



Jigsaw

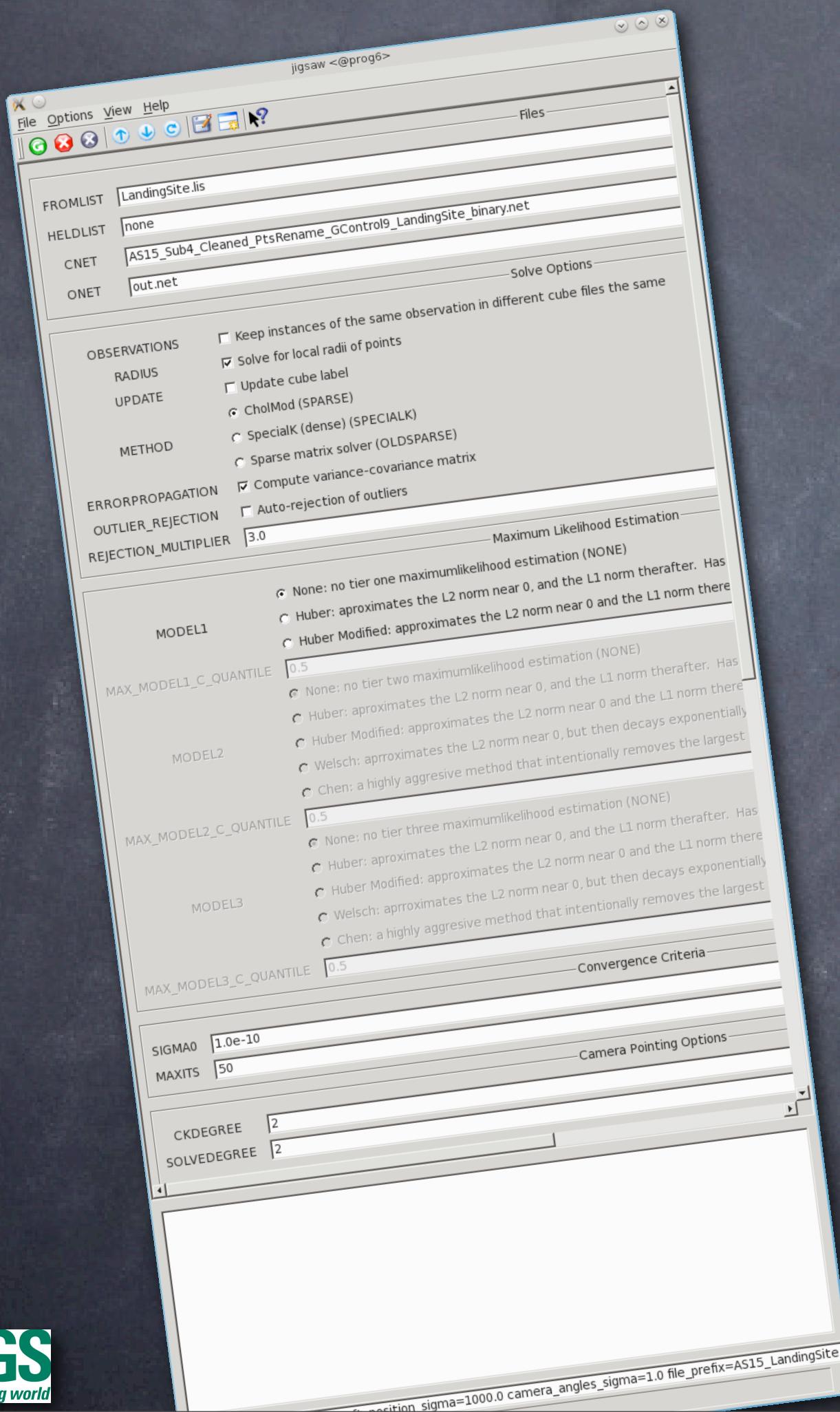
The ISIS Bundle
Adjustment for
Extraterrestrial
Photogrammetry

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Astrogeology / Geomatics Team

Least Squares Bundle Adjustment



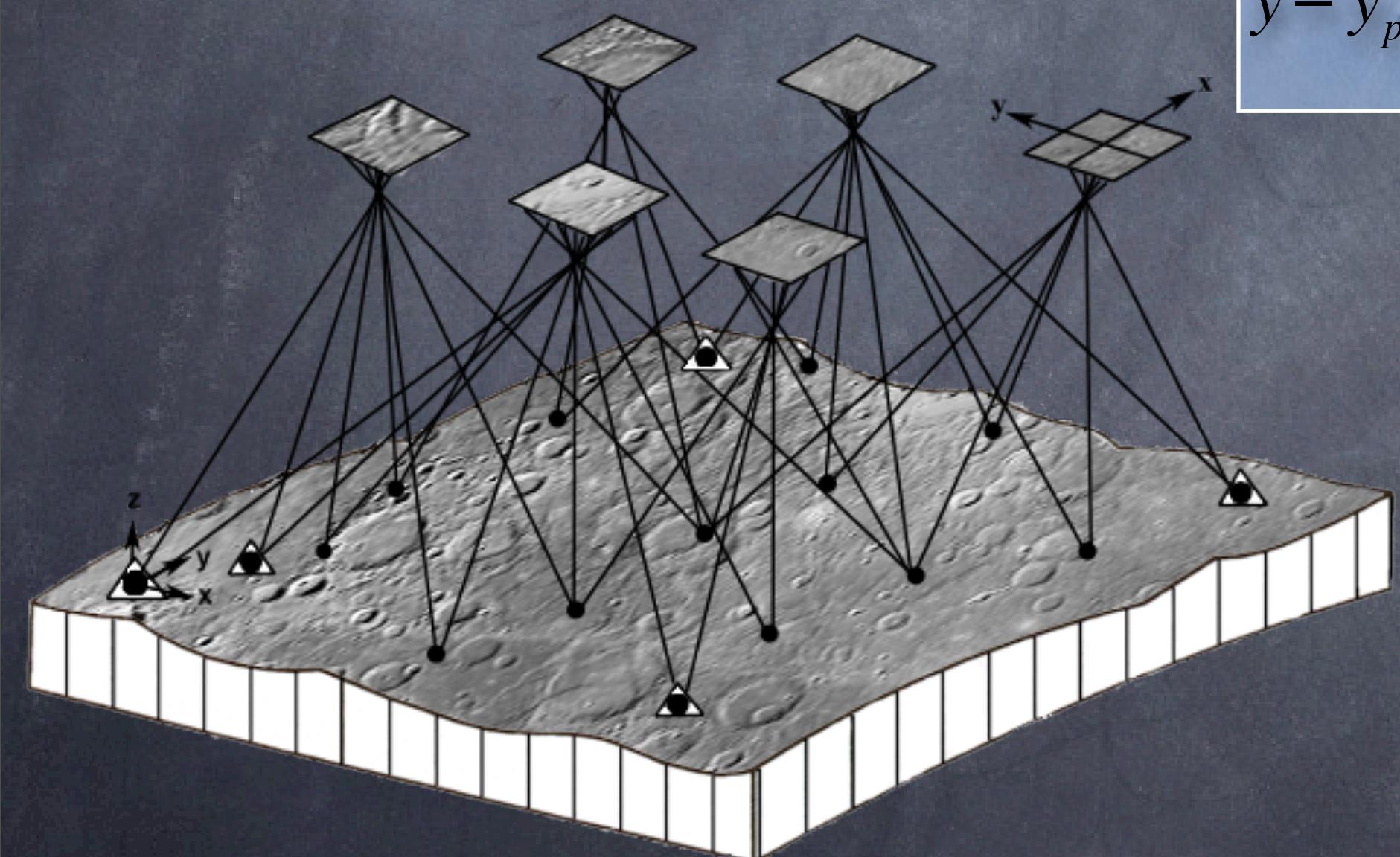
Input

- Image Measurements.
- Initial values for image pointing/position and ground point coordinates.
- 'a priori' precisions for above parameters if available.

Output

- Refined image pointing/position and ground point coordinates.
- Their uncertainties.
- Solution statistics.

