FROM OFF-LINE TO ON-LINE GEOCODING: THE EVOLUTION OF SENSOR ORIENTATION

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A SUCCESS STORY

2006	ALS block adjustment for calibration and orientation
1995	AT with INS/GPS aerial control
1993	Direct sensor orientation with INS/GPS concept
1991	Automatic digital AT / Modern ALS concept
1989	Self-calibrating bundle adjustment for RS
1986	AT with GPS aerial control concept
1980	Robust estimation for blunder detection in AT
1976	Maturity of SCBA and SW packages
1970	Self-calibrating bundle adjustment concept (SCBA) / PATM

TODAY'S CONTEXT

– social

- **geoinformation**
  a fundamental resource and part of modern information society infrastructures
- **contradictory situation**
  a demanding society that is not willing to pay for what is being demanded
- **mapping companies**
  tight budget, higher time pressure with —many times— less prepared staff
- **solution**
  outsourcing, higher productivity (technology + education)

– technological

- manifold of data sources
- "high resolution" (broad sense) data sets $\longrightarrow$ large data sets
- "precise" (broad sense) data sets but not necessarily accurate data sets

TODAY'S CONTEXT

– huge data sets to be processed... time pressure, less prepared staff, tight budget

– **automated, robust** procedures

	assumptions hold	**wrong assumptions**
standard procedure	**optimal performance** **within spec**	**unpredictable** **out of spec**
robust procedure	**sub-optimal performance** **within spec**	**sub-optimal performance** **within spec**

The geomatic community cannot become mainstream if its systems and procedures fail just because a user did not read and did not faithfully apply the user's manual.

FORMAL AGENDA

1. Short review of current enabling technologies for C&O and their performance
2. Progress in Positioning, Navigation and Timing (PNT) technologies
3. Progress in sensor/network modeling for C&O
   - From off-line to on-line C&O: a collection of misunderstandings
4. Example of a robust procedure
5. Conclusions

ENABLING TECHNOLOGIES FOR SENSOR C & O

- **GPS** satellite positioning-navigation-timing (PNT) - kinematic, 2-freq, $\geqslant$ 5 sats
  $\sigma_{E,N} \approx$ 0.05-010 m - $\sigma_h \approx$ 0.07-0.15 m on GPS we trust - reliability?
- **INS/GPS** position-velocity-attitude (PVA) determination - nav grade
  $\sigma_\psi \approx$ 0.005 deg - $\sigma_{\vartheta,\gamma} \approx$ 0.008 deg "abs" on INS/GPS we trust - reliability?
- geodetic and topographic surveying - GPS surveying
  $\sigma_{E,N} \approx$ 0.02 m $\sigma_h \approx$ 0.03 m
- mono- and multi-sensorial **image correspondence** - 0.2 px mono-
- sensor modeling and **network modeling/adjustment** - sensor dependent

	ADS		DMC		UCD	
	E/N	h	E/N	h	E/N	h
RMS at check-points in ppm (of flying height)	25	55	25	65	25	50

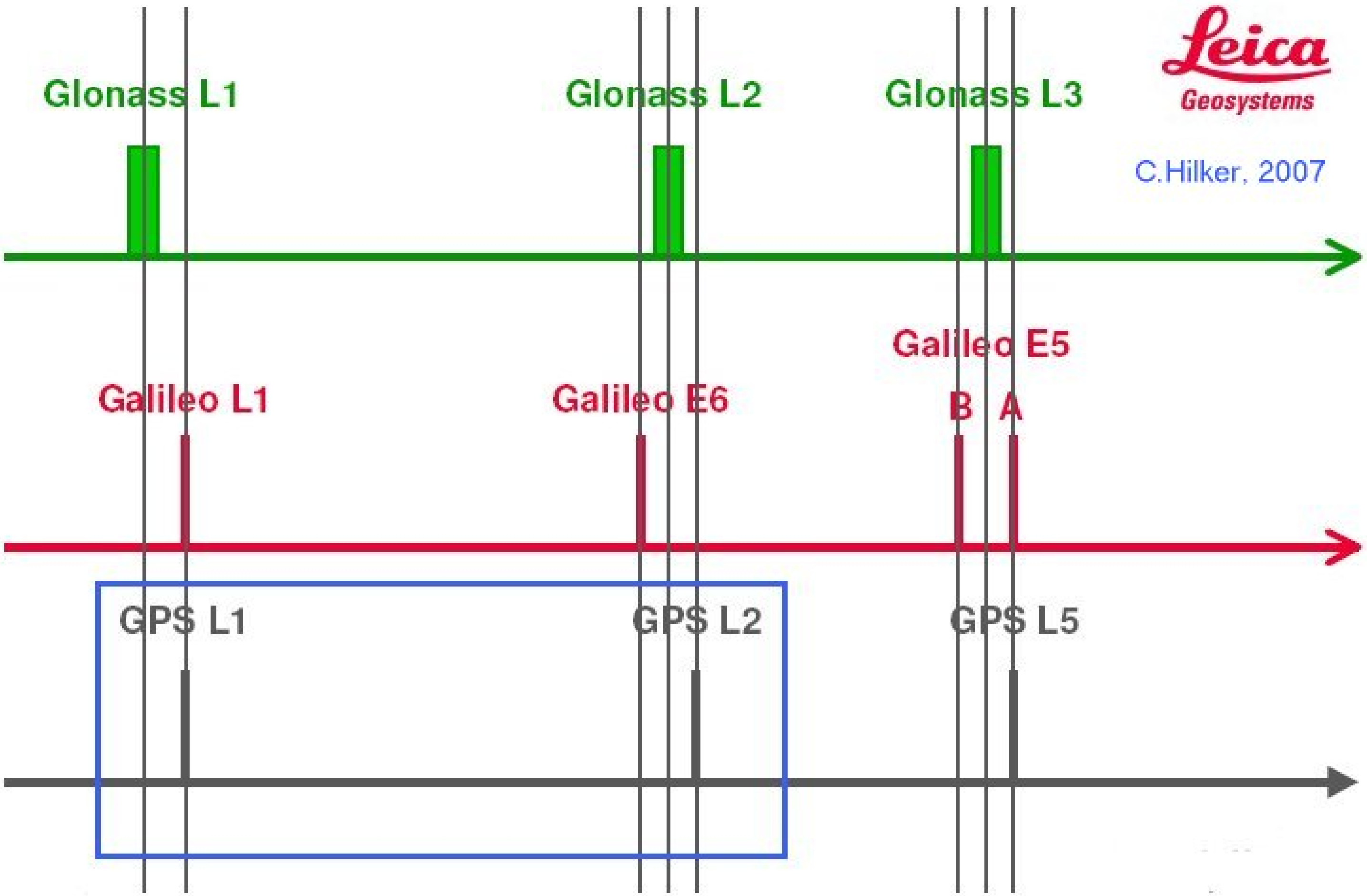
Cramer, M. (2007): Results from the EuroSDR network on digital camera calibration and validation, High-Resolution Earth Imaging for Geospatial Information, Hannover.

