DBAT — The Damped Bundle Adjustment Toolbox for Matlab
v0.8.5.0

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,
pierre.grussenmeyer@insa-strasbourg.fr

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With contributions from:

- Arnaud Durand, ICube-SERTIT, University of Strasbourg, France.
- Jan Hieronymus, TU Berlin, Germany.
- Jean-François Hullo, EDF, France.
- Fabio Menna, Fondazione Bruno Kessler, Trento, Italy.
- Arnadi Murtiyoso, ICube, INSA Strasbourg, France.
- Kostas Naskou, University of Nottingham, UK.
- Erica Nocerino, Fondazione Bruno Kessler, Trento, Italy.
- Deni Suwardhi, Bandung Institute of Technology, Indonesia.

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 9.5 (release R2018b). 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 (Stewénius 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.
  - Works with prior observations of camera positions.
  - 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 Börlin 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[1]. The corresponding high resolution images can be downloaded from `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 Börlin and Grussenmeyer (2013a,b, 2014, 2016); Börlin 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.

[1]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.
#
#
```

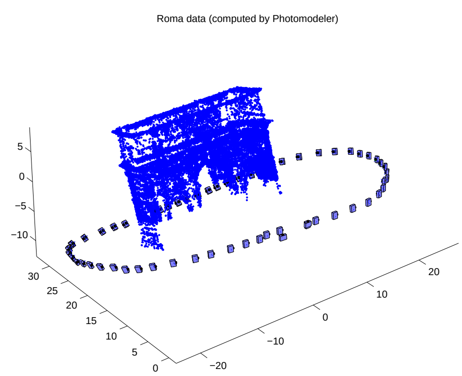


Figure 1: The figure generated by the `loadplotdemo` demo.

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.,

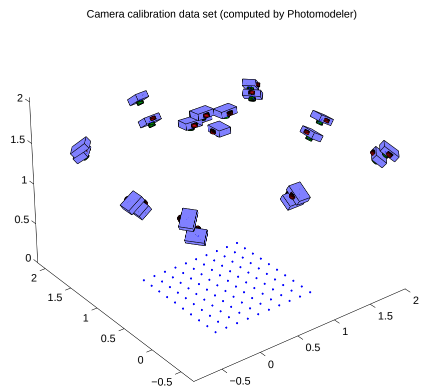


Figure 2: The figure generated by the `loadplotdemo('cam')` demo.

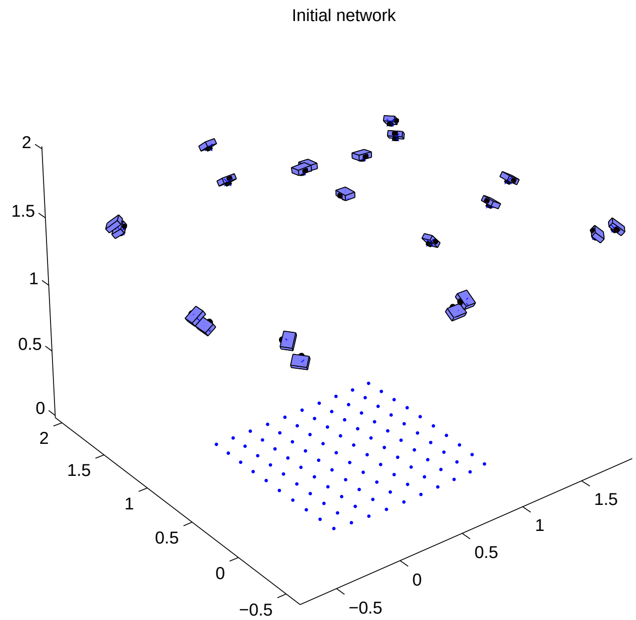
2004, Chap. 11.1.3.4) using the control points defined for the PhotoModeler calibration sheet. The initial OP coordinates are subsequently computed by forward intersection.

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 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.

