Reliability in Direct Georeferencing:
Beyond the Achilles' Heel of Modern Airborne Mapping

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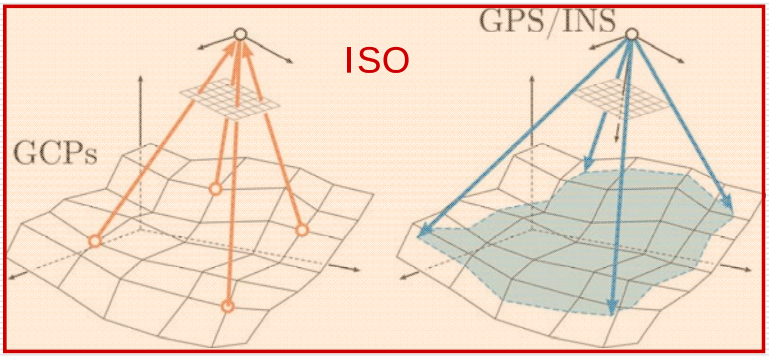
Photogrammetric Week 2007
Stuttgart



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Direct georeferencing – old or new?

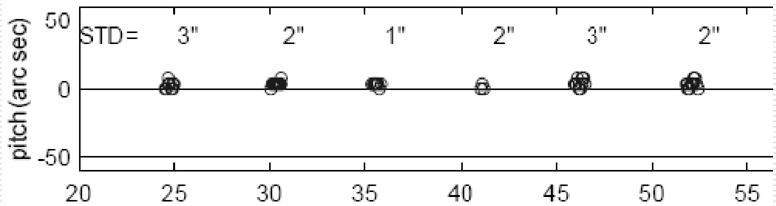
1st decade of DG:

- +10 years in industry, bit longer in academia
- improved mapping with passive sensors (cameras)
- enabled mapping with active sensors (LiDAR, SAR)

2nd decade of DG: What are the new goals?

- smaller & cheaper
- higher accuracy?
- faster?
- more reliable?

1995: Orientation differences AT-GPS/INS



Skaloud, J., Cramer, M., Schwarz, K.P., 1996.
Exterior Orientation by Direct Measurements of Camera Position &Attitude,
XVII. ISPRS Congress, Vienna, July 9-19

motivation for reliability …

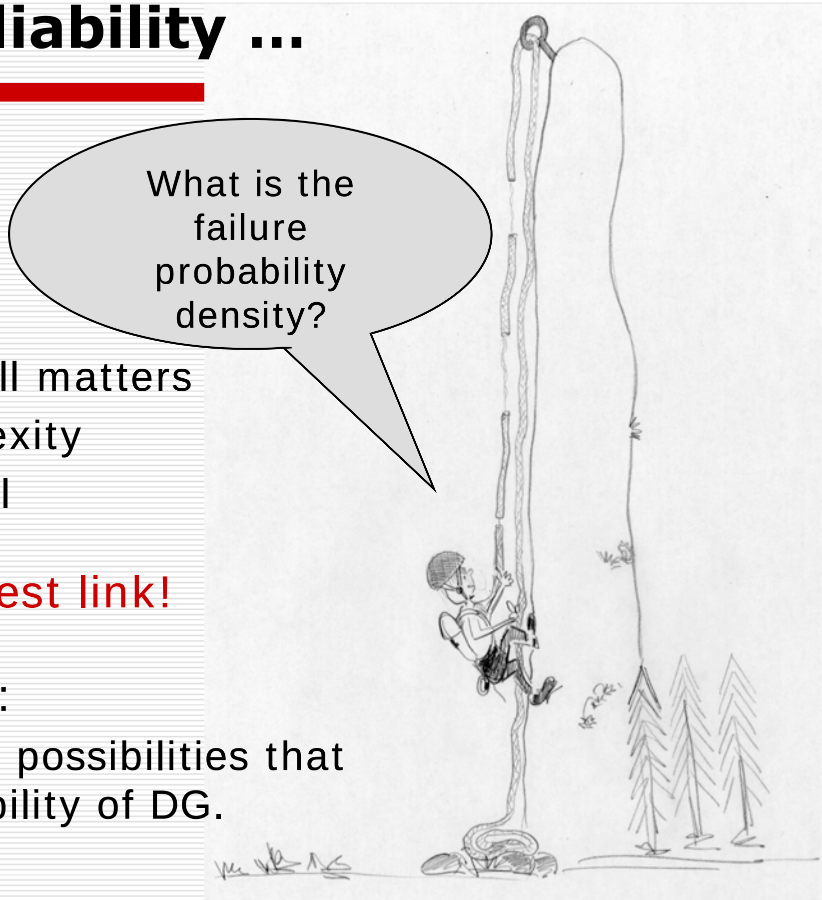
Concept of DG :

- long chain of info, all matters
- considerable complexity
- limited ‘user’ control

DG is strong as its weakest link!