PROGRESS IN POSITIONING/NAVIGATION

- GPS
  - **from** GPS **to** GNSS (GPS + GLONASS + Galileo + ...) **more satellites**
  - **from** L1 C/A **to** L1 C/A, L2C, L5 + E1, E5a, E5b, (E6) + ... **better signals**
  - radio defined SW receivers **more flexibility**
  - $>$ 2 $\times$ satellites, $>$ 4-5 $\times$ signals
    higher precision/accuracy, less multipath, robustness, fast ambiguity resolution, ...
    86 channel receivers...

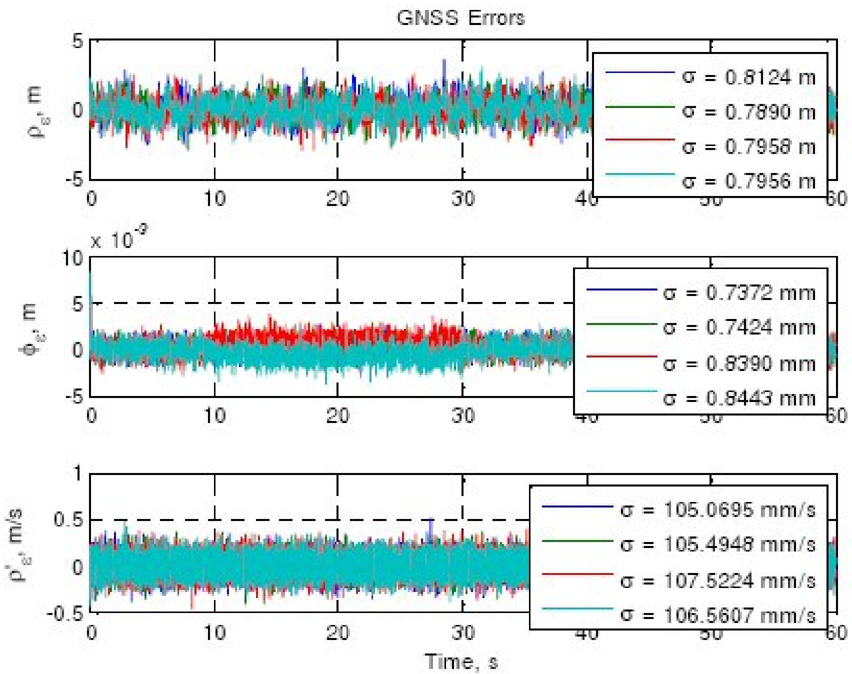
- INS and INS/GNSS
  - INS no significant evolution in terms of INS performance
  - Development effort is put on cost and size reduction
  - **from** INS/GPS loosely coupled **to** INS/GNSS tightly/deeply coupled

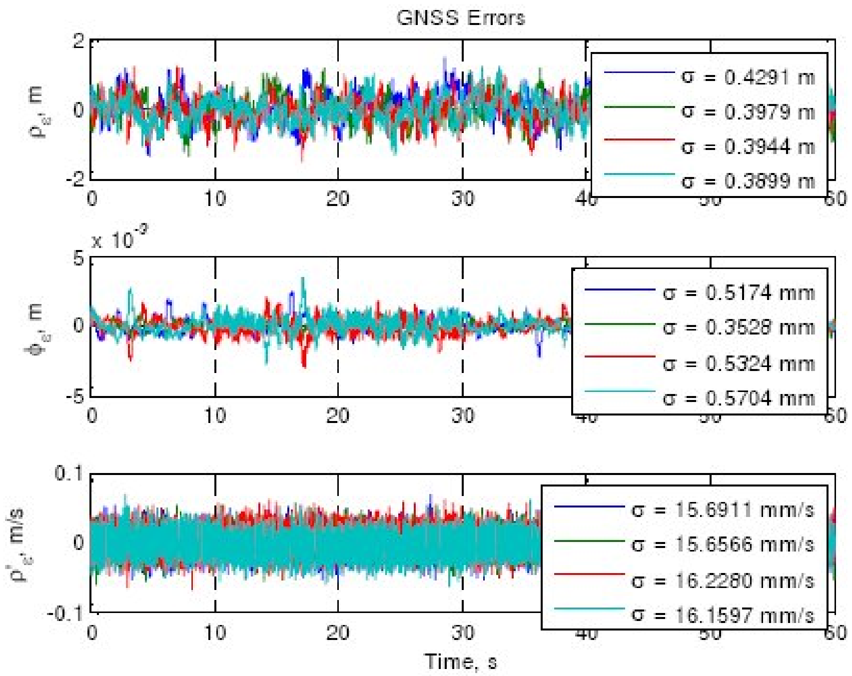
PROGRESS IN POSITIONING/NAVIGATION



INS/Galileo LOOSELY vs. DEEPLY COUPLED ARCHITECTURES

- results from DEIMOS Engenharia/IG follow-up research of GJU's IADIRA project
- Galileo L1 BOC(1,1) + IMU automotive-grade

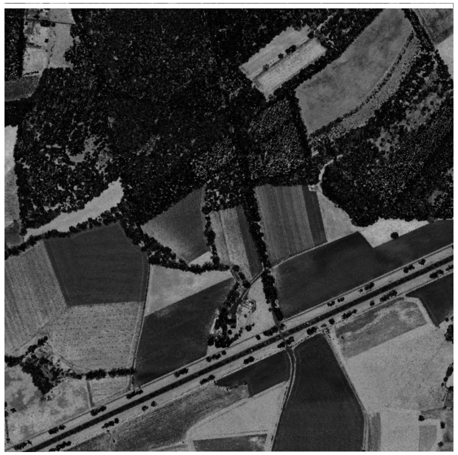


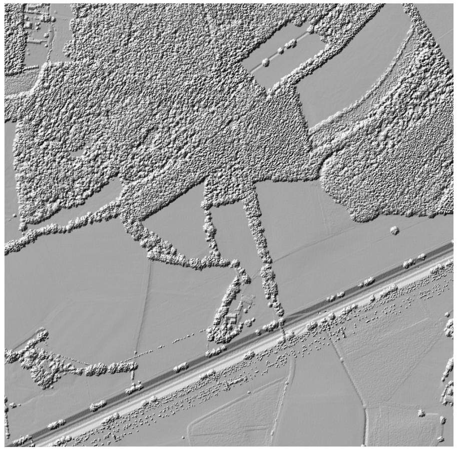


Silva, P.F., Silva, J.S., Lorga, J.F.M., Wis, M., Parés, E., Colomina, I., Fernández, A., Díez,J. (2007): Inertial aiding: performance analysis using tight integrated architecture. European Navigation Conference 2007, Geneva.