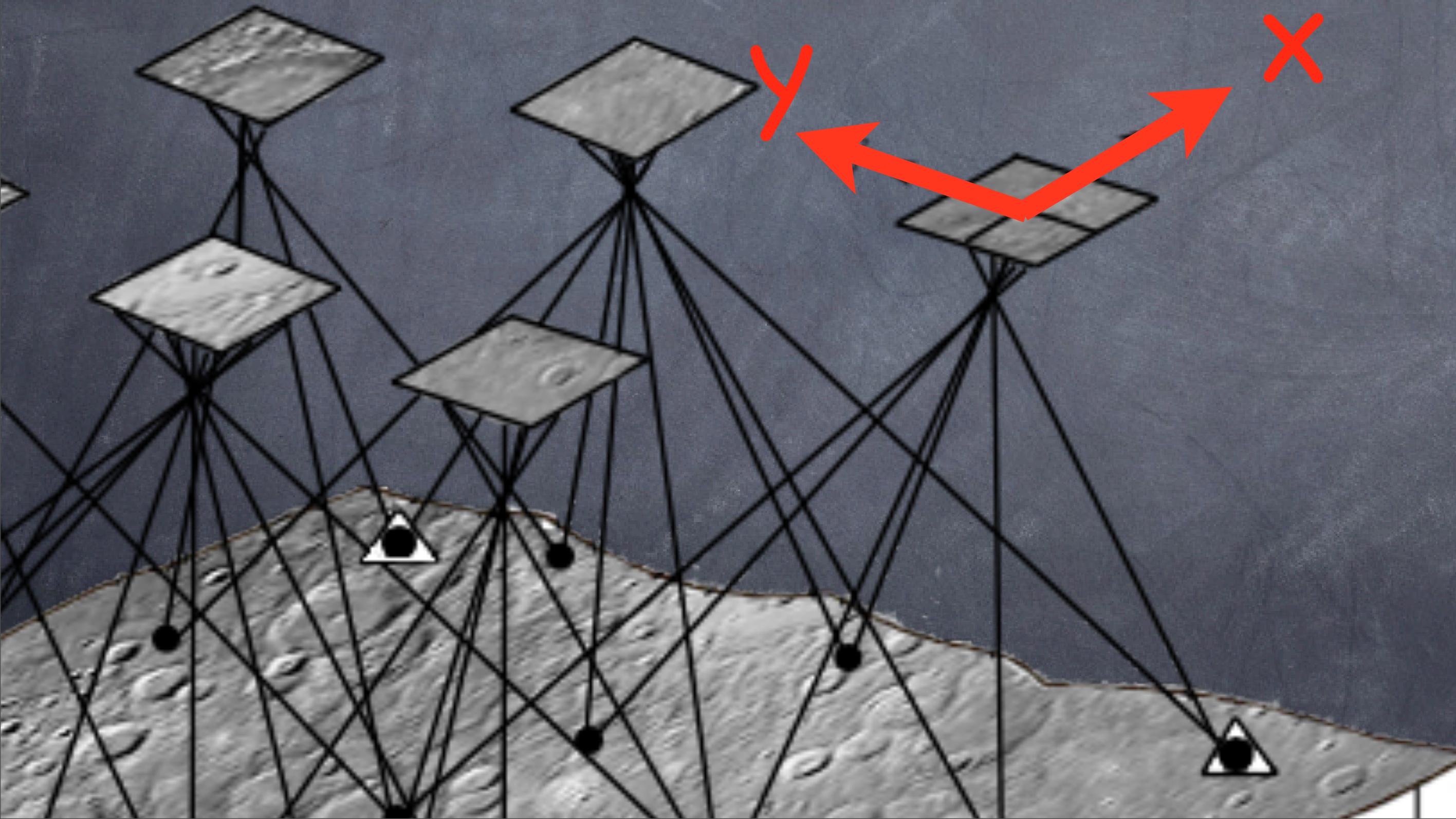
The Mathematical Model



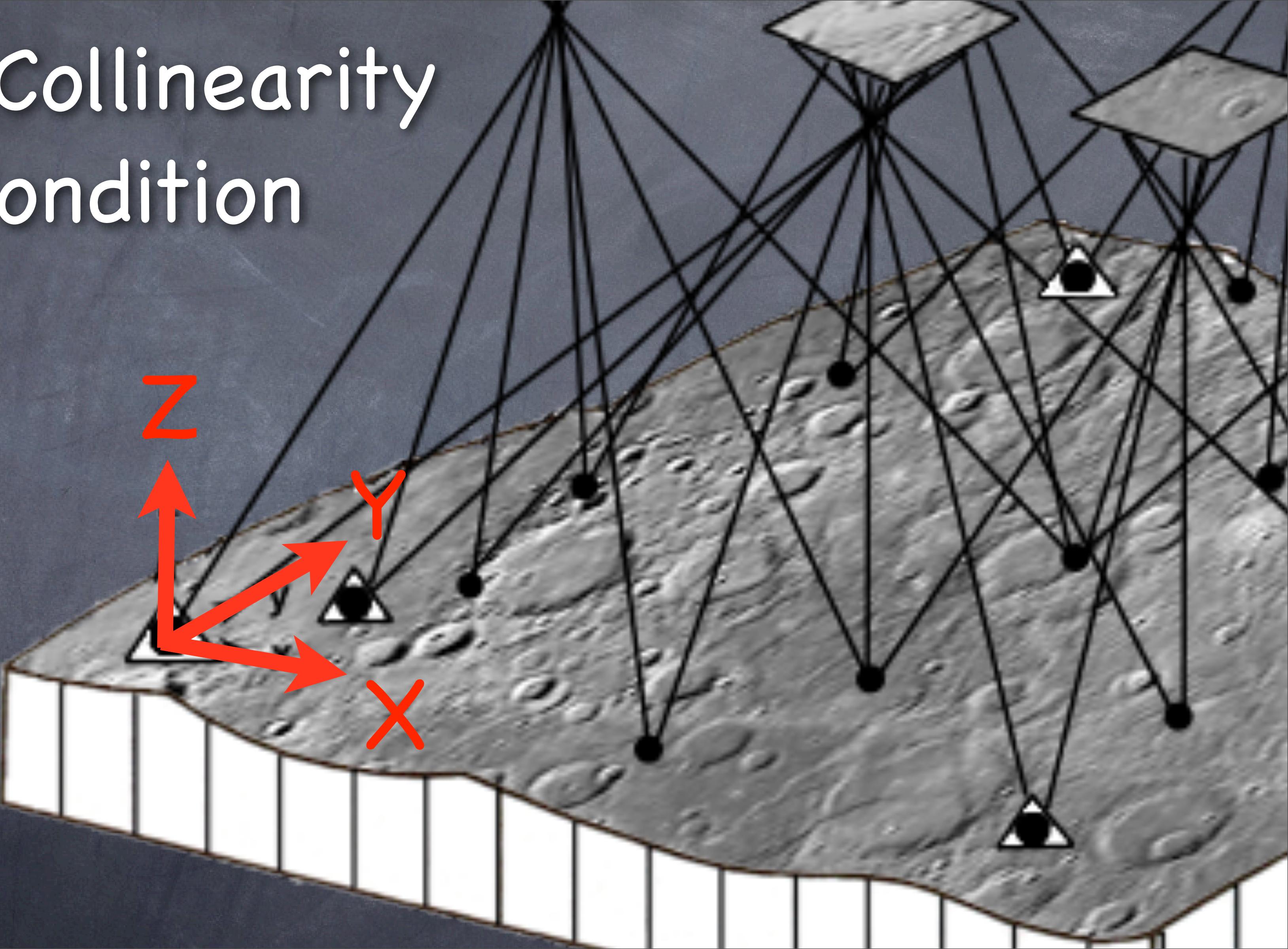
$$x - x_p + \delta_x = -c \frac{m_{11}(X - X_c) + m_{12}(Y - Y_c) + m_{13}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}$$
$$y - y_p + \delta_y = -c \frac{m_{21}(X - X_c) + m_{22}(Y - Y_c) + m_{23}(Z - Z_c)}{m_{31}(X - X_c) + m_{32}(Y - Y_c) + m_{33}(Z - Z_c)}$$