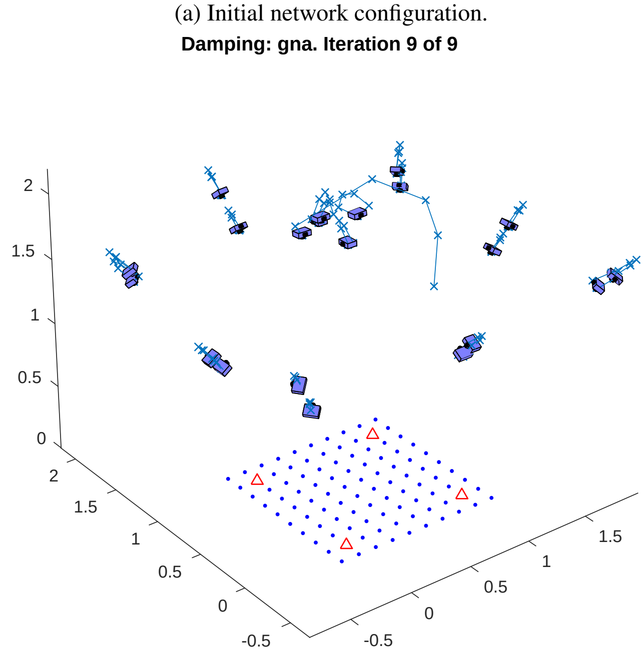
Evolution plots The evolution plots are collected in figures 3–7. Figure 3 shows a snapshot of the 3D trace figure at the beginning and end of the iterations. As default, the evolution is presented iteration by iteration with intervening presses of the return key. The figure window is interactive and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



(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.

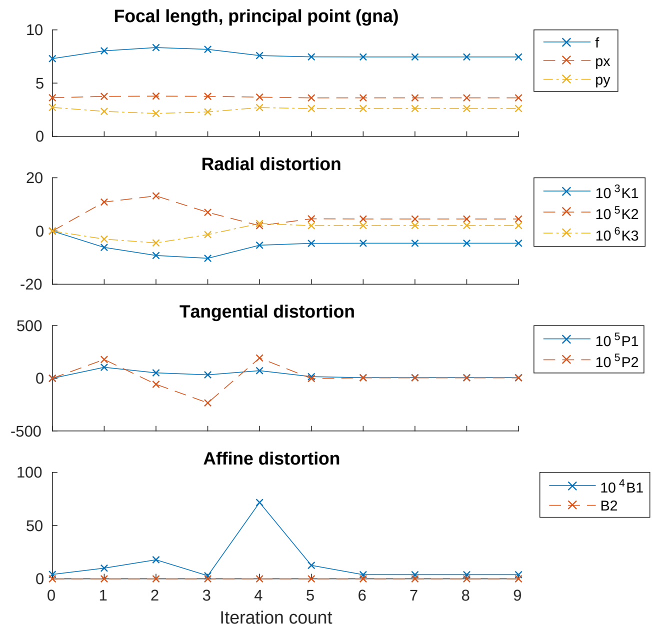


Figure 4: Evolution of IO parameters during the iteration sequence.

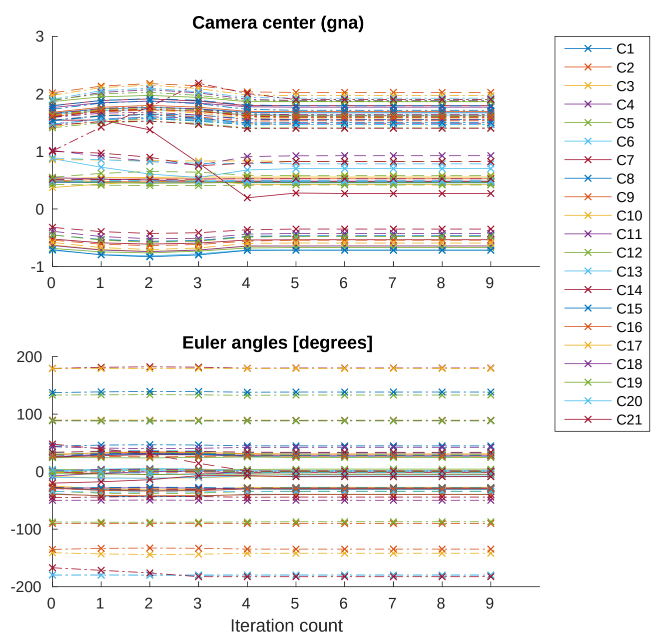


Figure 5: Evolution of EO parameters during the iteration sequence.