MONO- & MULTI-SENSOR "IMAGE" CORRESPONDENCE

- mono
  - operational for multi/hyper-spectral imagery - ✓
  - in its infancy for ALS, but promising results - ✓
- multi
  - can you match those... - X





source: Optech Int.

  - theory and algorithms exist (mutual information, etc.)
  - in general, a difficult problem

PROGRESS IN ISO & DSO

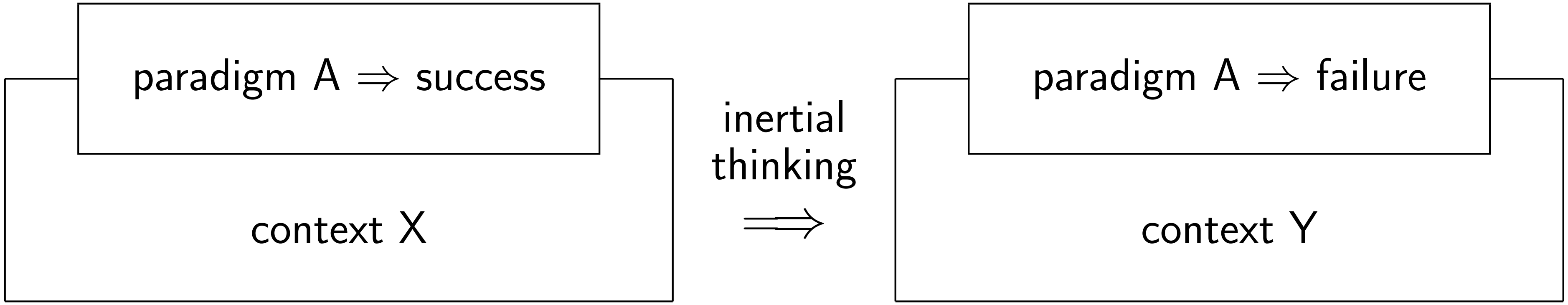
- after $>$ 15 years of GPS AT
- after $>$ 10 years of INS/GPS AT (ISO) and DSO

- **... things have not changed that much**

- testing effort high (OEEPE, EuroSDR, many national tests, ...)
- global understanding of the ISO and DSO technologies low
- paradoxical situation... industry does the R&D and universities do the testing
- **modeling effort low $\Longrightarrow$ some problems unsolved ... robustness, reliability**

- the concept of ALS block adjustment has been formulated and validated
- the concept of radiometric block adjustment has been formulated and tested

SUCCESSFUL PARADIGMS AND INERTIAL THINKING



- there is some inertial thinking in sensor orientation and calibration

  ... there is life in between ISO and DSO

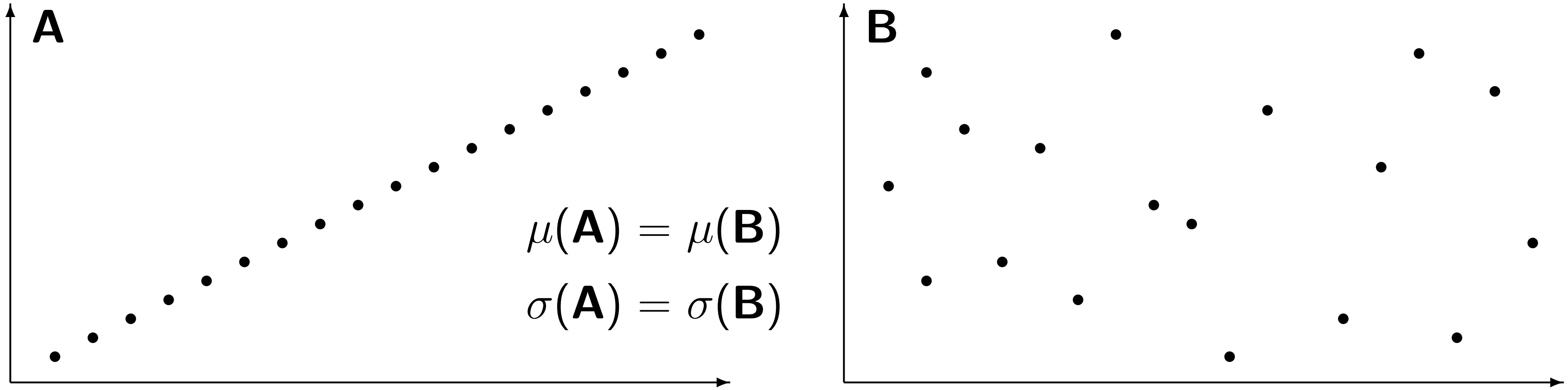
  ...

- there is some inertial thinking in INS/GPS

  ... there is life beyond the Kalman filter

  ...

MU 1: STOCHASTIC PROPERTIES OF INS/GPS



- INS/GPS actual error properties follow pattern A
- ISO / DSO SW packages assume that INS/GPS errors follow B
- double negative impact ($\Rightarrow$ sub-optimal results)
  - correlations are neglected
  - [relative] precision is not fully exploited

Martínez,M.,Blázquez,M.,Gómez,A.,Colomina,I. (2007): A new approach to the use of attitude control in camera orientation. Proceedings of the 7th International Geomatic Week, Barcelona.

MU 2: ATTITUDE REPARAMETRIZATION OF INS/GPS ATTITUDE

- **time is lost**, additional unnecessary SW is developed and used, **money is paid** and **mistakes are made** just because the

simple, correct attitude-control observation equation

$$R^l_c(\omega, \varphi, \kappa) = R^l_{l'} \cdot R^{l'}_{b'}(\psi + v_\psi, \vartheta + v_\vartheta, \gamma + v_\gamma) \cdot R^{b'}_b \cdot R^b_c(\gamma_x, \gamma_y, \gamma_z)$$

with

$$R^l_{l'} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad \text{and} \quad R^{b'}_b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

is not used

No need to re-parameterize form ψ, ϑ, γ to ω, φ, κ. SW makers: please correct...

MU 3: INS/GPS INFORMATION

- INS/GPS delivers a tPVA trajectory, not just a tPA one

- **classical** position and attitude (tPA) aerial control observation equations

$$
\begin{aligned}
{\ell_X}^l + {v_X}^l &= X^l + R^l_c(\omega,\varphi,\kappa)A^c + S^l \\
R^l_c(\omega,\varphi,\kappa) &= R^l_{l'} \cdot R^{l'}_{b'}(\ell_\psi + v_\psi, \ell_\vartheta + v_\vartheta, \ell_\gamma + v_\gamma) \cdot R^{b'}_b \cdot R^b_c(\gamma_x,\gamma_y,\gamma_z)
\end{aligned}
$$

- **new** position, velocity and attitude (tPVA) aerial control observation equations can be derived

- $\sigma_X \approx 0.03$ m, $\Delta t \approx 10$ s $\Longrightarrow$ $\sigma_{\delta t} \approx 0.6$ ms
  $\sigma_V \approx 0.005$ m/s, $V \approx 100$ m/s

Blázquez,M.,Colomina,I. (2008): On the use of inertial/GPS velocity control in sensor calibration and orientation. Submitted to the EuroCOW 2008, Castelldefels.