The Collinearity Condition

The Collinearity Condition



The Collinearity Condition



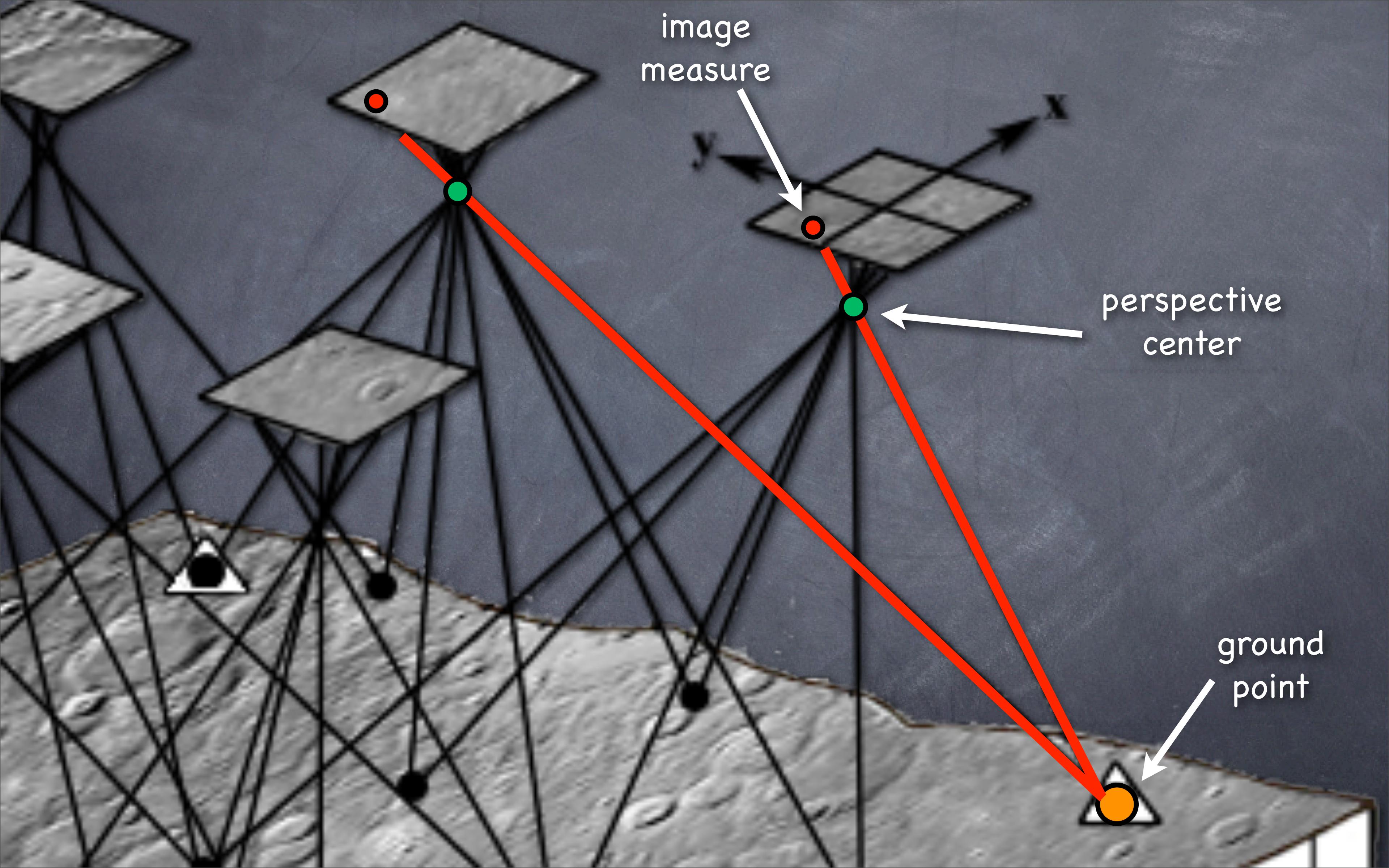


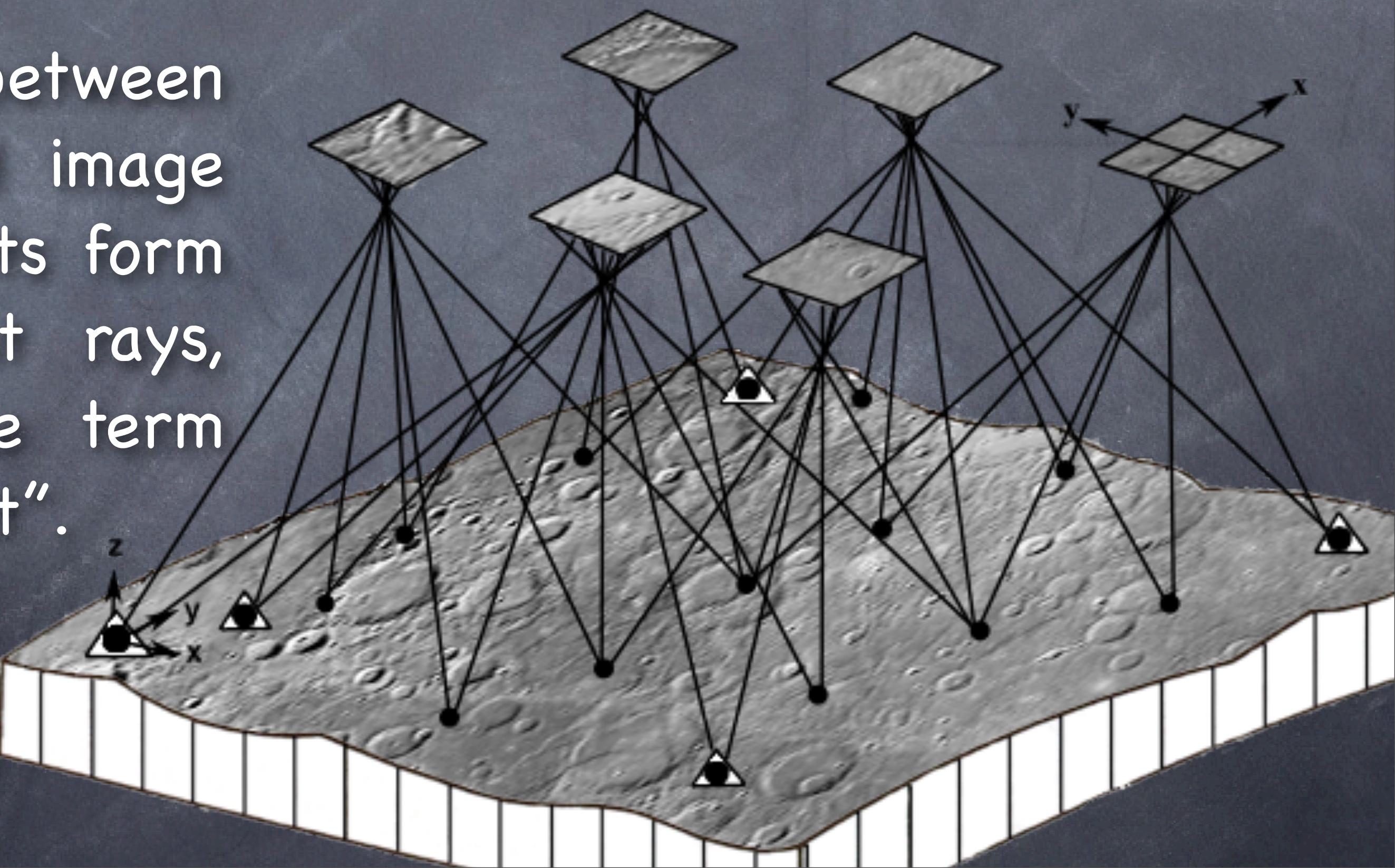
image
measure

perspective
center

ground
point

The Bundle Adjustment

All connections between object points and image space measurements form a bundle of light rays, the origin of the term "Bundle Adjustment".



Jigsaw Interface



Screenshot of the Jigsaw software interface, showing configuration parameters for a landing site analysis.