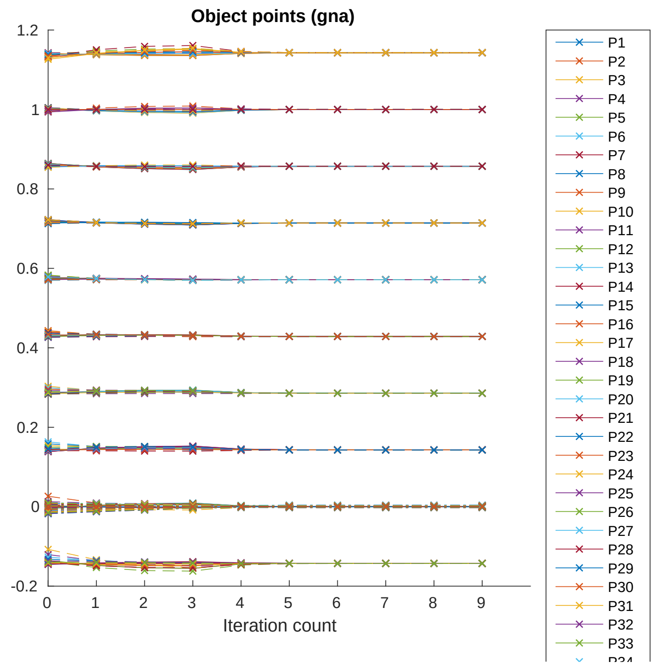


Figure 6: Evolution of OP coordinates during the iteration sequence.

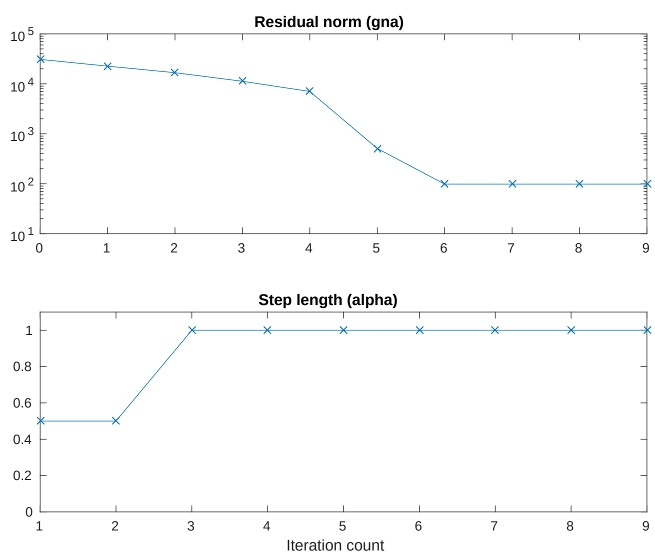


Figure 7: Residual evolution and damping behaviour during the iterations.

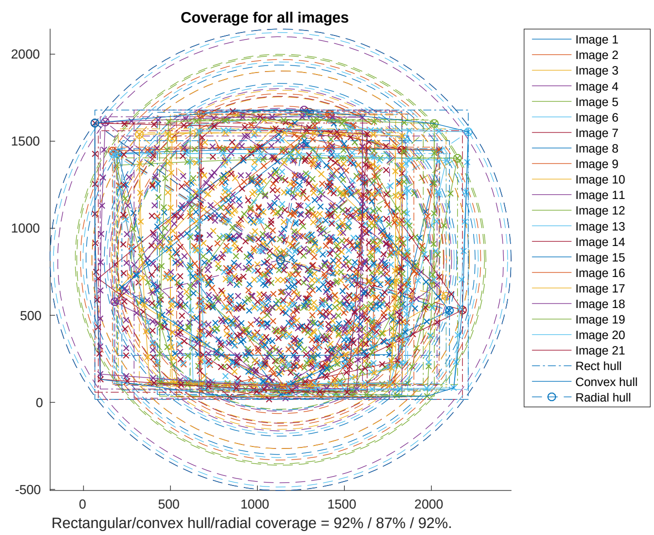


Figure 8: Plots of input/output statistics: Image coverage.