MU 4: SENSOR CALIBRATION & ORIENTATION IS A 4D PROBLEM

- Sensor orientation and calibration is a 4D problem, not a 3D problem (not to speak of radiometric and spectral calibration)

- Time synchronization in [multisensor] systems is dealt with at the HW level
- If HW fails or in low cost multisensor systems $\Longrightarrow$ we are disarmed

- What we usually have

$$x^e = f_i^e \left(y^i\right)$$

- What we need

$$x^{e,\tau} = f_{i,\upsilon}^{e,\tau} \left(y^{i,\upsilon}\right)$$

- At least we could check if $\delta t = 0$

MU 5: INS/GPS AND THE KALMAN-FILTER SOLUTION APPROACH

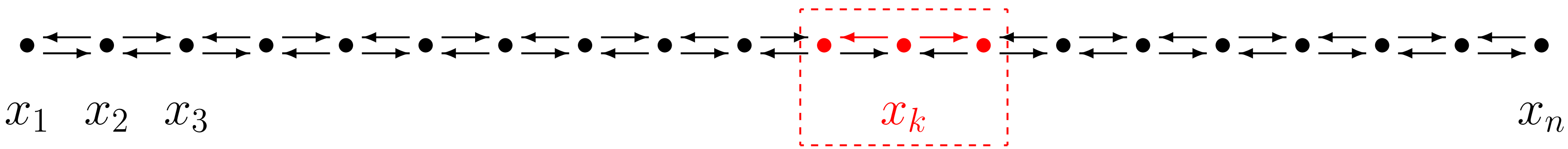
- It is [wrongly] believed that the derivation of GPS tP and inertial/GPS tPVA trajectories requires the use of the "predictor - Kalman filter" approach

- INS mechanization equations - Differential Equation model

$$
\begin{aligned}
\dot{x}^e &= v^e \\
\dot{v}^e &= R^e_b f^b - 2\Omega^e_{ie} v^e + g^e(x^e) \\
\dot{R}^e_b &= R^e_b \left(\Omega^b_{ei} + \Omega^b_{ib}\right)
\end{aligned}
$$

- INS mechanization equations - Difference Equation model

$$
\begin{aligned}
x^e_{k+1} - x^e_{k-1} &= \delta t \cdot v^e_k \\
v^e_{k+1} - v^e_{k-1} &= \delta t \cdot \left([R^e_b]_k {f^b}_k - 2\Omega^e_{ie} v^e_k + g^e(x^e_k)\right) \\
[R^e_b]_{k+1} - [R^e_b]_{k-1} &= \delta t \cdot [R^e_b]_k \left([\Omega^b_{ei}]_k + [\Omega^b_{ib}]_k\right)
\end{aligned}
$$



MU 5: INS/GPS AND THE KALMAN-FILTER SOLUTION APPROACH

- a particular case of dynamic networks (general Gauß-Helmert formulation)

$$0 = f(\ell + v, x) \quad \text{classical [static] observation equation}$$
$$0 = f(\ell + v, x, \dot{x}) \quad \text{new dynamic observation equation (an SDE)}$$

- interesting... to analyze the typical figures of least-squares network adjustment for INS/GPS dynamic networks

  redundancy numbers / leverages, internal/external reliability, orthogonal projectors

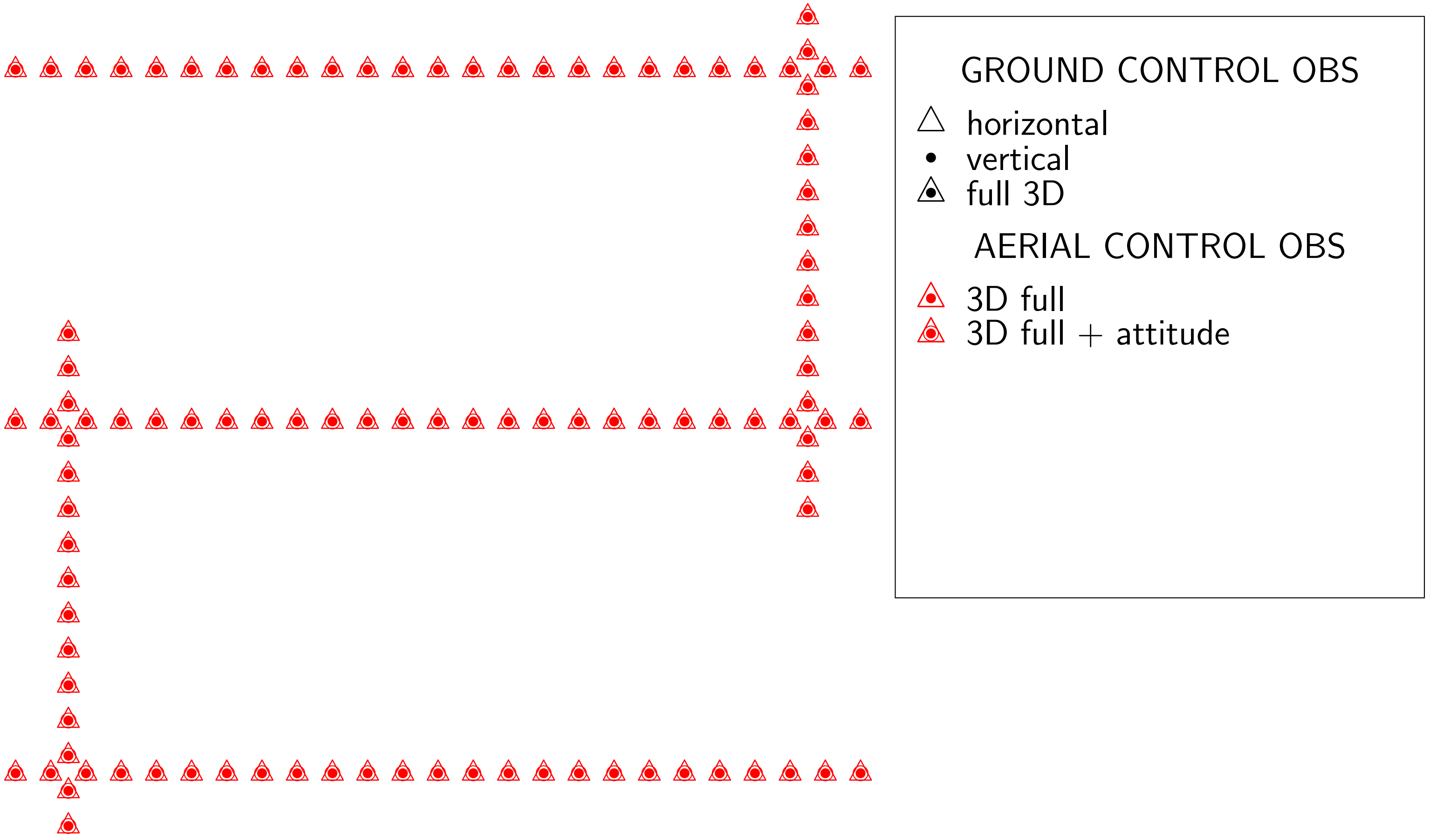
  - low reliability of INS/GPS
  - limitations of contextual calibration

Colomina,I.,Blázquez,M. (2005): On the stochastic modeling and solution of time dependent networks. Proceedings of the 6th International Geomatic Week, Barcelona.