File Options View Help jigsaw <@prog6>

Files

FROMLIST: LandingSite.lis
HELDLIST: none
CNET: AS15_Sub4_Cleaned_PtsRename_GControl9_LandingSite_binary.net
ONET: out.net

Solve Options

Keep instances of the same observation in different cube files the same
 Solve for local radii of points
 Update cube label
 CholMod (SPARSE)
 SpecialK (dense) (SPECIALK)
 Sparse matrix solver (OLDSPARSE)
 Compute variance-covariance matrix
 Auto-rejection of outliers

OBSERVATIONS

RADIUS
UPDATE
METHOD: CholMod (SPARSE)

ERRORPROPAGATION

OUTLIER_REJECTION
REJECTION_MULTIPLIER: 3.0

Maximum Likelihood Estimation

MODEL1
MAX_MODEL1_C_QUANTILE: 0.5

None: no tier one maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there

MODEL2
MAX_MODEL2_C_QUANTILE: 0.5

None: no tier two maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there
 Welsch: approximates the L2 norm near 0, but then decays exponentially
 Chen: a highly aggresive method that intentionally removes the largest

MODEL3
MAX_MODEL3_C_QUANTILE: 0.5

None: no tier three maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there
 Welsch: approximates the L2 norm near 0, but then decays exponentially
 Chen: a highly aggresive method that intentionally removes the largest

Convergence Criteria

SIGMA0: 1.0e-10
MAXITS: 50

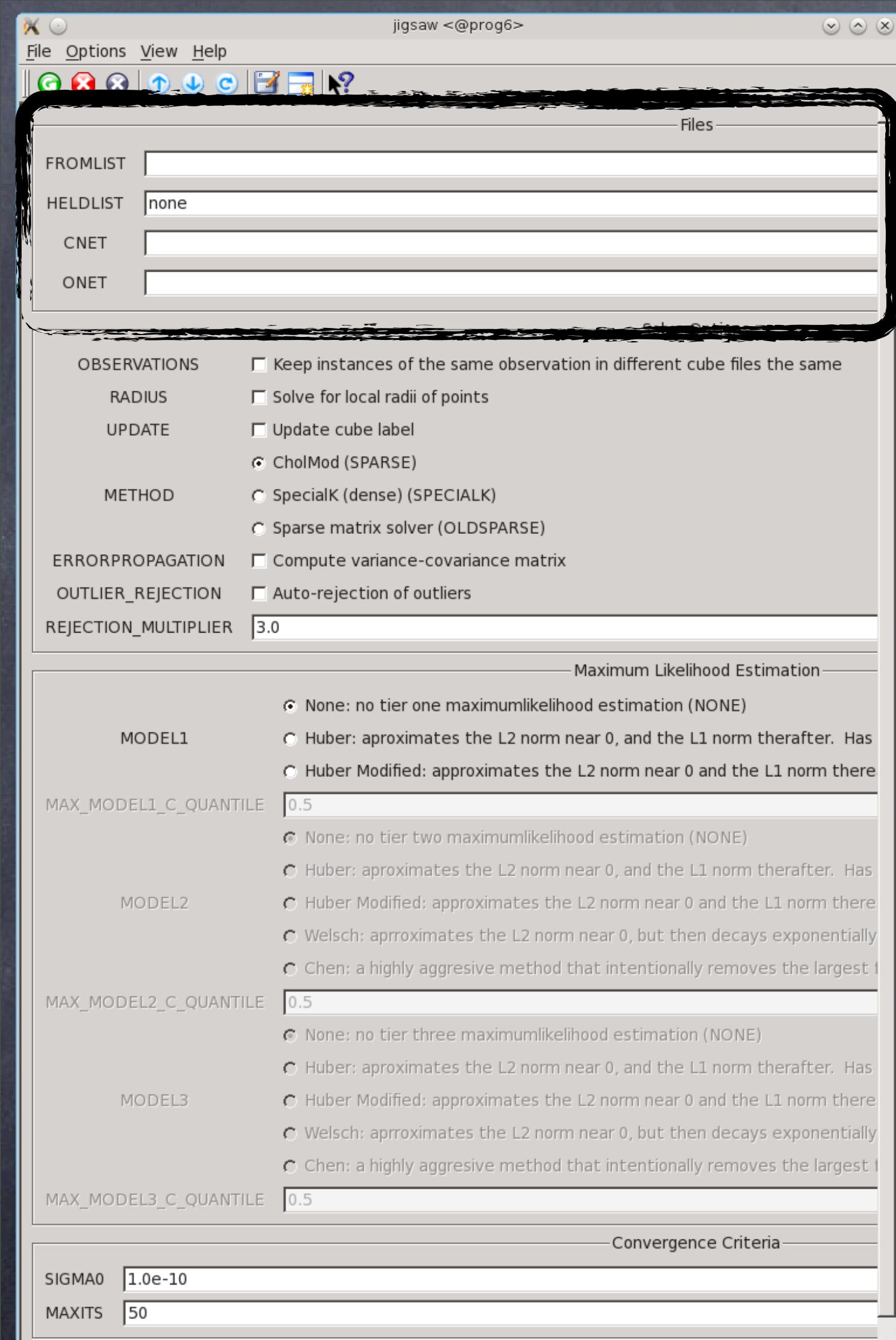
Camera Pointing Options

CKDEGREE: 2
SOLVEDEGREE: 2

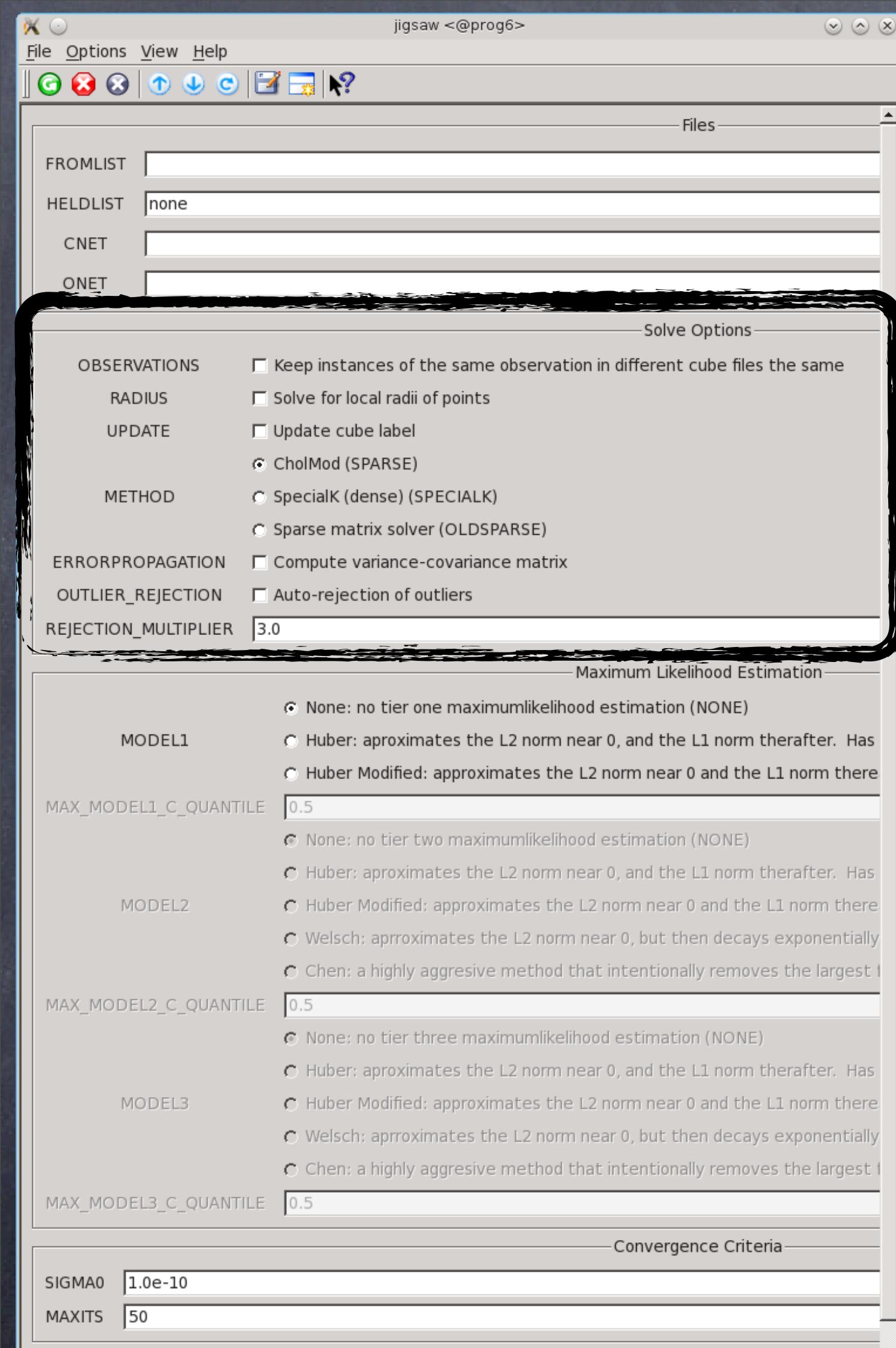
Bottom Status Bar

sigma=10000.0 spacecraft_position_sigma=1000.0 camera_angles_sigma=1.0 file_prefix=AS15_LandingSite
0% Ready