Quality plots The quality plots 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.

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 generate for each model.

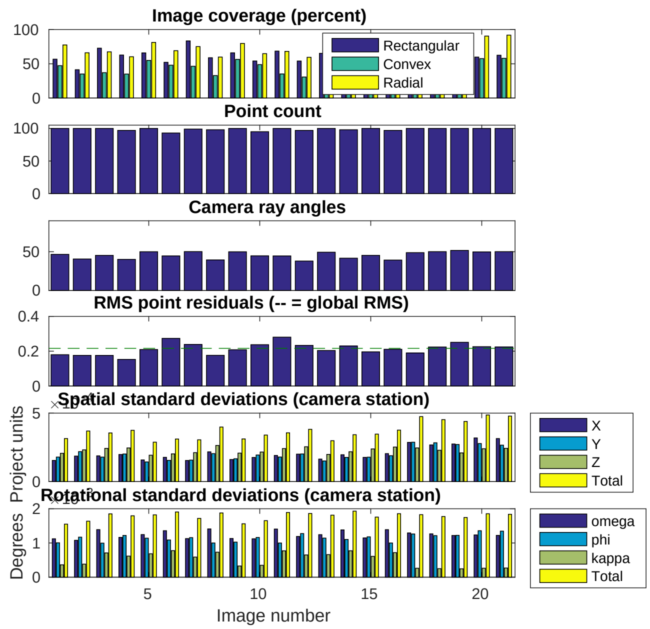


Figure 9: Plots of input/output statistics: Image statistics.

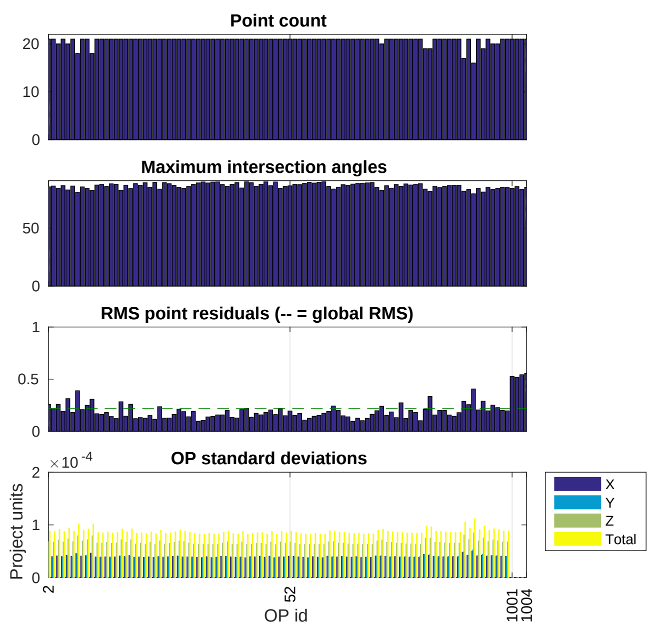


Figure 10: Plots of input/output statistics: Object point statistics.

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). Similarily, 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.

PRIOR CAMERA OBSERVATIONS The sxb_prior_eo demo shows how to include prior observations of the camera positions in the bundle.

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 distorion 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
`sxb_prior_eo`	Use of prior camera positions in bundle	Weighted ctrl pts, cam pos from text file	no

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. As of DBAT version 0.8.5.0, prior observations of the camera positions are acknowledged and used in the bundle.

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 the toolbox authors and request an import function. Althought 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.

