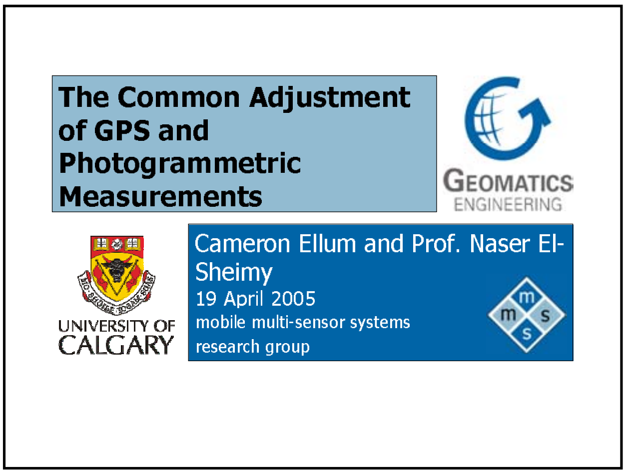

# The Common Adjustment of GPS and Photogrammetric Measurements

Cameron Ellum and Prof. Naser El-Sheimy
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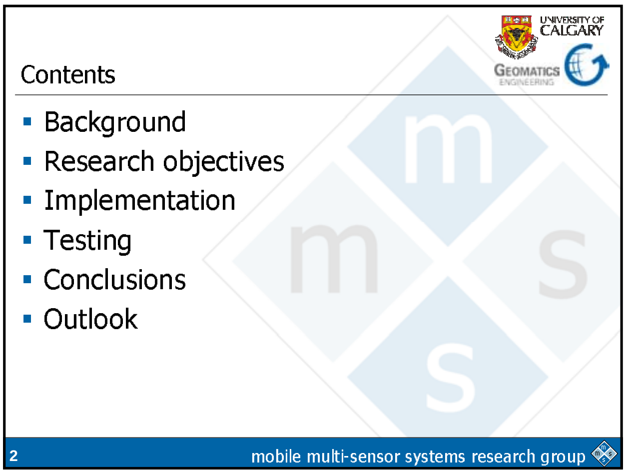
mobile multi-sensor systems research group



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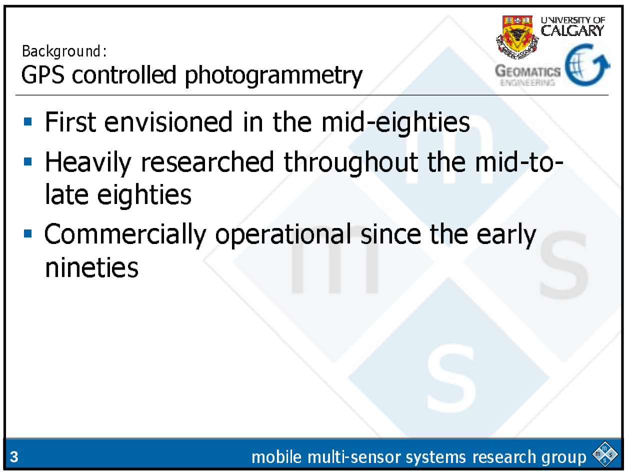
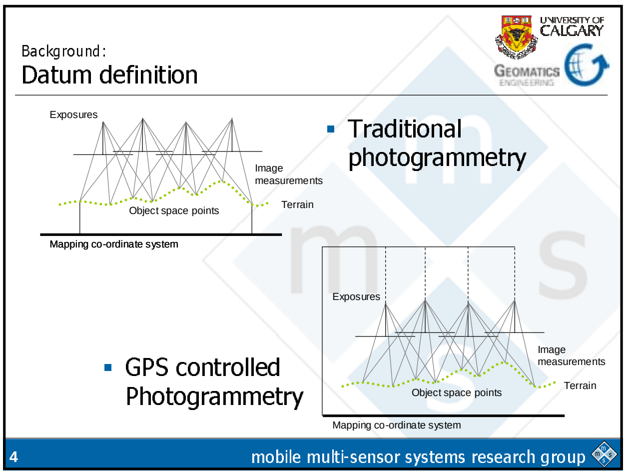