Files

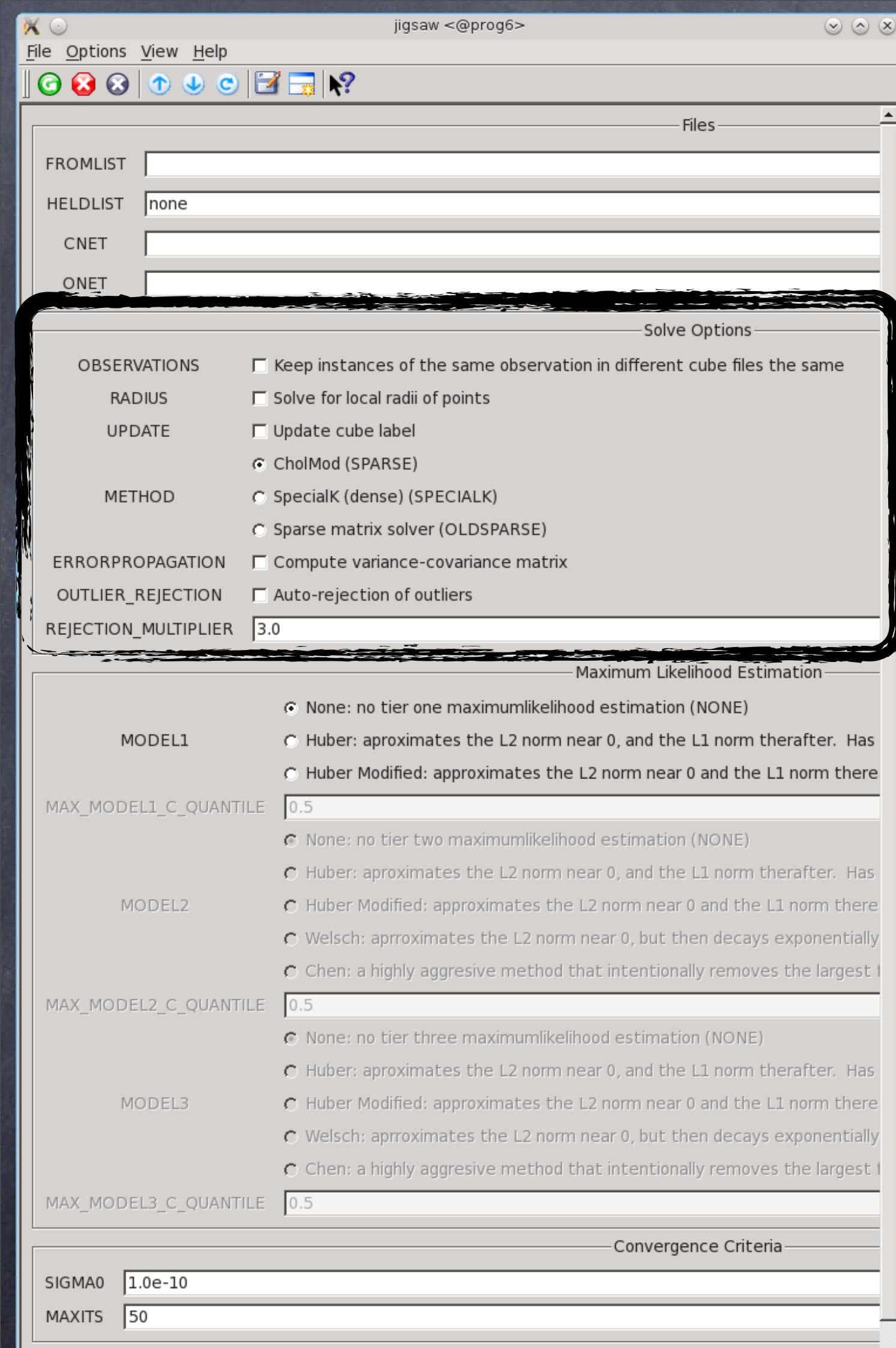


- **FROMLIST**
 - ascii list of images in the control network.
- **HELDLIST**
 - ascii list of images for which position & pointing parameters are to be held fixed.
- **CNET**
 - Input control network.
- **ONET**
 - Output control network.



Solve Options

- **OBSERVATIONS (Observation Mode)**
 - All images within an “observation” have the same position & pointing.
 - Example: LRO NAC L/R
- **RADIUS**
- **UPDATE**
- **METHOD**
 - CholMod (default)
 - SpecialK
 - OLDSPARSE



Solve Options

- ERRORPROPAGATION
 - Generation of parameter uncertainties.
- OUTLIER REJECTION
 - Automated rejection of outliers
- REJECTION_MULTIPLIER
- METHOD
 - CholMod (default)
 - SpecialK
 - OLDSPARSE

jigsaw <@prog6>

File Options View Help

Files

FROMLIST

HELDLIST none

CNET

ONET

Solve Options

OBSERVATIONS Keep instances of the same observation in different cube files the same

RADIUS Solve for local radii of points

UPDATE Update cube label
 CholMod (SPARSE)

METHOD SpecialK (dense) (SPECIALK)
 Sparse matrix solver (OLDSPARSE)

ERRORPROPAGATION Compute variance-covariance matrix

OUTLIER_REJECTION Auto-rejection of outliers

REJECTION_MULTIPLIER 3.0

Maximum Likelihood Estimation

MODEL1 None: no tier one maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there

MAX_MODEL1_C_QUANTILE 0.5

MODEL2 None: no tier two maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there
 Welsch: approximates the L2 norm near 0, but then decays exponentially
 Chen: a highly aggressive method that intentionally removes the largest 1

MAX_MODEL2_C_QUANTILE 0.5

MODEL3 None: no tier three maximumlikelihood estimation (NONE)
 Huber: approximates the L2 norm near 0, and the L1 norm thereafter. Has
 Huber Modified: approximates the L2 norm near 0 and the L1 norm there
 Welsch: approximates the L2 norm near 0, but then decays exponentially
 Chen: a highly aggressive method that intentionally removes the largest 1

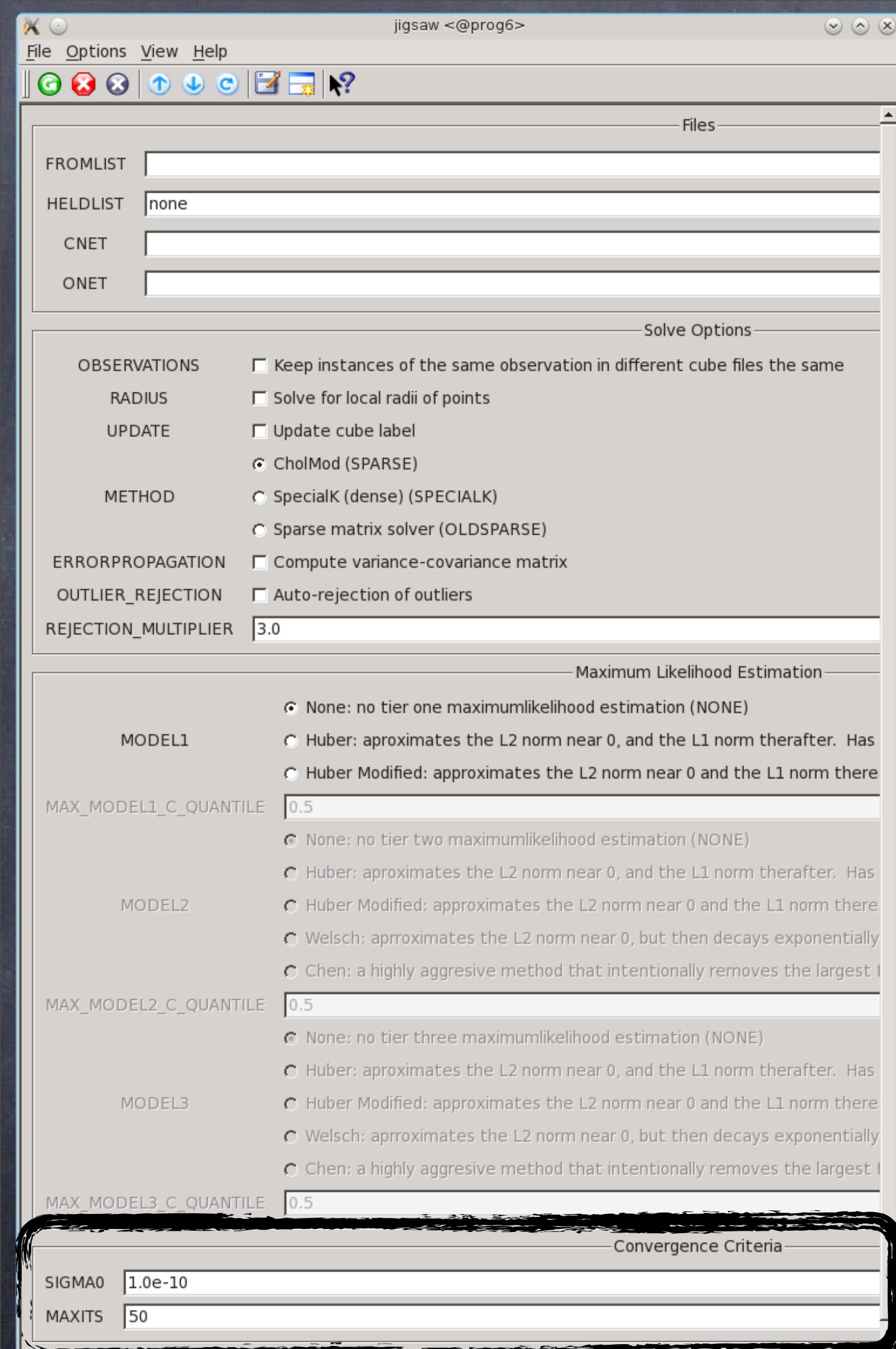
MAX_MODEL3_C_QUANTILE 0.5

SIGMA0 1.0e-10

MAXITS 50

Maximum Likelihood Estimation

SEE NEXT
PRESENTATION!