Motivation for this study:

- Provide synthesis of possibilities that could improve reliability of DG.



agenda

- some definitions
- areas of interests:
  - I. GNSS
  - II. inertial sensors & estimation methods
  - III. integrity & communication
  - IV. calibration & ISO
  - V. transformations

definition of reliability

- **probability** to function under stated conditions for a specific period of time (physical)
  Failure Probability Density Function (FPDF):

$$R(t) = \int_t^{\infty} f(x)dx$$

- **controllability** of observations (int- vs. ext-ernal)
  - blunder detection
  - estimation of effects of blunders on solution
- **solution: redundancy**
  - Comes et higher price of additional components, signals or methods

definition of integrity

- measure of trust/correctness of the supplied information
- ability to detect problems and provide timely warnings
- NOTE #1: systems can be of high reliability and low integrity (GPS?) and vice versa
- NOTE #2: reliability & integrity are definable and measurable quantities and therefore safer to adapt then 'quality control', 'consistency checks', etc.

I. beyond the C/A code

- Current situation
  - B. Parkinson, Geneva 2007: 50-100*10^6 users depends on 1 signal! (GPS L1 C/A)
  - Double dependency in DG:
    - CP-DGPS in post-mission
    - decisive factor of mission (success or failure)

modernization needs time …

- GPS (victim of its success)
  - L2C (C/A code on L2) on IIR-M block
    Receiver ready, but replacement schedule: 2005 – 2014!
    3dB gain, no large impact!
  - L5 (new frequency) on IIIA block
    large impact, but no earlier then in 10-15 years!
- GLONASS
  - New boom! Plan to reach full constellation in 2012!
- Galieo
  - Always 5 years goal over last ten years!
    This tendency will most likely prevail over next ten years, although some like to believe in miracles …

bit of inspiration from …

Civil aviation

- ABAS (Aircraft based augmented system)
- SBAS (Satellite based …)
- GBAS (Ground based …)

- Geodesy ("the network is the *receiver*!")
  - Less suitable concepts (for GD):
    - Position or measurement domain corrections
    - Virtual stations
  - Better suitable concepts (for GD)
    - State-space domain corrections
    - Use the raw data! (possible in RTCM 3.0)

GNSS summary

Segment	Mitigation RT	Mitigation Later	Situation in DG
SV OK?	SBAS	DGPS analyses	rarely in RT*
Rover OK?	RAIM/ABAS	too late	RT–only geometry?
Base(s) OK?	RT-Network	Network	sometimes, no RT
Atmosphere	SBAS (iono)	PPP, DGPS	via DGPS, no RT
Diff. Troposphere	Sensors at carrier + base(s)		not observed
Multipath/interf.	Rx + antenna hw/sw design		follows the evolution
Long baseline	Multi-base, Master-Auxiliary		Not optimal, no RT
Ambiguity OK?	RTK	CP-DGPS	separated per base, no RT

*RT = Real Time

II. beyond "the" Kalman filter ...

- Current situation:
  - no sensor redundancy, all hopes in GPS/INS
  - GPS/INS in DG usually engineered to 'trust' INS (uses models build for optimal performance, not marginal cases)

- Available technologies:
  - physical redundancy
  - analytical redundancy

physical redundancy

- Sensor redundancy
  - complementary (e.g. redundant sensors in 1 IMU)
  - supplementary (e.g. multiple IMU)