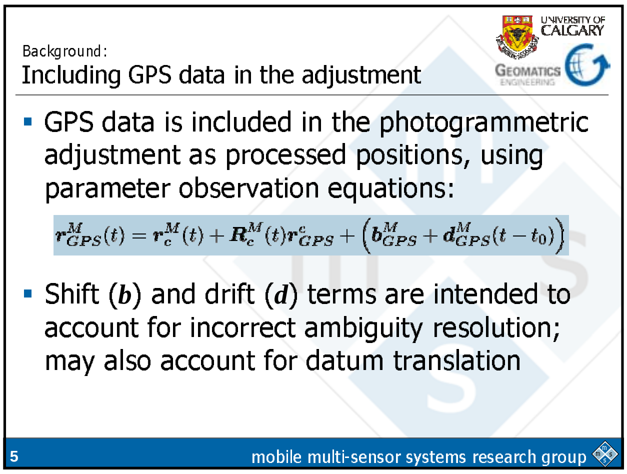
Background:
## GPS controlled photogrammetry

- First envisioned in the mid-eighties
- Heavily researched throughout the mid-to-late eighties
- Commercially operational since the early nineties



Background:
## Datum definition

- Traditional photogrammetry
- GPS controlled Photogrammetry

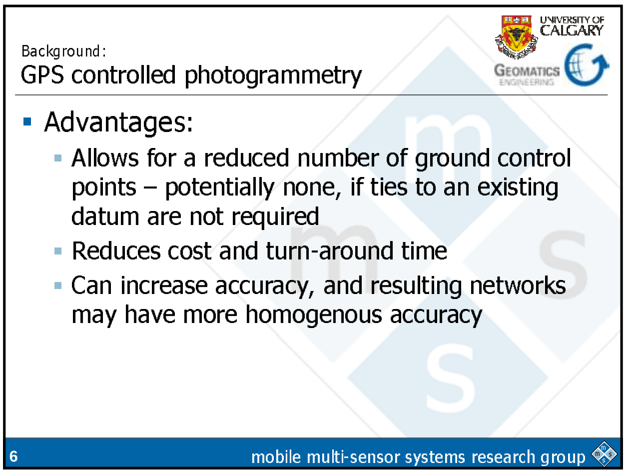


Background:
## Including GPS data in the adjustment

- GPS data is included in the photogrammetric adjustment as processed positions, using parameter observation equations:

$$\boldsymbol{r}^M_{GPS}(t) = \boldsymbol{r}^M_c(t) + \boldsymbol{R}^M_c(t)\boldsymbol{r}^c_{GPS} + \left(\boldsymbol{b}^M_{GPS} + \boldsymbol{d}^M_{GPS}(t - t_0)\right)$$

- Shift ($\boldsymbol{b}$) and drift ($\boldsymbol{d}$) terms are intended to account for incorrect ambiguity resolution; may also account for datum translation



Background:
## GPS controlled photogrammetry

- Advantages:
  - Allows for a reduced number of ground control points – potentially none, if ties to an existing datum are not required
  - Reduces cost and turn-around time
  - Can increase accuracy, and resulting networks may have more homogenous accuracy

Background:

## Limitations of current technique

- The sharing of information between the photogrammetric and navigation processors is strictly one-way. The navigation processing stream does not benefit from the photogrammetric data.
- Current integration strategies have always presupposed differential GPS. The possibilities of undifferenced GPS have not been examined.
- The traditional "shift-and-drift" approach for including GPS data assumes that incorrect ambiguity resolution manifests itself as a linear error. In reality, this is not the case.

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Research Objectives:

## Combined adjustment

- Combine the raw GPS measurements and photogrammetric measurements in a single adjustment
  - Enables GPS data to be used even when less than four satellites are visible
  - Simplified, single-step processing
  - Ultimate goal: utilise photogrammetric network to aid GPS ambiguity resolution
  - Hopefully, will improve accuracy and, more importantly, reliability

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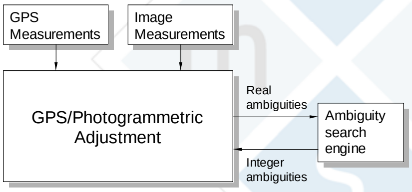
Implementation:

## Combined adjustment overview

- Undifferenced or double-difference ranges
- Code ranges or carrier phase ranges



GPS Measurements

Image Measurements

GPS/Photogrammetric Adjustment

Real ambiguities

Ambiguity search engine

Integer ambiguities

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Implementation:

## Modified collinearity equations

- Implementation of the combined adjustment is made easier by recasting the collinearity equations so that they – like the GPS observation equations – are explicitly functions of the GPS positions:

$$x_p = -c\frac{r_{11}X^M_{GPS/P} + r_{12}Y^M_{GPS/P} + r_{13}Z^M_{GPS/P} + x^c_{GPS}}{r_{31}X^M_{GPS/P} + r_{32}Y^M_{GPS/P} + r_{33}Z^M_{GPS/P} + z^c_{GPS}}$$

$$y_p = -c\frac{r_{21}X^M_{GPS/P} + r_{22}Y^M_{GPS/P} + r_{23}Z^M_{GPS/P} + y^c_{GPS}}{r_{31}X^M_{GPS/P} + r_{32}Y^M_{GPS/P} + r_{33}Z^M_{GPS/P} + z^c_{GPS}}$$

- Additional advantages:
  - Simpler parameter observation equations: $\mathbf{0} = \mathbf{r}^M_{GPS} - \hat{\mathbf{r}}^M_{GPS}$
  - GPS positions can directly be used as initial approximates
  - Multiple-camera systems only need a single position solved for per epoch

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Implementation:

## GPS Observation Equations

- Undifferenced code range observation equation:

$$p = |\boldsymbol{r}_{rx/sv}| + c\Delta t_{rx}$$

  - Receiver clock offsets are added to the adjustment as additional parameters
- Double-difference code range observation equation

$$\Delta\nabla p = \left(|\boldsymbol{r}_{m/b}| - |\boldsymbol{r}_{m/i}|\right) - \left(|\boldsymbol{r}_{r/b}| - |\boldsymbol{r}_{r/i}|\right)$$

  - No additional parameters
- Double-difference carrier-phase observation equation

$$\Delta\nabla\Phi = \left(|\boldsymbol{r}_{m/b}| - |\boldsymbol{r}_{m/i}|\right) - \left(|\boldsymbol{r}_{r/b}| - |\boldsymbol{r}_{r/i}|\right) + \Delta\nabla N$$

  - Double-difference ambiguities are added to the adjustment as additional parameters

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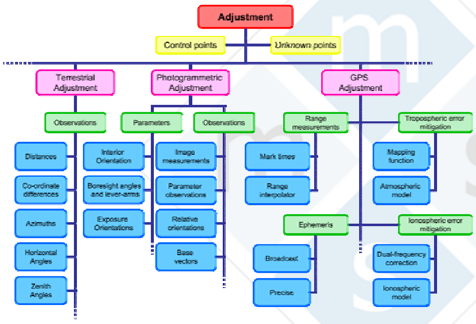
Implementation:

## Combined adjustment framework



Adjustment

Control points

Unknown points

Terrestrial Adjustment

Photogrammetric Adjustment

GPS Adjustment

Observations

Parameters

Observations

Range measurements

Tropospheric error mitigation

Distances

Co-ordinate differences

Azimuths

Horizontal Angles

Zenith Angles

Interior Orientation

Boresight angles and lever-arms

Exposure Orientations

Image measurements

Parameter observations

Relative orientations

Base vectors

Mark times

Range interpolator

Mapping function

Atmospheric model

Ephemeris

Ionospheric error mitigation

Broadcast

Precise

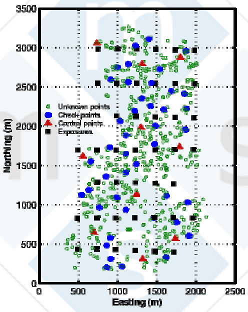
Dual-frequency correction

Ionospheric model

Testing:

## Data set description

- Aerial photogrammetric block
  - 42 images, 7 flight lines
  - 4096 × 4069 pixels
  - Field of view ≈ 37°
  - Flying height ≈ 900m
  - Sidelap ≈ 30%
  - Endlap ≈ 60%
  - 53 control/check points



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Testing:

## Nominal scenarios

- Ground controlled network

| | Horiz. | Vert. |
|---|---|---|
| Mean | 0.20 m | -0.04 m |
| Std. dev. | **0.13 m** | **0.35 m** |

- Double-difference carrier phase exposure station positions

| | Horiz. | Vert. |
|---|---|---|
| Mean | 0.28 m | -40.16 m |
| Std. dev. | **0.21 m** | **0.37 m** |

  - Noise level of ≈15cm horizontal, ≈35cm vertical

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Testing:

## Smoothed, undifferenced code ranges

- Combined adjustment

| | Horiz. | Vert. |
|---|---|---|
| mean | 4.11 m | -53.65 m |
| std. dev. | **0.40 m** | **1.34 m** |

- Position observations

| | Horiz. | Vert. |
|---|---|---|
| mean | 4.11 m | -53.18 m |
| std. dev. | **0.78 m** | **1.42 m** |