Convergence Criteria

- **SIGMA0**
 - Convergence occurs when change in Sigma0 in successive iterations is less or equal to this value.
 - Setting to a larger value results in fewer iterations.
- **MAXITS**
 - Adjustment stops (regardless of convergence) upon reaching maximum iterations.

Camera Pointing Options

Camera Pointing Options

CKDEGREE	2
SOLVEDEGREE	2
<input type="radio"/> Don't solve for any camera pointing factors (NONE)	
<input checked="" type="radio"/> Solve for camera angles: right ascension, declination and optionally twist (ANGLES)	
<input type="radio"/> Solve for camera angles AND their angular velocities (VELOCITIES)	
<input type="radio"/> Solve for camera angles, their angular velocities and accelerations (ACCELERATIONS)	
<input type="radio"/> Solve for all coefficients in the polynomials fit to the camera angles. (ALL)	
TWIST	<input checked="" type="checkbox"/> Solve for twist
<input type="radio"/> Don't solve for any spacecraft position parameters (NONE)	
<input type="radio"/> Solve for the spacecraft positions (POSITION)	
<input type="radio"/> Solve for the spacecraft positions and velocities (VELOCITIES)	
<input type="radio"/> Solve for the spacecraft positions, velocities, and accelerations (ACCELERATIONS)	
Parameter Uncertainties	
POINT_LATITUDE_SIGMA	none
POINT_LONGITUDE_SIGMA	none
POINT_RADIUS_SIGMA	none
SPACECRAFT_POSITION_SIGMA	none
SPACECRAFT_VELOCITY_SIGMA	none
SPACECRAFT_ACCELERATION_SIGMA	none
CAMERA_ANGLES_SIGMA	none
CAMERA_ANGULAR_VELOCITY_SIGMA	none
CAMERA_ANGULAR_ACCELERATION_SIGMA	none
Output Options	
FILE_PREFIX	none
BUNDLEOUT_TXT	<input checked="" type="checkbox"/> Standard bundle output file - bundleout.txt
OUTPUT_CSV	<input checked="" type="checkbox"/> Outputs point and image data (body-fixed) to csv file - bundleout_points.csv
RESIDUALS_CSV	<input checked="" type="checkbox"/> Outputs image coordinate residuals to csv file - residuals.csv

(RGB) jigsaw Konsole Making_A_Mosaic.txt - KW BundleAdjust.c

- CKDEGREE

- Degree of polynomial for computation of initial values (time-dependent sensors, e.g. line scan).

Camera Pointing Options

- SOLVEDEGREE

- Degree of polynomial in adjustment.

- e.g., degree of 2 \Rightarrow solving for 3 polynomial coefficients.

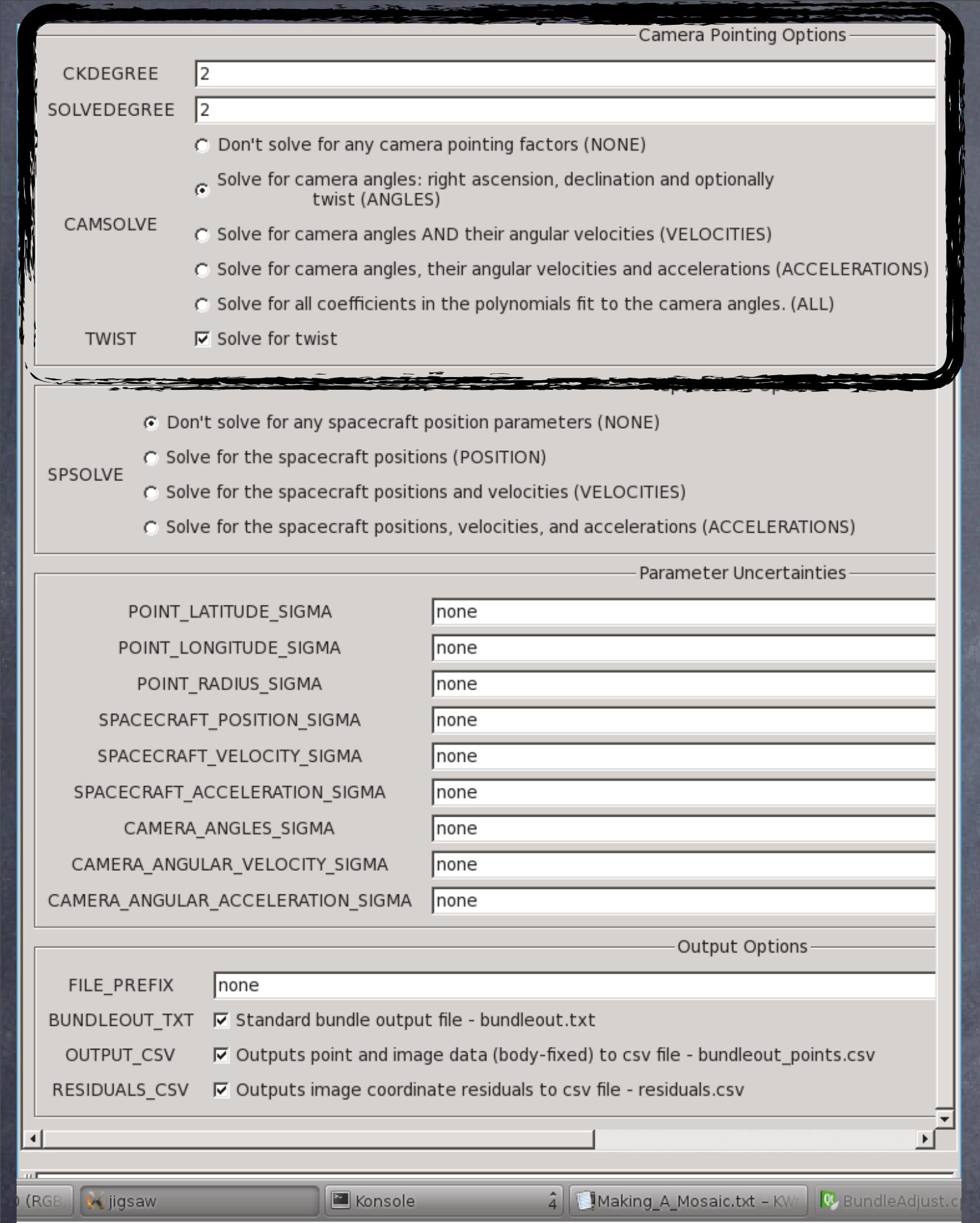
- $at^2 + bt + c$; where

- t = time

- a = angular acceleration

- b = angular velocity

- c = angle



Camera Pointing Options

Camera Pointing Options

CKDEGREE	2
SOLVEDEGREE	2
<input type="radio"/> Don't solve for any camera pointing factors (NONE)	
<input checked="" type="radio"/> Solve for camera angles: right ascension, declination and optionally twist (ANGLES)	
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<input type="radio"/> Solve for camera angles, their angular velocities and accelerations (ACCELERATIONS)	
<input type="radio"/> Solve for all coefficients in the polynomials fit to the camera angles. (ALL)	
TWIST	<input checked="" type="checkbox"/> Solve for twist
<input type="radio"/> Don't solve for any spacecraft position parameters (NONE)	
<input type="radio"/> Solve for the spacecraft positions (POSITION)	
<input type="radio"/> Solve for the spacecraft positions and velocities (VELOCITIES)	
<input type="radio"/> Solve for the spacecraft positions, velocities, and accelerations (ACCELERATIONS)	
Parameter Uncertainties	
POINT_LATITUDE_SIGMA	none
POINT_LONGITUDE_SIGMA	none
POINT_RADIUS_SIGMA	none
SPACECRAFT_POSITION_SIGMA	none
SPACECRAFT_VELOCITY_SIGMA	none
SPACECRAFT_ACCELERATION_SIGMA	none
CAMERA_ANGLES_SIGMA	none
CAMERA_ANGULAR_VELOCITY_SIGMA	none
CAMERA_ANGULAR_ACCELERATION_SIGMA	none
Output Options	
FILE_PREFIX	none
BUNDLEOUT_TXT	<input checked="" type="checkbox"/> Standard bundle output file - bundleout.txt
OUTPUT_CSV	<input checked="" type="checkbox"/> Outputs point and image data (body-fixed) to csv file - bundleout_points.csv
RESIDUALS_CSV	<input checked="" type="checkbox"/> Outputs image coordinate residuals to csv file - residuals.csv