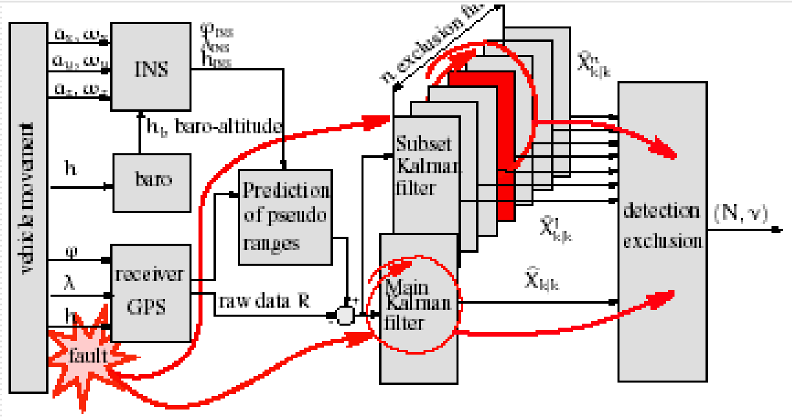
- Architecture
  - skew redundant
  - orthogonally redundant

- Increased reliability and integrity
  - failure detection and isolation
  - integrity monitoring of the navigation solution

Colomina et al. 2004.
Redundant IMUs for precise trajectory determination.
Int. Arch. of Photogrammetry, Remote Sensing, 34 Part B.

analytical redundancy

- simultaneous evaluation of multiple models and assumptions; FDE possible
  - 1. filter bank (computationally intesive)



  - 2. artificial neural network (new development)
- application of advance estimation methods

III. towards early alarms ...

- integrity asks for the alarm in RT or with a predefined latency
- as DG requires data fusion (ground & air), the integrity in DG requires communication
- current situation:
  - integrity is practically non existing in DG

I&C available technologies

- Integrity GNSS
  - Code: SBAS, GBAS, RAIM
  - Phase: TCAR, RTK (CP-DGPS)
- Integrity GNSS/IMU(/Sensor)
  - ABAS
  - Pushbroom, Lidar, other sensors ...
- Communication
  - Radio, GSM, GPRS/UTMS, SatCom, Wi-Fi

integrated sensor orientation (ISO)

- ISO = current reliability + needed for calibration
  - AT-GPS/INS (frame, line-scan)
  - ALS cross-over adjustment
- Problems:
  1. additional work (not automated) and cost
  2. comes as a last step (bit too late for integrity)
- Situation:
  - development bit ‘static’ – proven concepts prevail
  - new concepts are possible! (e.g. I. Colomina)

IV. towards better calibration…

- Aerial sensor
  - ISO – more tolerant to 'mis-modeling'
  - DG – need for precise models, e.g. temperature/pressure camera model (Gruber, 2006)
  - Situation
    - Frame, line cameras – relative well documented
    - LiDAR – less clear
    - SAR – only few centers
- Installation parameters
  - Lever arm
  - Boresight – better in cameras, worse otherwise