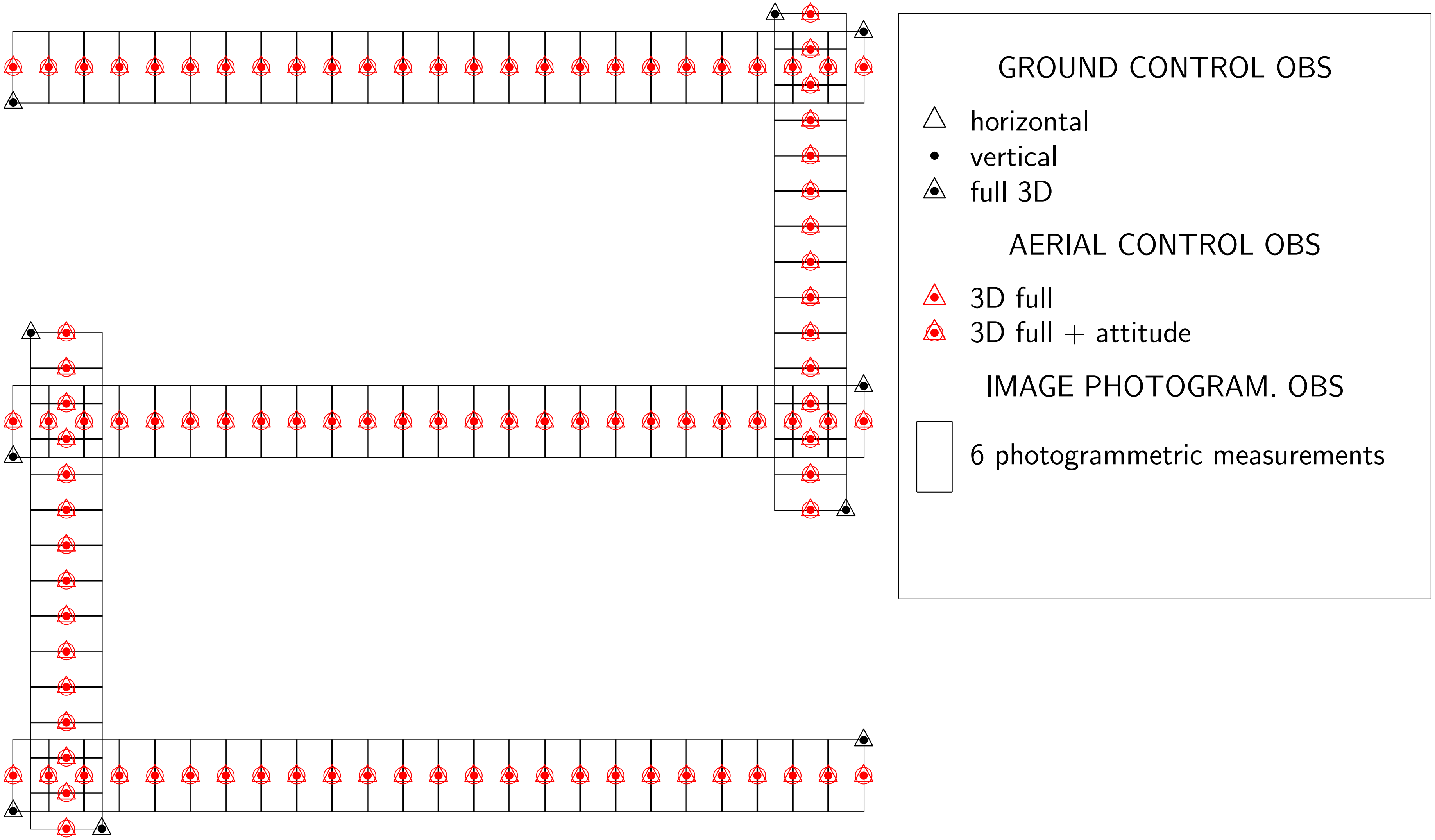
Sansò,F. (2006): Navigazione geodetica e rilevamento cinematico. Polipress, Milano.

MU 6: WHAT INTEGRATED SENSOR ORIENTATION IS

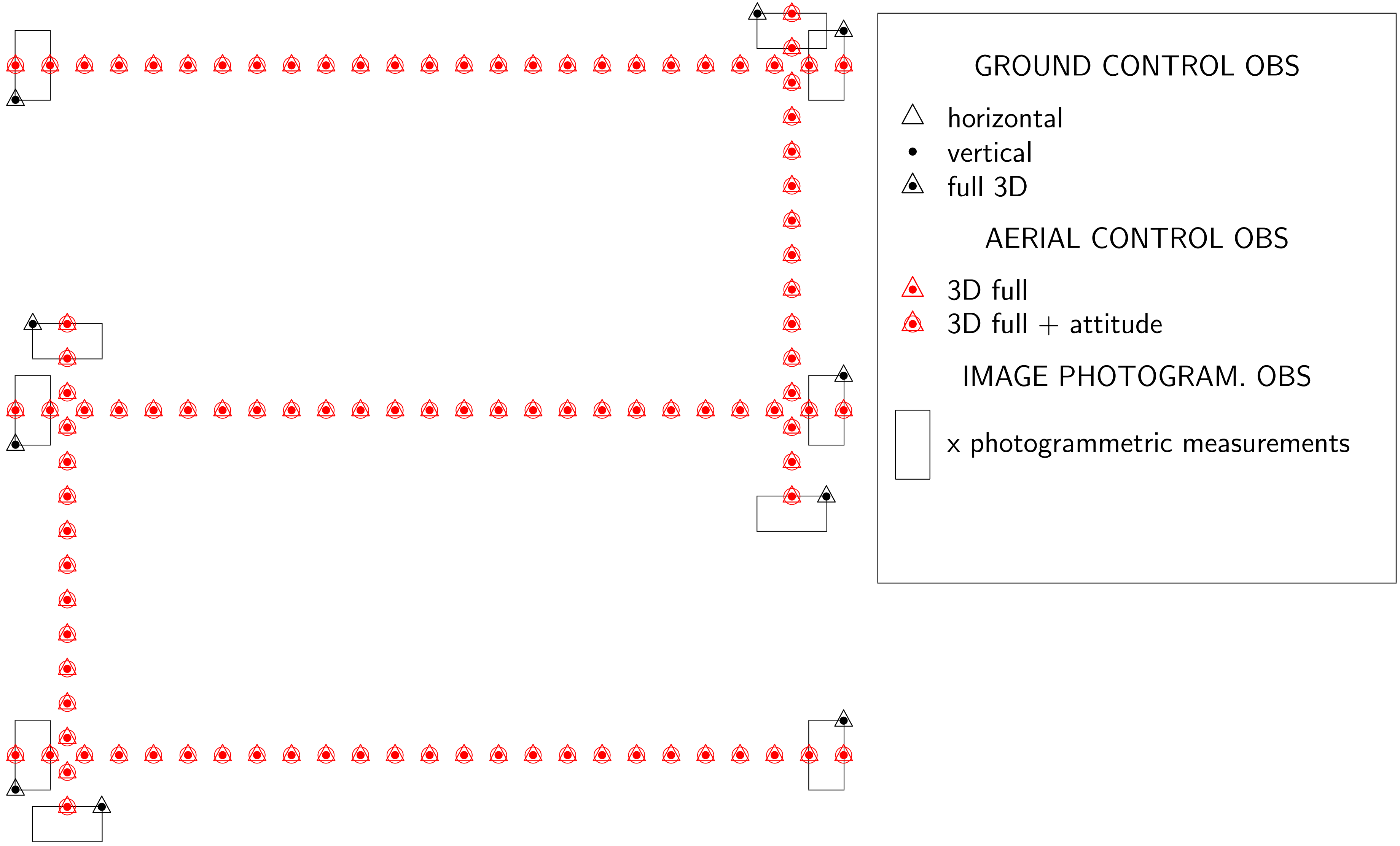
- It is [wrongly] believed that ISO = classical AT + INS/GPS
- It is [wrongly] believed that ISO ⇒ off-line, traditional least-squares
  (ISO can be performed with PP sequential least-squares and with RT Kalman-filtering)