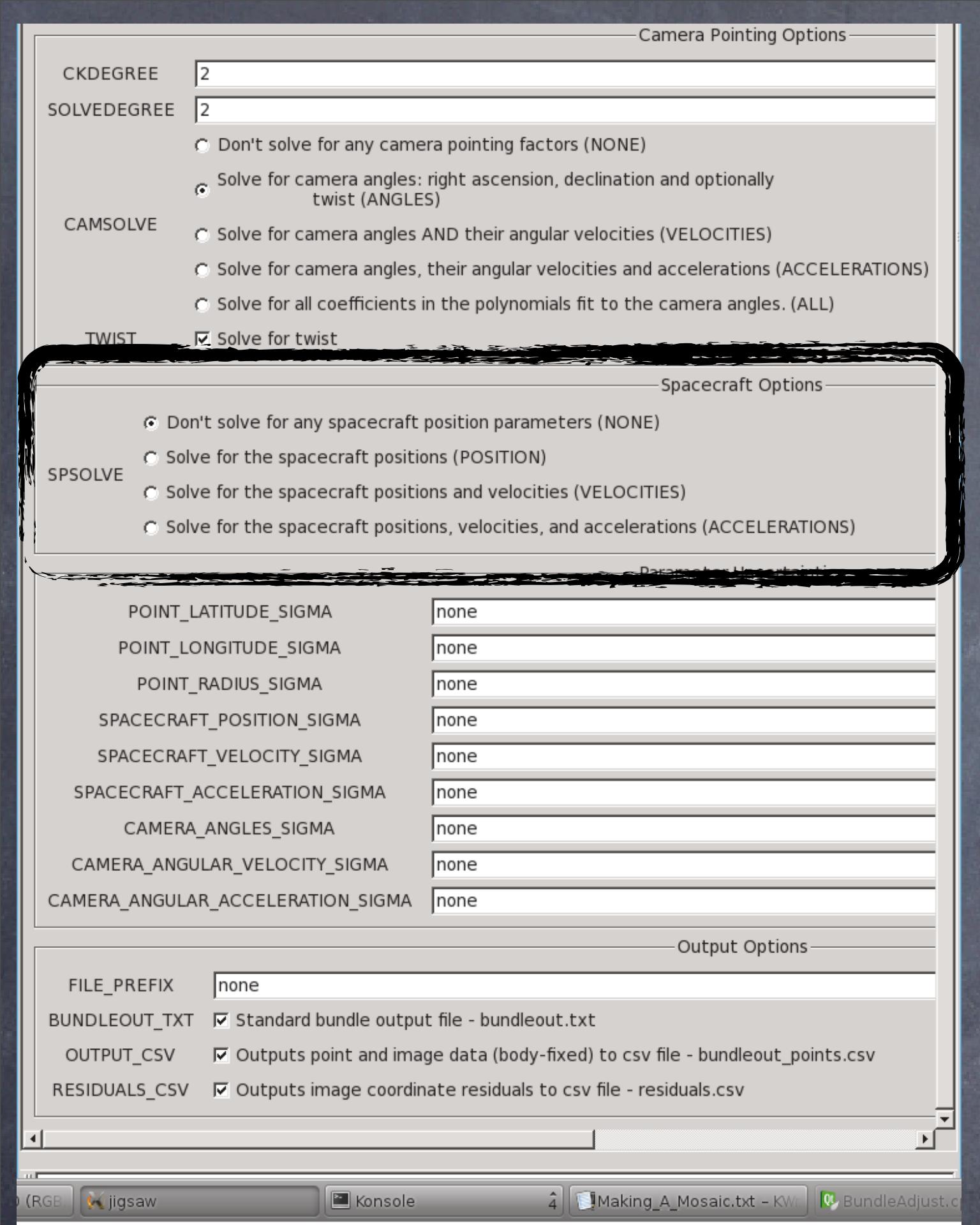
- CAMSOLVE

- Selection of angular parameters in the adjustment.

- TWIST

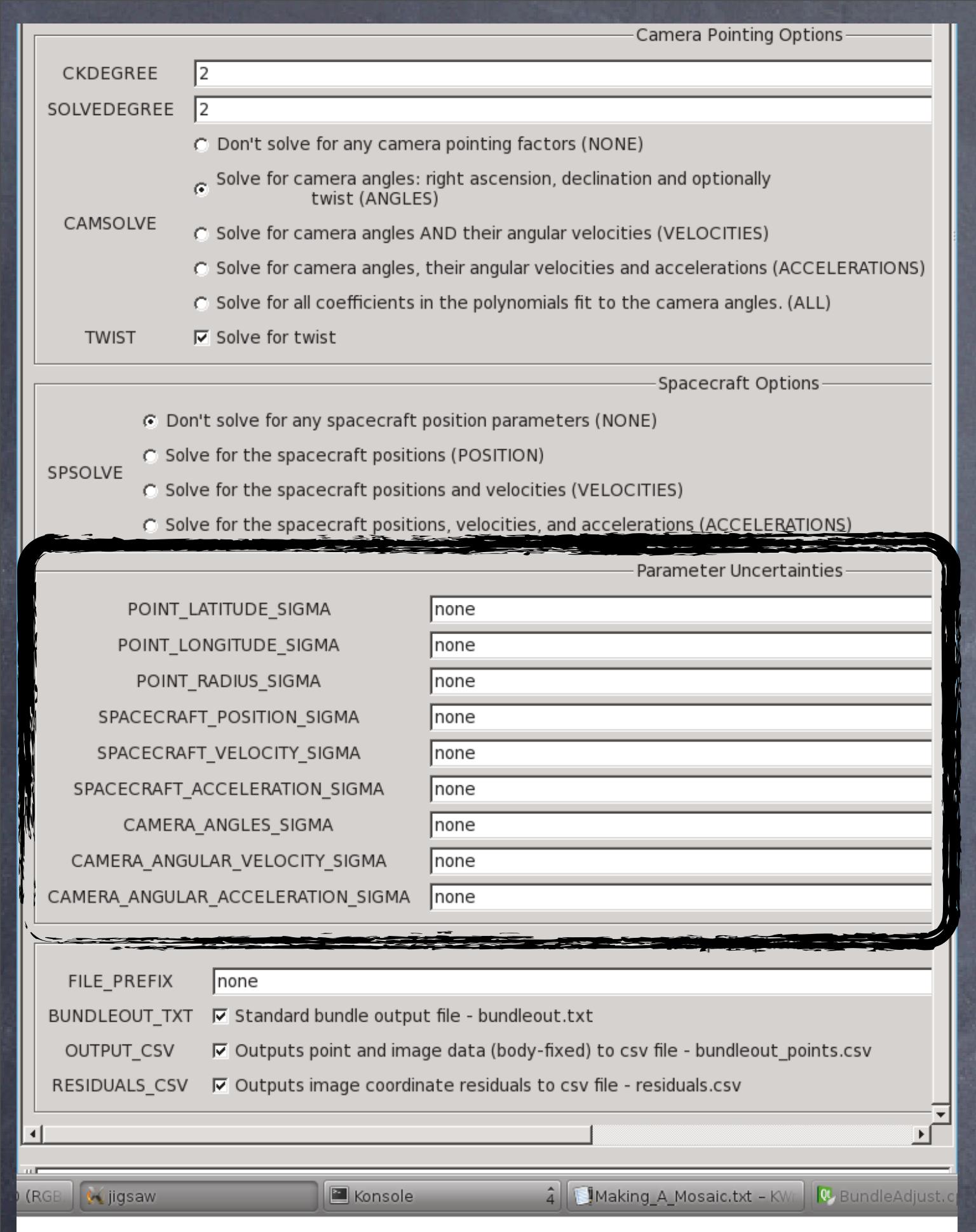
Spacecraft Options

- SPSOLVE
 - Selection of spacecraft position parameters in the adjustment.
- NOTE: capability to solve for coefficients of higher degree polynomials (as with pointing) is coming soon.