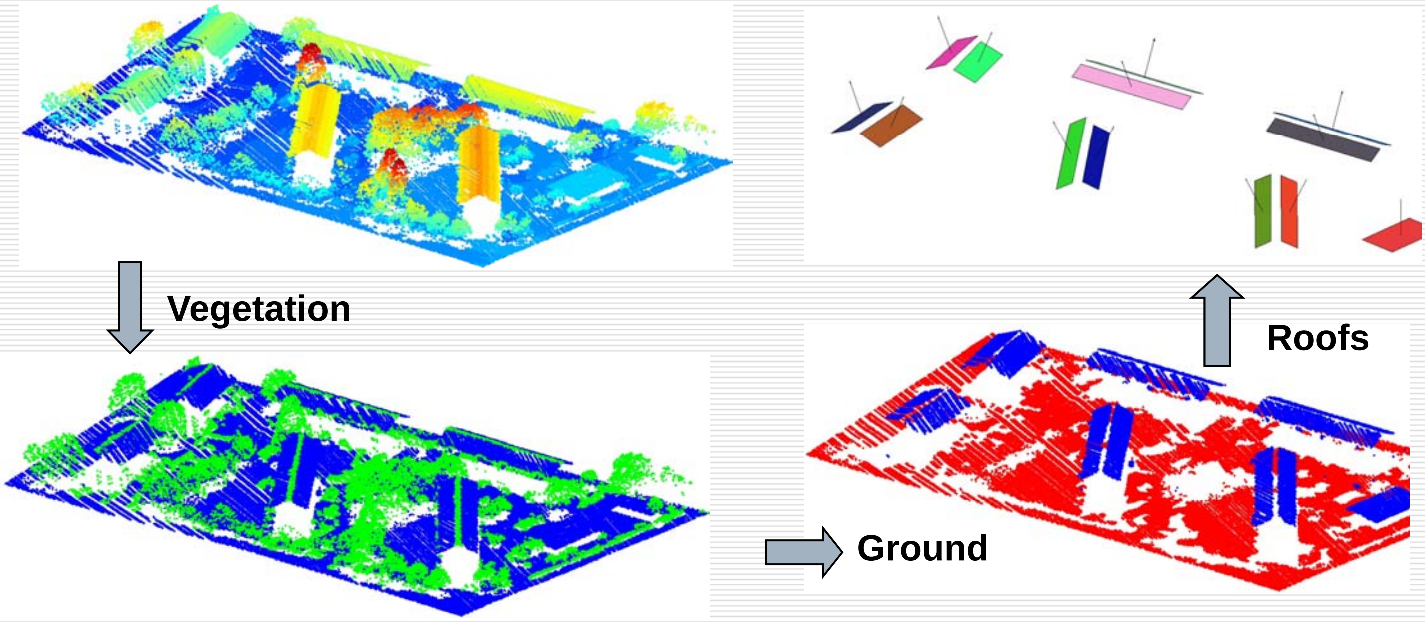
LiDAR sensor & boresight calibration

- Approaches
  - physical boundaries or cross-section (Schenk, 2001)
  - DTM Gradients (Burman, 2000)
  - 'like' photogrammetry (Morin,2002)
- Problems:
  - lack or simplification of assurance measures
  - correlation with unknown terrain shape
  - uncertainty in laser pointing accuracy and beam-width
  - laborious or requiring absolute reference
- Possibility to do it differently …

Skaloud, J., Lichti, D., 2006.
Rigorous approach to boresight self-calibration in airborne laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 61

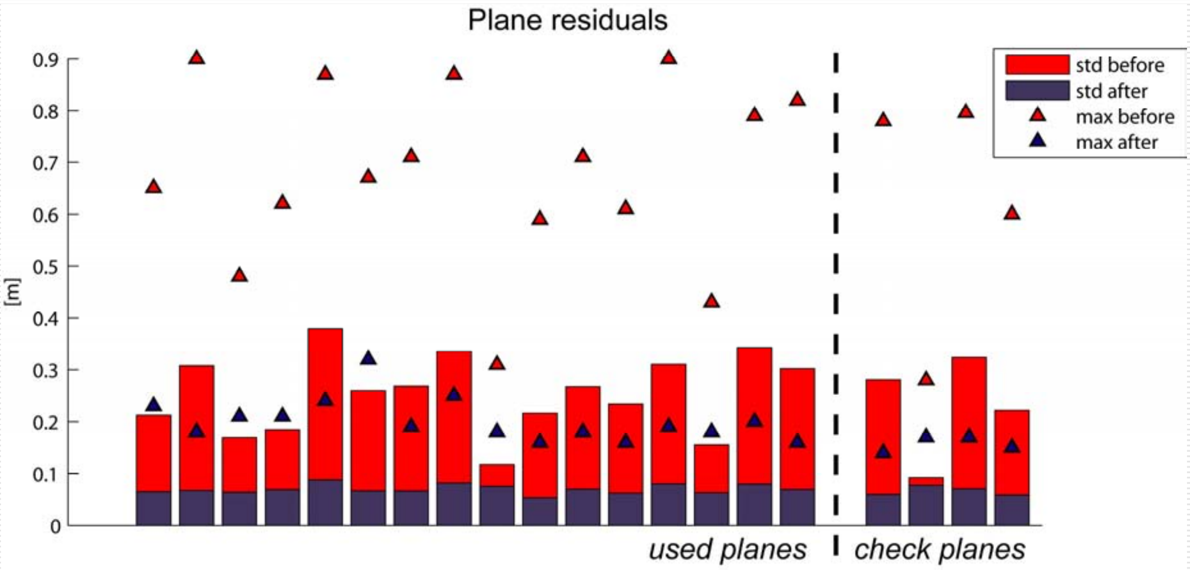
LiDAR self-calibration

- LIBOR (EPFL) – conditioning to surfaces of known form
- Gauss Helmert: >10^6 conditions, x 8 observations …