MU 6: WHAT INTEGRATED SENSOR ORIENTATION IS



MU 6: WHAT INTEGRATED SENSOR ORIENTATION IS



MU 7: LIMITATIONS OF ISO FOR RAPID-RESPONSE APPLICATIONS

(related to MU 6)

- It is generally [wrongly] believed that ISO cannot be used for rapid-response and real-time applications because the measurement of image coordinates takes too long (sic).

MU 8: THE ROLE OF BORESIGHT CALIBRATION

- It is [wrongly] believed that the rotation/boresight matrix R_b^c between the camera frame c and IMU frame b has always to be known or estimated

- **classical absolute** position and attitude (tPA) aerial control observation equations

$$\begin{aligned} {\ell_X}^l + {v_X}^l &= X^l + R_c^l(\omega,\varphi,\kappa)A^c + S^l \\ R_c^l(\omega,\varphi,\kappa) &= R_{l'}^l \cdot R_{b'}^{l'}(\ell_\psi + v_\psi, \ell_\vartheta + v_\vartheta, \ell_\gamma + v_\gamma) \cdot R_b^{b'} \cdot R_c^b(\gamma_x,\gamma_y,\gamma_z) \end{aligned}$$

- **new relative** position and attitude (tPA) aerial control observation equations

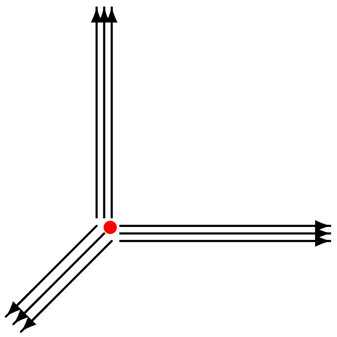
$$\begin{aligned} {\ell_{X_2}}^l + {v_{X_2}}^l - \left({\ell_{X_1}}^l + {v_{X_1}}^l\right) &= {X_2}^l - {X_1}^l + \left(R_c^l(\Omega_2) - R_c^l(\Omega_1)\right) A^c \\ R_c^l(\Omega_2)\cdot R_l^c(\Omega_1) &= R_{l'}^l \cdot R_{b'}^{l'}(\ell_{\Psi_2} + v_{\Psi_2}) \cdot R_{b'}^{l'}(\ell_{\Psi_1} + v_{\Psi_1})^T \cdot R_l^{l'} \end{aligned}$$

(successful results so far, on-going check of possible *Bierbauch* effects in large blocks)

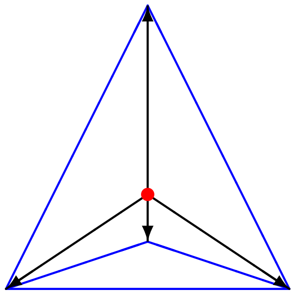
Martínez,M.,Blázquez,M.,Gómez,A.,Colomina,I. (2007): A new approach to the use of attitude control in camera orientation. Proceedings of the 7th International Geomatic Week, Barcelona.

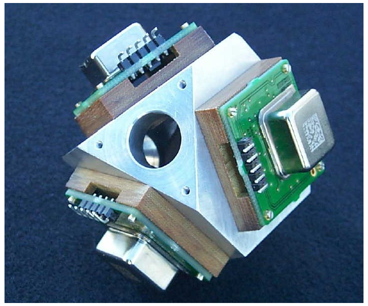
MU 9: IMU BOXES

- IMUs were not designed by/for geodesists. IMUs are just instruments.
- ORIMU (Orthogonal Redundant IMU).



- SRIMU (Skewed Redundant IMU).

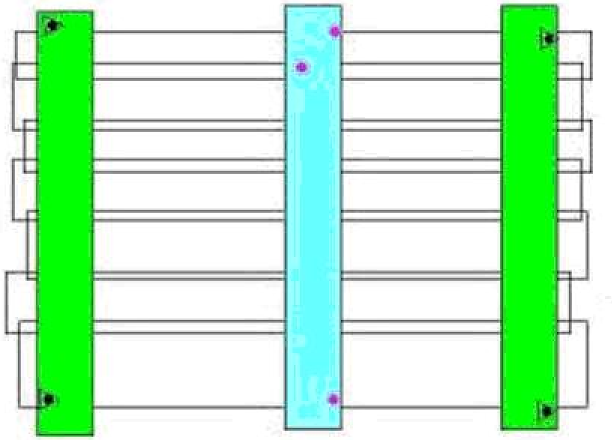




Colomina,I.,Giménez,M.,Rosales,J.J.,Wis,M. (2004): Geodetic applications of redundant Inertial Measurement Unit configurations. Gravity, Geoid and Space Missions - GGSM2004, 2004-08-30–2004-08-03, Porto.