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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 Rotation model

Currently, the only supported rotation model is the omega-phi-kappa Euler angle rotation 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
      File name   : $DBATROOT/demo/data/dbat/pmexports/camcal-pmexport.txt
      Ctrl pt file: $DBATROOT/demo/data/dbat/ref/camcal-fixed.txt
   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:        03-Jan-2019 01:49:51
      DBAT version:           0.8.5.0 (2019-01-03)
      MATLAB version:         9.5.0.944444 (R2018b)
      Host system:            GLNXA64 (endian=L, max #elems=281474976710655)
      Host name:              slartibartfast
      Status:                 OK
      Sigma0:                 1.6148
      Sigma0 (pixels):        0.16148
      Redundancy              3725
      Number of params:       423 (9 IO, 126 EO, 288 OP)
      Number of observations: 4148 (4148 IP, 0 IO, 0 EO, 0 OP)
      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:          30873.9
   Last error:           98.556
   Execution time (s):   1.89
Lens distortion models:
   Backward (Photogrammetry) model 3
Cameras:
   Calibration: yes (cc px py as K1 K2 K3 P1 P2)
   Camera1 (simple)
      Lens distortion model:
         Backward (Photogrammetry) model 3
      Camera Constant:
         Value:        7.457 mm
         Deviation:    0.00105 mm
      px - principal point x:
         Value:        3.61546 mm
         Deviation:    0.00082 mm
      py - principal point y:
         Value:        2.61329 mm
         Deviation:    0.00098 mm
      Format width:
         Value:        7.25301 mm
      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
         Cumulative significance:p=1.00
      K2 - radial distortion 2:
         Value:        -4.51351e-05 mm^(-5)
         Deviation:    2.65e-06 mm^(-5)
         Significance: p=1.00
         Cumulative 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
         Cumulative 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)
      as - off-unit aspect parameter:
         Value:        0.000389598
         Deviation:    2.08e-05
         Significance: p=1.00
      sk - skew:
         Value:        0
      Image width:
         Value:        2272 px
      Image height:
         Value:        1704 px
      X resolution:
         Value:        313.249 px/mm
      Y resolution:
```

```
         Value:        313.371 px/mm
      Pixel width:
         Value:        0.00319235 mm
      Pixel height:
         Value:        0.0031911 mm
   Rated angle of view (h,v,d): (52, 40, 63) deg
   Largest distortion: 0.37 mm (116.2 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 (1 simple, 0 mixed)
      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
      Reference points outside calibrated region:
         Camera 1: 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, label CP3)
         Maximum: 85.8 degrees (CP 1002, label CP2)
         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, CP1
           1002,      1.000,      1.000,      0.000,          0,          0,          0, CP2
           1003,      0.000,      0.000,      0.000,          0,          0,          0, CP3
           1004,      1.000,      0.000,      0.000,          0,          0,          0, CP4
         Posterior
             id,          x,          y,          z,       stdx,       stdy,       stdz, rays, label
           1001,      0.000,      1.000,      0.000,          0,          0,          0,   21, CP1
           1002,      1.000,      1.000,      0.000,          0,          0,          0,   21, CP2
           1003,      0.000,      0.000,      0.000,          0,          0,          0,   21, CP3
           1004,      1.000,      0.000,      0.000,          0,          0,          0,   21, CP4
         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, CP1
           1002,      0.000,      0.000,      0.000,      0.000,      0.000,       0.0%,       0.0%,       0.0%,   21, CP2
           1003,      0.000,      0.000,      0.000,      0.000,      0.000,       0.0%,       0.0%,       0.0%,   21, CP3
           1004,      0.000,      0.000,      0.000,      0.000,      0.000,       0.0%,       0.0%,       0.0%,   21, CP4
         Ctrl point delta
            Max: 0.000 ou (CP1, pt 1001)
            Max X,Y,Z
               X: 0.000 ou (CP1, pt 1001)
               Y: 0.000 ou (CP1, pt 1001)
               Z: 0.000 ou (CP1, pt 1001)
            RMS: 0.000 ou (from 4 items)
      Check measurements
         none
End of result file
```