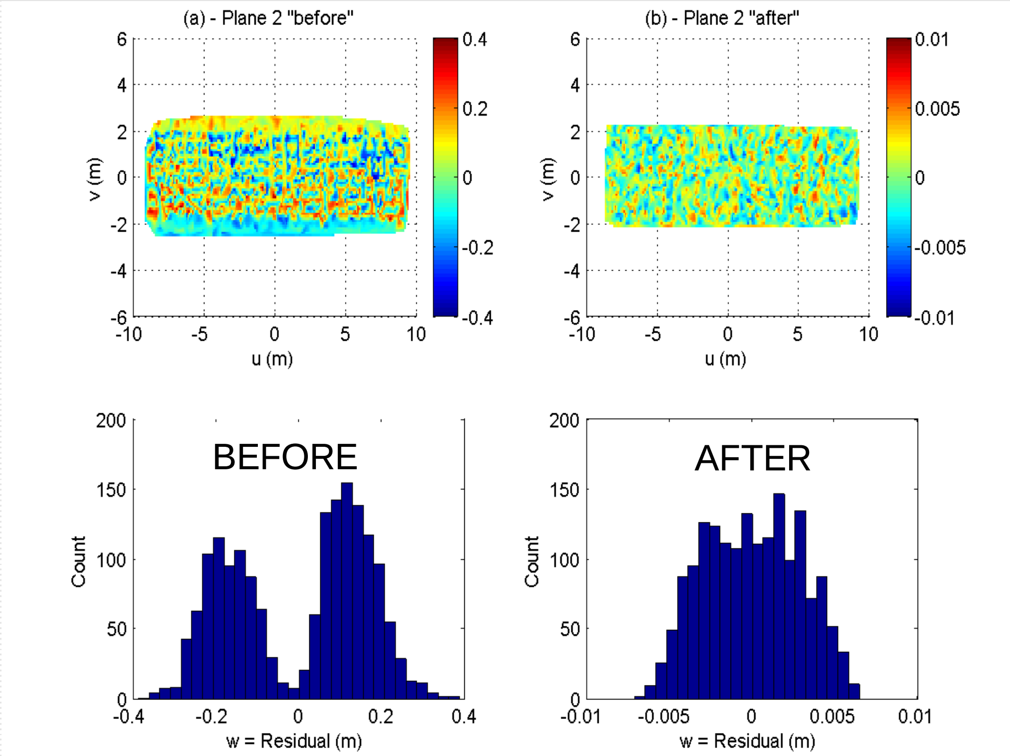
LIBOR - conditions

Planes needs to vary in aspect in orientation!



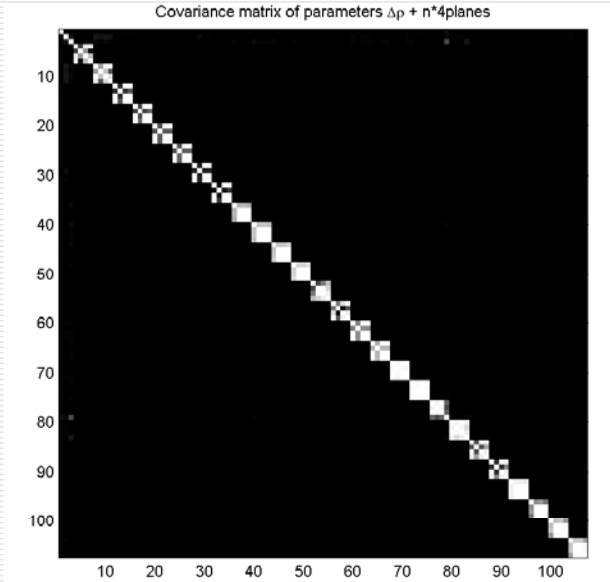
Successfully (re)calibrated systems: Riegl, Optech, Leica

LIBOR – residual distributions



LIBOR–example of recalibrated systems

- ALTM 3100
  - no boresight in heading provided by the manufacture!
- ALS50
  - larger differences in heading calibration!
  - 20-30 cm differences in range finder calibration!
  - parameters not correlated:



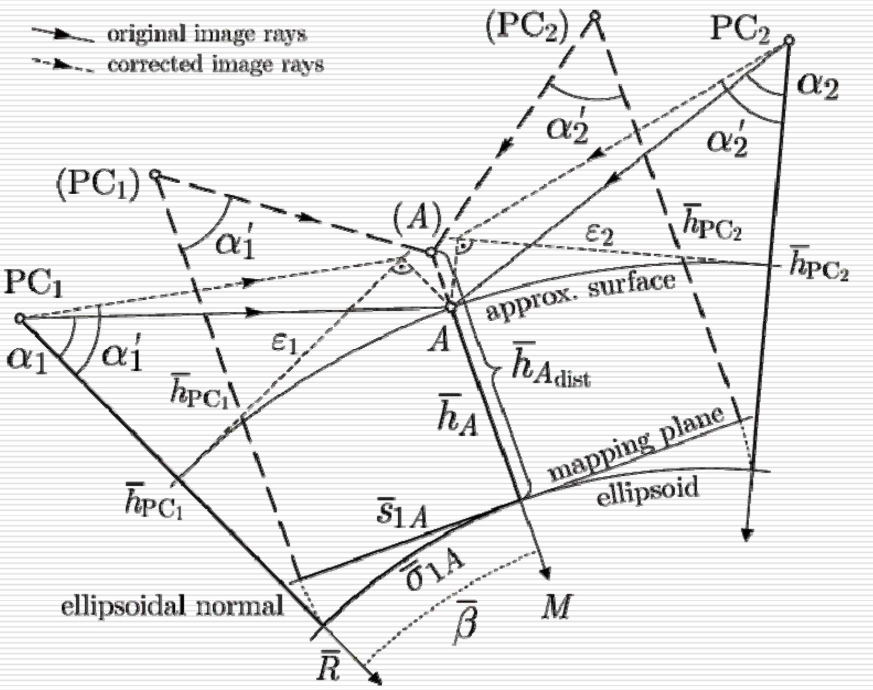
V. better handling of transformations …

s/c → b → l/e → $n/\bar{l}$ → p → *corrections*

- Citation (software manual for DG):

  "In aerial photography, it has been demonstrated that it is very common to find a **Z-bias** between the ground control points coordinates and the airborne-GPS derived elevation **due to mapping projections.**"

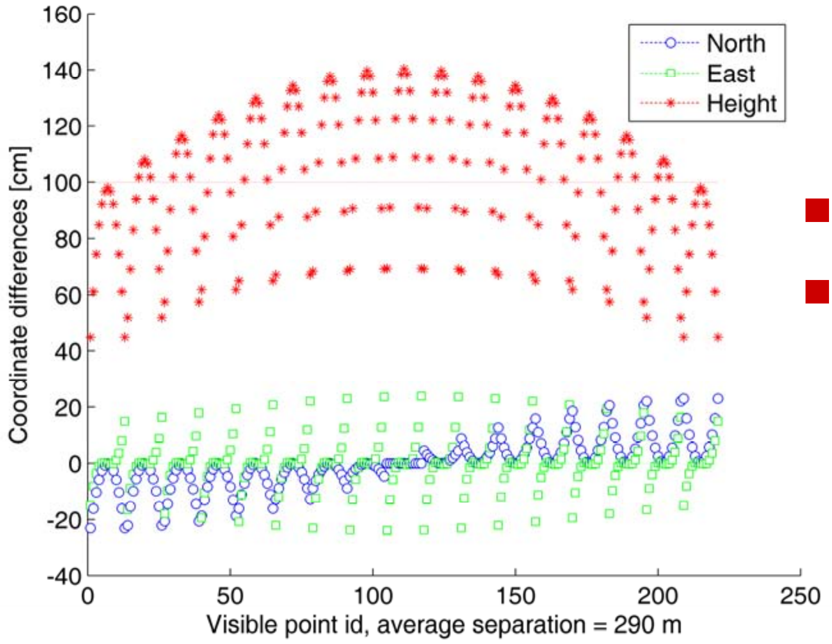
Situation: DG ≠ AT



Legat, K., 2006.
Approximate direct georeferencing in national coordinates.
ISPRS Journal of Photogrammetry and Remote Sensing 60.