  - Same data, slightly improved results

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Testing:

## Smoothed, double-difference code-ranges

- Position observations

| | Horiz. | Vert. |
|---|---|---|
| mean | 0.36 m | -40.78 m |
| std. dev. | **0.17 m** | **0.38 m** |

- Combined adjustment

| | Horiz. | Vert. |
|---|---|---|
| mean | 0.31 m | -40.73 m |
| std. dev. | **0.15 m** | **0.36 m** |

  - Virtually the same
  - Close to best results possible from the network

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## Conclusions

- Optimist
  - With undifferenced observations, accuracy improves
- Pessimist
  - With double-differences, no change
- Realist
  - Inconclusive, more testing required
- Results are sensitive to relative weights on image measurements and GPS ranges

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Outlook:

## Combined adjustment

- Ultimate goals:
  - Improve reliability
  - GPS ambiguity resolution
- A negligible or non-existent accuracy increase is okay, if the above two goals can be met

Outlook:

## Information sharing between processors

- Two-way sharing of information between a photogrammetric adjustment and a kinematic GPS processor
  - Kalman-filter-based kinematic GPS processor will provide positions to the photogrammetric adjustment
  - Photogrammetric adjustment will, in turn, provide position updates (and covariance) to the Kalman filter

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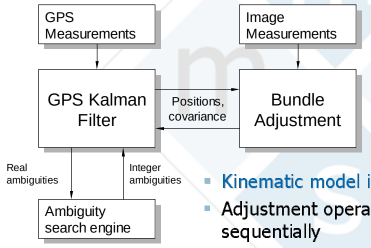
Outlook:

## Information sharing between processors

- Navigation filter is aided by the photogrammetric adjustment



- Kinematic model is retained
- Adjustment operates sequentially

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## Acknowledgements

- Test data provided by Applanix Corporation
- Financial support from:
  - Killam Trusts
  - NSERC

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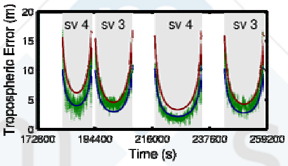
Implementation:

## Atmospheric error mitigation

- Troposphere
  - UNB3 zenith delay model
  - Neill mapping function



- Ionosphere
  - Not mitigated because of resulting increase in noise
- Orbit and clock
  - Not mitigated because it primarily introduces a bias, and because it differences out in the double-difference observations

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Implementation:

## Combined adjustment software

- Some statistics:
  - Lines of code > 83,000
  - Existing GPS/INS processor < 33,000
- Goal: maintainability and extensibility
- Adjustment program has been divided into individual adjustment modules connected in a hierarchical fashion
  - Photogrammetric adjustment
  - GPS adjustment
  - Terrestrial network adjustment

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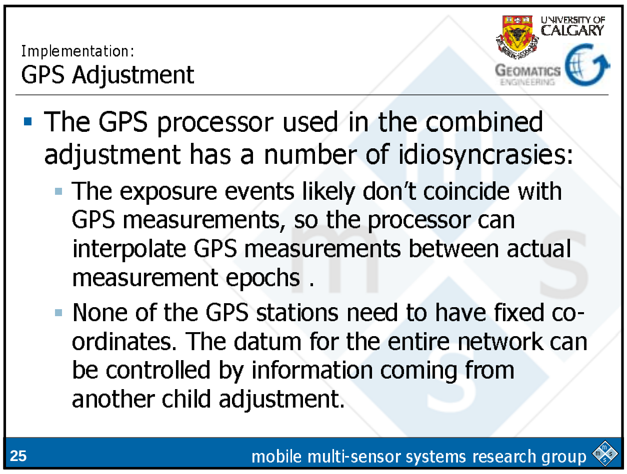
Implementation:

## Combined adjustment framework

- Each sub-adjustment makes a few generic routines available to the parent adjustment
- The parent adjustment then only has to call the routines in the appropriate order
- The adjustments inherit a generic behaviour from a common base, or, when necessary, implement their own custom behaviour.
- Program is more maintainable:
  - Individual adjustments can be tested and debugged in isolation.
  - Inheritance and polymorphism results in less code



Implementation:

## GPS Adjustment

- The GPS processor used in the combined adjustment has a number of idiosyncrasies:
  - The exposure events likely don't coincide with GPS measurements, so the processor can interpolate GPS measurements between actual measurement epochs .
  - None of the GPS stations need to have fixed co-ordinates. The datum for the entire network can be controlled by information coming from another child adjustment.