MU 10: ISO AND NON-OPTICAL SENSORS

- It was for a long time accepted that ISO would only apply to optical sensors



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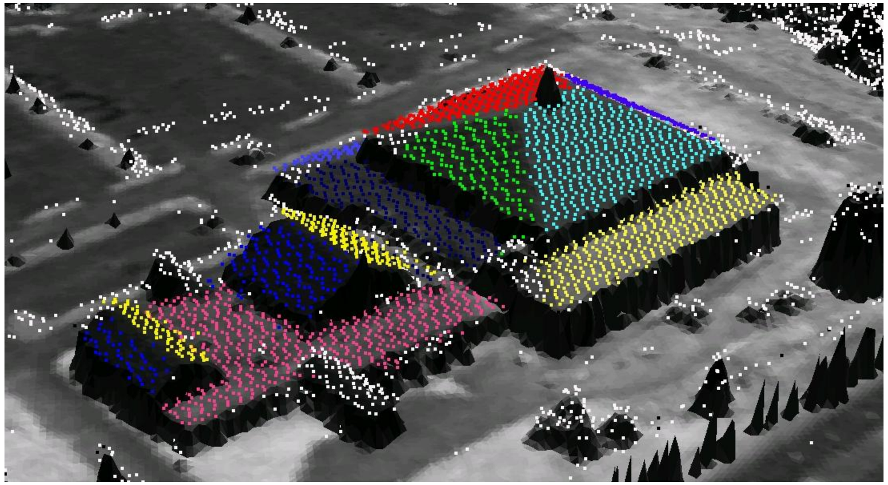


Kager.,H. (2004): Discrepancies between overlapping laser scanning strips - simultaneous fitting of aerial laser scanner strips. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 35-B1, pp. 555-560.

Frieß,P. (2006): Toward a rigorous methodology for airborne laser mapping. Proceedings of the EuroCOW 2006, pp. 121-130, Castelldefels, European Spatial Data Research - EuroSDR.

Škaloud,J.,Lichti,D. (2006): Rigorous approach to bore-sight self-calibration in airborne laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 61, pp. 47-59.

MU 11: COMPUTATIONAL vs. MAPPING COORD. REF. FRAMES

- Coordinate Reference Frame (CRF) = Reference Frame (RF) + Coordinate System (CS)
- INS/GPS family of CRFs: global RF + geocentric or geodetic CS
- mapping/geoinformation CRFs: ITRF2006 + EGM96 / UTM(32,N) + Ho
  - RF issue - ✓ - more or less
  - CS issue - **X** - a big mess
- solutions to the CS problem: 3 approaches [among others]
  1. **correction++** approach: keep the wrong model + "correct" the correct data (family of **incompatible** approximate solutions: height corrections, focal length corrections, image corrections, etc.)
  2. **modeling** approach: keep the correct data + implement the correct model
  3. **point interface** approach: set $\{(X, Y, Z, x, y), \ldots\}$

$$X^l\left((E, N, h)^T\right) = X^l\left((E_0, N_0, h_0)^T\right) + \mu\, r_i^l\, \mathbf{x}^i$$

MU 11: COMPUTATIONAL vs. MAPPING COORD. REF. FRAMES

$$(E, N, h)^T = (E_0, N_0, h_0)^T + (\Delta E, \Delta N, \Delta h)^T$$

$$X^l : (E, N, h)^m \longrightarrow (\lambda, \phi, h)^e \longrightarrow (X, Y, Z)^e \longrightarrow (x, y, z)^l$$

$$X^l \left((E_0, N_0, h_0)^T\right) + J \cdot (\Delta E, \Delta N, \Delta h)^T + (\Delta E, \Delta N, \Delta h) K (\Delta E, \Delta N, \Delta h)^T + \ldots$$
$$= X^l \left((E_0, N_0, h_0)^T\right) + \mu \, r_i^l \, \mathbf{x}^i$$

$$J \cdot (\Delta E, \Delta N, \Delta h)^T + (\Delta E, \Delta N, \Delta h) K (\Delta E, \Delta N, \Delta h)^T = \mu \, r_i^l \, \mathbf{x}^i$$

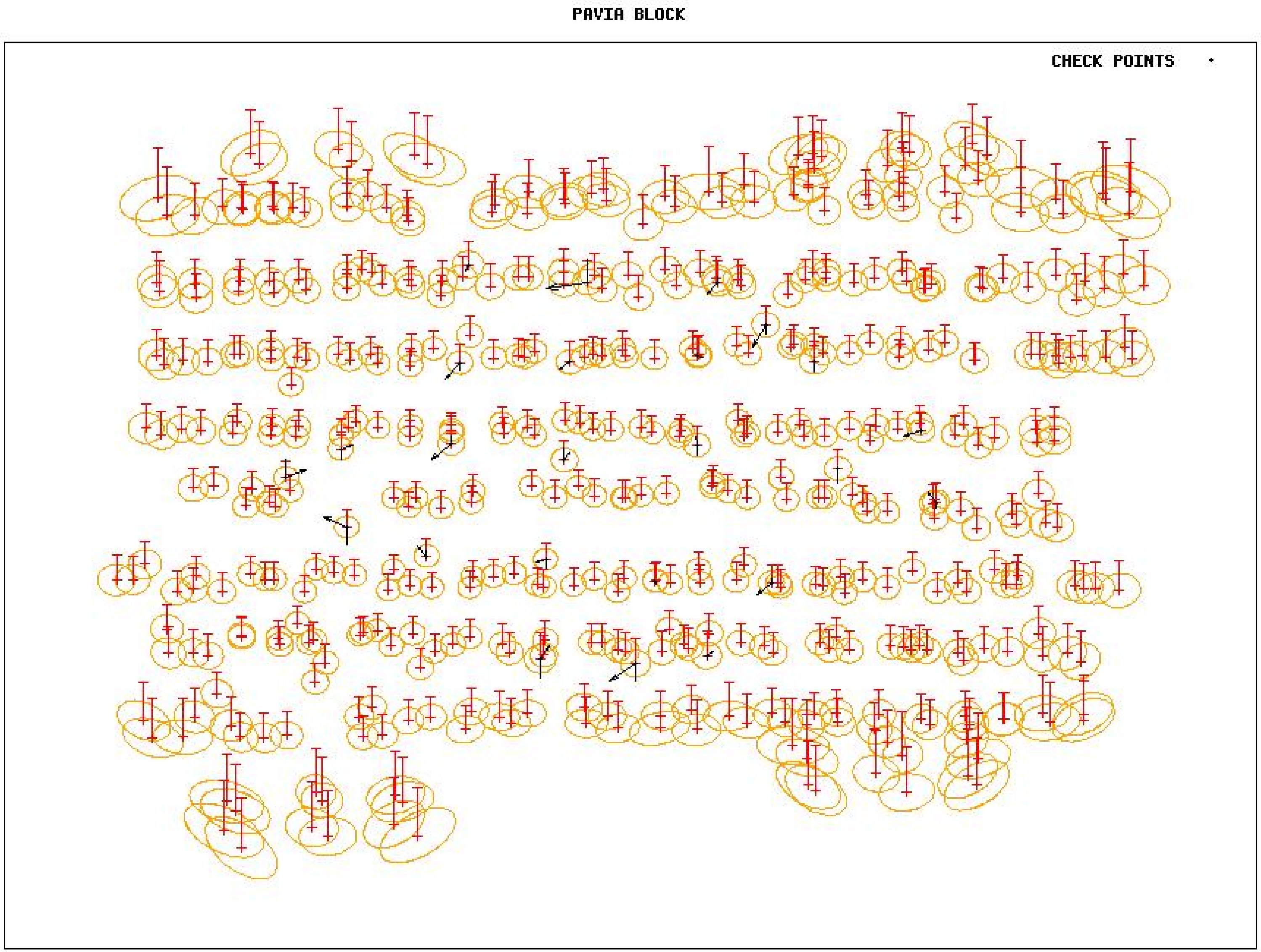
Colomina,I.,Blázquez,M. (2007): Lecture Notes. International Executive M.Sc. in Airborne Photogrammetry and Remote Sensing, Sensor Orientation (3): Sensor Calibration And Block Adjustment. Castelldefels.