DG – simulated situation of 1 stereo pair

- terrain height 500 m, flight height 3000 m, UTM



- Earth curvature ☒
- Height correction ☒

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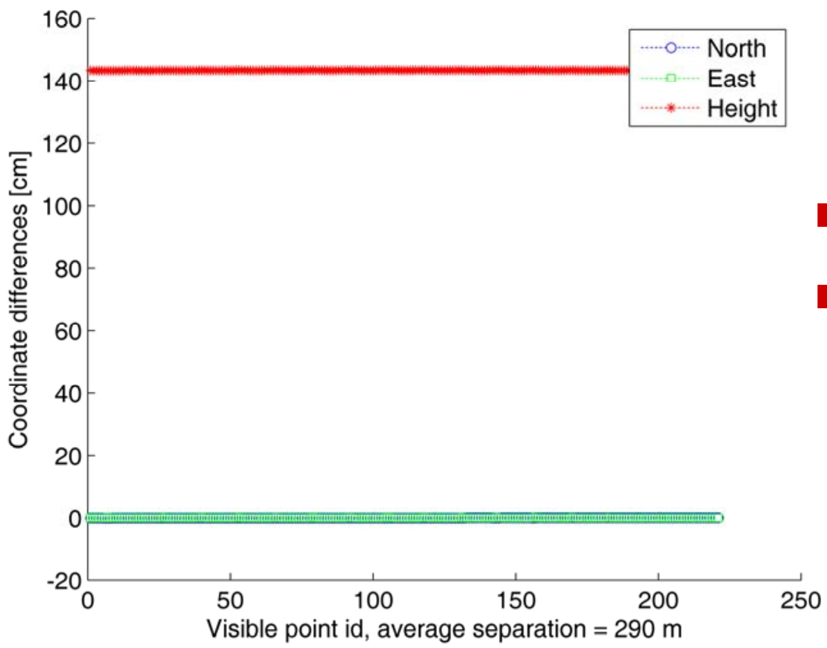

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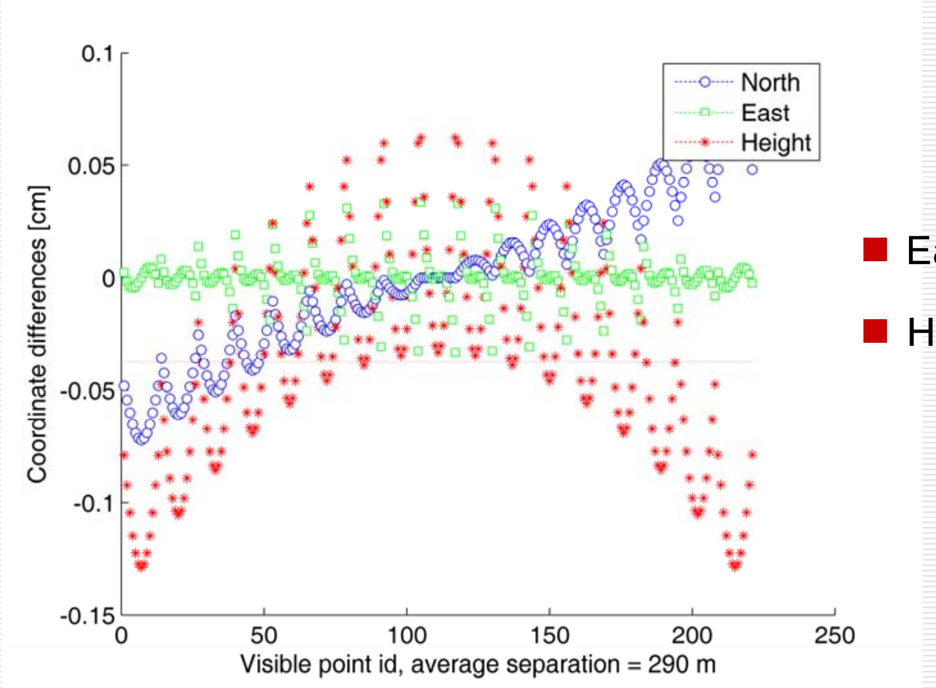
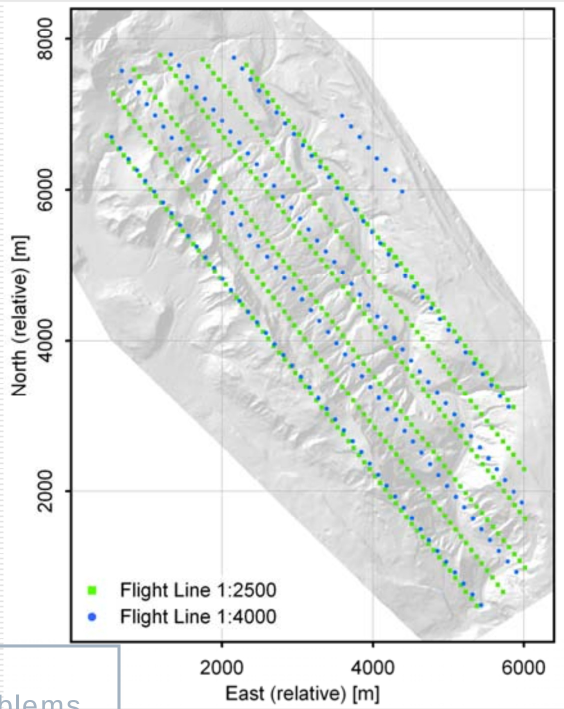