Global Parameter Uncertainties

- Global ‘a priori’ uncertainties for ground point coordinates, position, & pointing parameters.
- Parameter weights in the adjustment are computed from uncertainties.
- Point sigmas in control network take precedence.



Output Options

- FILE_PREFIX
- BUNDLEOUT_TXT
- Standard report “bundleout.txt” contains...
- adjusted parameters
- adjusted parameter uncertainties (if error propagation is on)
- Statistics
- OUTPUT_CSV
 - “bundleout_images.csv”
 - “bundleout_points.csv”

Camera Pointing Options

CKDEGREE	2
SOLVEDEGREE	2
<input type="radio"/> Don't solve for any camera pointing factors (NONE)	
<input checked="" type="radio"/> Solve for camera angles: right ascension, declination and optionally twist (ANGLES)	
<input type="radio"/> Solve for camera angles AND their angular velocities (VELOCITIES)	
<input type="radio"/> Solve for camera angles, their angular velocities and accelerations (ACCELERATIONS)	
<input type="radio"/> Solve for all coefficients in the polynomials fit to the camera angles. (ALL)	
TWIST	<input checked="" type="checkbox"/> Solve for twist

Spacecraft Options

<input checked="" type="radio"/> Don't solve for any spacecraft position parameters (NONE)	
<input type="radio"/> Solve for the spacecraft positions (POSITION)	
<input type="radio"/> Solve for the spacecraft positions and velocities (VELOCITIES)	
<input type="radio"/> Solve for the spacecraft positions, velocities, and accelerations (ACCELERATIONS)	

Parameter Uncertainties

POINT_LATITUDE_SIGMA	none
POINT_LONGITUDE_SIGMA	none
POINT_RADIUS_SIGMA	none
SPACECRAFT_POSITION_SIGMA	none
SPACECRAFT_VELOCITY_SIGMA	none
SPACECRAFT_ACCELERATION_SIGMA	none
CAMERA_ANGLES_SIGMA	none
CAMERA_ANGULAR_VELOCITY_SIGMA	none
CAMERA_ANGULAR_ACCELERATION_SIGMA	none

Output Options

FILE_PREFIX	none
BUNDLEOUT_TXT	<input checked="" type="checkbox"/> Standard bundle output file - bundleout.txt
OUTPUT_CSV	<input checked="" type="checkbox"/> Outputs point and image data (body-fixed) to csv file - bundleout_points.csv
RESIDUALS_CSV	<input checked="" type="checkbox"/> Outputs image coordinate residuals to csv file - residuals.csv

Output Options

- RESIDUALS_CSV
- “residuals_images.csv”

Camera Pointing Options

CKDEGREE	2
SOLVEDEGREE	2
<input type="radio"/> Don't solve for any camera pointing factors (NONE)	
<input checked="" type="radio"/> Solve for camera angles: right ascension, declination and optionally twist (ANGLES)	
<input type="radio"/> Solve for camera angles AND their angular velocities (VELOCITIES)	
<input type="radio"/> Solve for camera angles, their angular velocities and accelerations (ACCELERATIONS)	
<input type="radio"/> Solve for all coefficients in the polynomials fit to the camera angles. (ALL)	
TWIST	<input checked="" type="checkbox"/> Solve for twist

Spacecraft Options

<input checked="" type="radio"/> Don't solve for any spacecraft position parameters (NONE)	
<input type="radio"/> Solve for the spacecraft positions (POSITION)	
<input type="radio"/> Solve for the spacecraft positions and velocities (VELOCITIES)	
<input type="radio"/> Solve for the spacecraft positions, velocities, and accelerations (ACCELERATIONS)	

Parameter Uncertainties

POINT_LATITUDE_SIGMA	none
POINT_LONGITUDE_SIGMA	none
POINT_RADIUS_SIGMA	none
SPACECRAFT_POSITION_SIGMA	none
SPACECRAFT_VELOCITY_SIGMA	none
SPACECRAFT_ACCELERATION_SIGMA	none
CAMERA_ANGLES_SIGMA	none
CAMERA_ANGULAR_VELOCITY_SIGMA	none
CAMERA_ANGULAR_ACCELERATION_SIGMA	none

Output Options

FILE_PREFIX	none
BUNDLEOUT_TXT	<input checked="" type="checkbox"/> Standard bundle output file - bundleout.txt
OUTPUT_CSV	<input checked="" type="checkbox"/> Outputs point and image data (body-fixed) to csv file - bundleout_points.csv
RESIDUALS_CSV	<input checked="" type="checkbox"/> Outputs image coordinate residuals to csv file - residuals.csv

Output

Run Time: 2012-06-22T15:39:42
Network Filename: AS15_Sub4_Cleaned_PtsRename_GControl9_LandingSite_binary.net
Network Id: LandingSite
Network Description: cnetextracted
Target: Moon

Linear Units: kilometers
Angular Units: decimal degrees

INPUT: SOLVE OPTIONS

OBSERVATIONS: OFF
RADIUS: ON
SOLUTION TYPE: SPARSE
ERROR PROPAGATION: ON
OUTLIER REJECTION: ON
ECTION MULTIPLIER: 3.000000

MAXIMUM LIKELIHOOD ESTIMATION

Tier 0 Enabled: FALSE
Tier 1 Enabled: FALSE
Tier 2 Enabled: FALSE

INPUT: CONVERGENCE CRITERIA

SIGMA0: 1.000000e-10
MAXIMUM ITERATIONS: 50

INPUT: CAMERA POINTING OPTIONS

CAMSOLVE: ANGLES
TWIST: ON

INPUT: SPACECRAFT OPTIONS

SPSOLVE: POSITION

SOLVE: POSITION
INPUT: GLOBAL IMAGE PARAMETER UNCERTAINTIES

POINT LATITUDE SIGMA: N/A
POINT LONGITUDE SIGMA: N/A
POINT RADIUS SIGMA: N/A
SPACECRAFT POSITION SIGMA: 500.000000 (meters)
SPACECRAFT VELOCITY SIGMA: N/A
ACECRAFT ACCELERATION SIGMA: N/A
CAMERA ANGLES SIGMA: 3.000000 (dd)
MERA ANGULAR VELOCITY SIGMA: N/A
ANGULAR ACCELERATION SIGMA: N/A

JIGSAW: RESULTS

<i>Images:</i>	5
<i>Points:</i>	395
<i>Total Measures:</i>	950
<i>Total Observations:</i>	1900
<i>Good Observations:</i>	1844
<i>Rejected Observations:</i>	56
<i>efined Point Parameters:</i>	99
<i>ined Image Parameters:</i>	30
<i>Unknowns:</i>	1215
<i>Degrees of Freedom:</i>	758
<i>Convergence Criteria:</i>	$1e-10(\Sigma\sigma_0)$
<i>Iterations:</i>	5

```
Iterations: 6
Sigma0: 0.55322850893198283195
Error Propagation Elapsed Time: 0.0500 (seconds)
Total Elapsed Time: 0.4400 (seconds)
```

Residual Percentiles:		
Percentile	1:	-1.486
Percentile	2:	-1.118
Percentile	3:	-0.868
Percentile	4:	-0.756
Percentile	5:	-0.658
Percentile	6:	-0.602
Percentile	7:	-0.545
Percentile	8:	-0.498
Percentile	9:	-0.468

Percentile	34:	-0.014
Percentile	35:	-0.010
Percentile	36:	-0.008
Percentile	37:	-0.006
Percentile	38:	-0.004
Percentile	39:	-0.003
Percentile	40:	-0.003
Percentile	41:	-

Examining the Results

Things to look for...

- Sigma0: ideally close to 1.0.
- Examine measure residuals for outliers.
- Unreasonably high adjusted parameter uncertainties.
- Magnitude of the corrections to weighted parameters.

Potential problems to consider...

- Poor a priori parameter values
 - Bad SPICE? Problem DEM?
- Measurement errors - Wrong feature? Wrong point label?
- Improperly weighted point coordinates?
- Weak image geometry?
- Number and geometry of image measurements for a ground point
- Camera model problem?