
  Value:      0.701429 ou
  Deviation:  0.000319 ou
Yc:
  Value:      0.784042 ou
  Deviation:  0.000278 ou
Zc:
  Value:      1.925303 ou
  Deviation:  0.00024 ou
Photo 21: P8250041.JPG
Omega:
  Value:      -8.708623 deg
  Deviation:  0.00925 deg
Phi:
  Value:      1.058407 deg
  Deviation:  0.0102 deg
Kappa:
  Value:      -182.614638 deg
  Deviation:  0.00203 deg
Xc:
  Value:      0.269149 ou
  Deviation:  0.000314 ou
Yc:
  Value:      0.822761 ou
  Deviation:  0.000266 ou
Zc:
  Value:      1.904844 ou
  Deviation:  0.000243 ou
Quality
Photographs
  Total number: 21
  Numbers used: 21
Cameras
  Total number: 1
  Cameral:
  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
  Number of control pts: 4
  Number of check pts: 0
  Number of object pts: 96
  CP ray count: 21-21 (21.0 avg)
    4 points with 21 rays.
  CCP ray count: -
  OP ray count: 16-21 (20.7 avg)
    1 points with 16 rays.
    1 points with 17 rays.
    2 points with 18 rays.
    3 points with 19 rays.
    5 points with 20 rays.
    84 points with 21 rays.
Point Marking Residuals
  Overall point RMS: 0.216 pixels
  Mark point residuals:
    Maximum: 0.955 pixels (OP 1003 on photo 5)
  Object point residuals (RMS over all images of a point):
    Minimum: 0.095 pixels (OP 65 over 21 images)
    Maximum: 0.553 pixels (OP 1004 over 21 images)
  Photo residuals (RMS over all points in an image):
    Minimum: 0.153 pixels (photo 4 over 97 points)
    Maximum: 0.281 pixels (photo 11 over 100 points)
Point Precision
  Total standard deviation (RMS of X/Y/Z std):
    Minimum: 8.2e-05 (OP 49)
    Maximum: 0.00011 (OP 90)
  Maximum X standard deviation: 5e-05 (OP 90)
  Maximum Y standard deviation: 5.3e-05 (OP 90)
  Maximum Z standard deviation: 8.5e-05 (OP 90)
  Points with high correlations
    Points with correlation above 95%: 0
    Points with correlation above 99%: 0
Point Angles
  CP
    Minimum: 83.4 degrees (CP 1003)
    Maximum: 85.8 degrees (CP 1002)
    Average: 84.7 degrees
  CCP
    Minimum: -
    Maximum: -
    Average: -
  OP
    Minimum: 79.6 degrees (OP 90)
    Maximum: 90.0 degrees (OP 59)
    Average: 86.5 degrees
  Smallest angles (ID, angle [deg], vis in cameras)
    90: 79.61 ( 1 2 3 5 8 9 11 13 14 15 16 17 18 19 20 21)
    8: 81.00 ( 1 2 3 4 5 7 9 10 11 12 13 14 15 17 18 19 20
    92: 81.15 ( 1 2 3 4 5 7 8 9 10 11 13 14 15 16 17 18 19
Ctrl measurements
  Prior
    id,      x,      y,      z,      stdx,      stdy,      stdz, label
    1001,    0.000,    1.000,    0.000,    0,      0,      0,
    1002,    1.000,    1.000,    0.000,    0,      0,      0,
    1003,    0.000,    0.000,    0.000,    0,      0,      0,
    1004,    1.000,    0.000,    0.000,    0,      0,      0,
  Posterior
    id,      x,      y,      z,      stdx,      stdy,      stdz, rays, label

```



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1001, 0.000, 1.000, 0.000, 0, 0, 0, 21,
1002, 1.000, 1.000, 0.000, 0, 0, 0, 21,
1003, 0.000, 0.000, 0.000, 0, 0, 0, 21,
1004, 1.000, 0.000, 0.000, 0, 0, 0, 21,
Diff (pos=abs diff, std=rel diff)
  id,      x,      y,      z,      xy,      xyz,      stdx,      stdy,      stdz, rays, label
1001, 0.000, 0.000, 0.000, 0.000, 0.000, 0.0%, 0.0%, 0.0%, 21,
1002, 0.000, 0.000, 0.000, 0.000, 0.000, 0.0%, 0.0%, 0.0%, 21,
1003, 0.000, 0.000, 0.000, 0.000, 0.000, 0.0%, 0.0%, 0.0%, 21,
1004, 0.000, 0.000, 0.000, 0.000, 0.000, 0.0%, 0.0%, 0.0%, 21,
Ctrl point delta
  Max: 0.000 ou (, pt 1001)
  Max X,Y,Z
    X: 0.000 ou (, pt 1001)
    Y: 0.000 ou (, pt 1001)
    Z: 0.000 ou (, pt 1001)
  RMS: 0.000 ou (from 4 items)
Check measurements
  none

```