- Earth curvature ☑
- Height correction ☑

DG – real scenario with AT

- two flights over same controlled area
- GPS/INS – AT

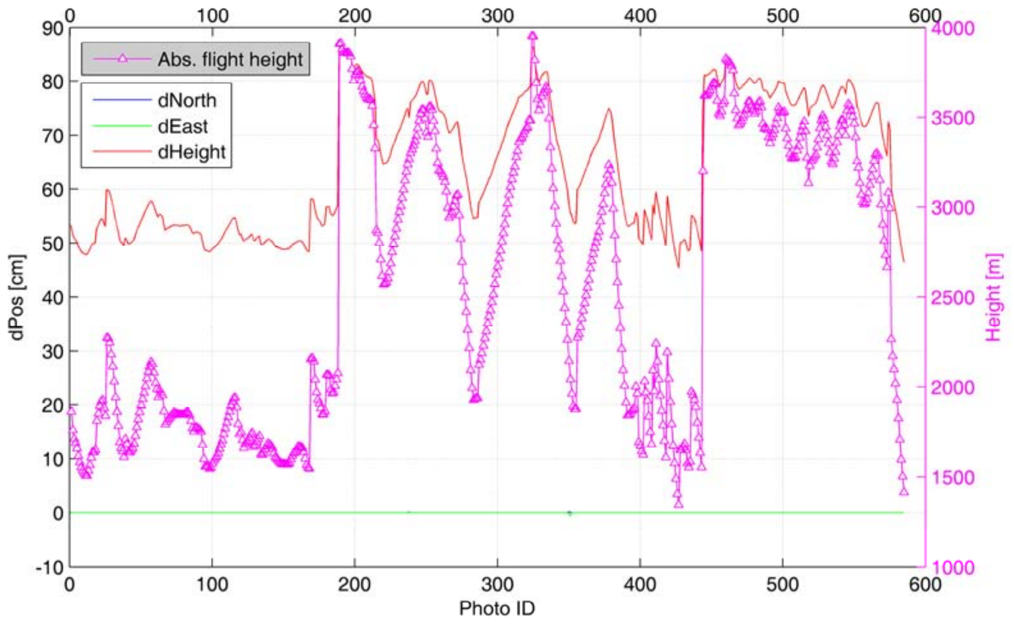
  No height correction:
  - Mean: ~ 5 cm for 1:2500
  - Mean: ~15 cm for 1:4000
- with height correction
  - Mean: <2 cm in both cases



Legat, K., Skaloud, J., Schmidt, R., 2006.
Reliability of DG 2: A case study on practical problems.
EuroSDR Official Publication 51

DG – real scenario w/o AT

- height corrections: problem in some commercial soft.
  - CAMEO(EPFL) – tested SW in WGS84/UTM32



concluding remarks

- If GPS/INS is the sole mean of sensor orientation; its reliability is primordial.

- The chain of data flow in DG is long and strong as its weakest link:
  - Galileo: “Waiting for Godot”?
  - rooms for improvement in GPS/INS, calibration and ISO

- Higher upfront expenses for more reliable systems can make saving in production:
  - quality control, consistency checks, etc. → reliability
  - control closer to real time → integrity

Thank you!

Boresight frame/line cameras calib.

Approach	Adjustment Space	Time correl.?	Remark
"No Step"	Global	Yes	Not developed, optimal but complicated
"1 Step"	AT	No	Too optimistic accuracy estimated, biased?
Reversed 1 Step	IMU' KF	Yes	Not developed, may lead to KF divergence
"2 Steps"	Independent	Yes	Developer independent

Height correction function