A [MORE] ROBUST INS/GPS CONTROL MODEL - 1

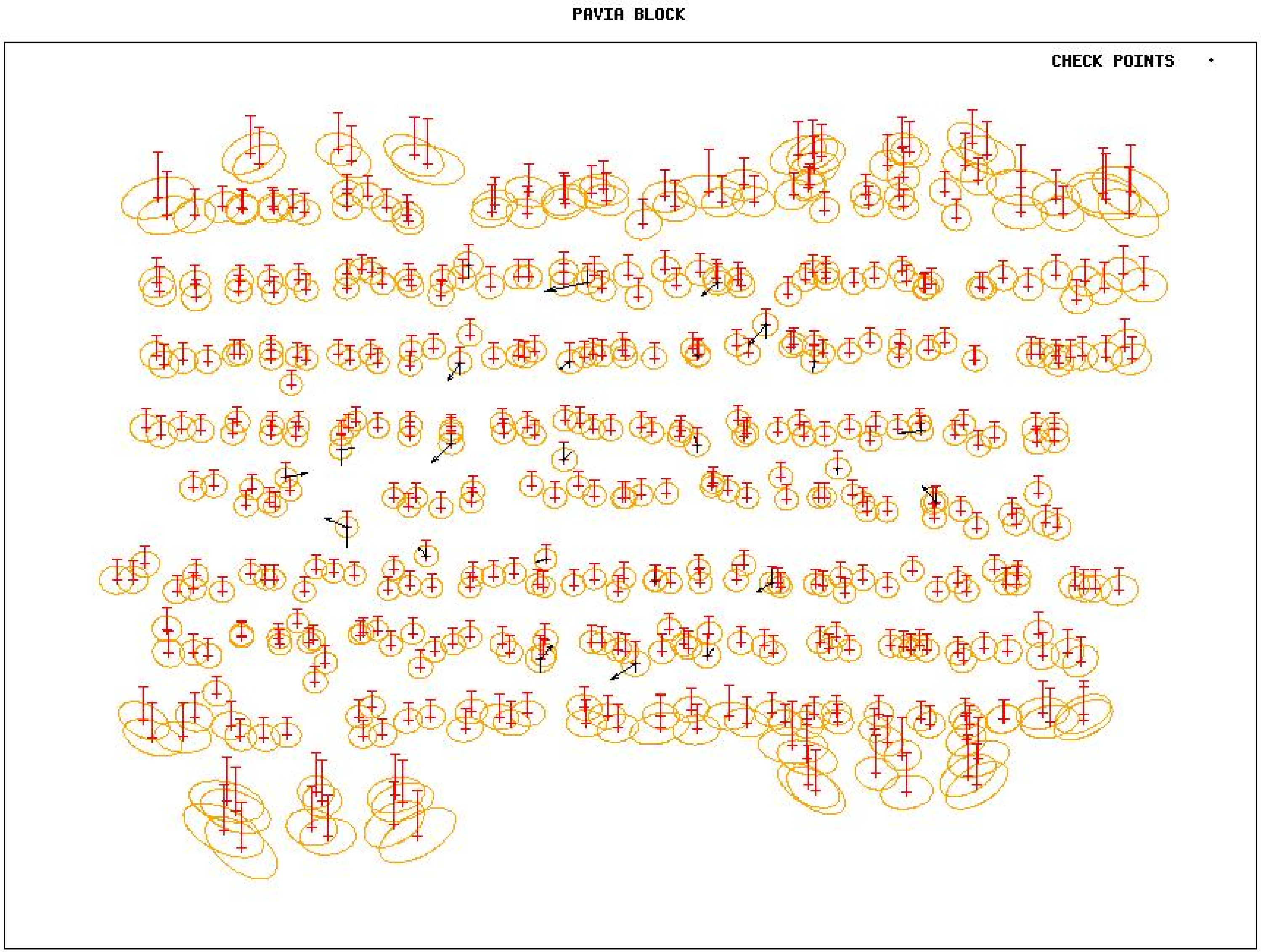
```
131 RC30 images   7+4 strips   477 points   8 GCPs   24 GcheckPs   1:8000   60%x60%

ground control points (cm)            sE, sN = 8 sh = 10
image coordinates (um)                sx, sy = 6
GPS abs. air control (cm)             sE, sN = 7 sh = 11
INS/GPS abs. air control (cm, deg)    sE, sN = 7 sh = 11  sPi, sRo = .005   sHe = .008
GPS rel. air control (cm)             sE, sN = 4 sh =  8
INS/GPS rel. air control (cm, deg)    sE, sN = 4 sh =  8  sPi, sRo = .0027 sHe = .0027
```

	GPS ABS			GPS REL			INS/GPS ABS			INS/GPS REL		
	E	N	h	E	N	h	E	N	h	E	N	h
RMS @ 24 check-points												
in cm	3.8	2.7	3.0	3.2	2.7	3.0	3.5	2.7	2.6	3.3	2.6	2.7
in um (at image scale)	4.7	3.4	3.8	4.0	3.4	3.8	4.4	3.4	3.2	4.1	3.2	3.4
in ppm (of flying height)	39	22	25	27	22	25	29	22	22	27	22	22

A [MORE] ROBUST INS/GPS CONTROL MODEL - 2 - RELATIVE



A [MORE] ROBUST INS/GPS CONTROL MODEL - 3 - ABSOLUTE



CONCLUSIONS

- After forty years of service, spatial-temporal sensor C&O continues to be a fundamental and necessary step in the geoinformation production line

  Within C&O, network modeling and adjustment continues to be an essential part as proven by its extension to almost all geomatic sensors

- Radiometric block adjustment will play a role

- Enabling technologies keep on evolving (GNSS, INS/GNSS, general matching, ...)

  Galileo and modernized GPS are the new big things to happen

- Efforts at all levels are required to improve on automation and robustness

- **... but we should not stop the modeling efforts**

There is nothing more practical than a good theory
– James C. Maxwell