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

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51. Photogrammetric Week, Stuttgart, 2007-09-05
A SUCCESS STORY

2006  AL S 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 → 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

<table>
<thead>
<tr>
<th></th>
<th>assumptions hold</th>
<th>wrong assumptions</th>
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<tbody>
<tr>
<td>standard procedure</td>
<td><em>optimal performance</em></td>
<td><em>unpredictable</em></td>
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<td></td>
<td><em>within spec</em></td>
<td><em>out of spec</em></td>
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<tr>
<td>robust procedure</td>
<td><em>sub-optimal performance</em></td>
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<tr>
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<td><em>within spec</em></td>
<td><em>within spec</em></td>
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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, \( \geq 5 \) sats
  \[ \sigma_{E,N} \approx 0.05-010 \text{ m} - \sigma_{h} \approx 0.07-0.15 \text{ m} \]
  on GPS we trust - reliability?

- **INS/GPS** position-velocity-attitude (PVA) determination - nav grade
  \[ \sigma_{\psi} \approx 0.005 \text{ deg} - \sigma_{\vartheta,\gamma} \approx 0.008 \text{ deg “abs”} \]
  on INS/GPS we trust - reliability?

- Geodetic and topographic surveying - GPS surveying
  \[ \sigma_{E,N} \approx 0.02 \text{ m} \quad \sigma_{h} \approx 0.03 \text{ m} \]

- Mono- and multi-sensorial **image correspondence** - 0.2 px mono-

- Sensor modeling and network modeling/adjustment - sensor dependent

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<tr>
<th></th>
<th>ADS</th>
<th>DMC</th>
<th>UCD</th>
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<tr>
<td>RMS at check-points</td>
<td>E/N</td>
<td>E/N</td>
<td>E/N</td>
</tr>
<tr>
<td>in ppm (of flying height)</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>65</td>
<td>50</td>
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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 × satellites, > 4-5 × 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

C.Hilker, 2007

Leica Geosystems

Glonass L1     Glonass L2     Glonass L3

Galileo L1     Galileo E6     Galileo E5

GPS L1         GPS L2         GPS L5

INSTITUT DE GEOMÁTICA

51. Photogrammetric Week, Stuttgart, 2007-09-05 – 8/31
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

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

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

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

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

\[ R_c^l(\omega, \varphi, \kappa) = R_{\psi}^l \cdot R_{b}^{b'}(\psi + v_\psi, \vartheta + v_\vartheta, \gamma + v_\gamma) \cdot R_{b}^b \cdot R_c^b(\gamma_x, \gamma_y, \gamma_z) \]

with

\[
R_{\psi}^l = \begin{pmatrix}
0 & 1 & 0 \\
1 & 0 & 0 \\
0 & 0 & -1 \\
\end{pmatrix}
\]

and

\[
R_b^b = \begin{pmatrix}
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & -1 \\
\end{pmatrix}
\]

is not used

No need to re-parameterize form \( \psi, \vartheta, \gamma \) to \( \omega, \varphi, \kappa \). 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

\[
\ell_X^l + v_X^l = X^l + R_c^l(\omega, \varphi, \kappa) A^c + S^l
\]

\[
R_c^l(\omega, \varphi, \kappa) = R_{l'b'} \cdot R_{l'b'}(\ell_\psi + v_\psi, \ell_\vartheta + v_\vartheta, \ell_\gamma + v_\gamma) \cdot R_{b'} \cdot R_c^b(\gamma_x, \gamma_y, \gamma_z)
\]

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

• \( \sigma_X \approx 0.03 \text{ m}, \quad \Delta t \approx 10 \text{ s} \quad \Rightarrow \quad \sigma_{\delta t} \approx 0.6 \text{ ms} \)

\( \sigma_V \approx 0.005 \text{ m/s}, \quad V \approx 100 \text{ m/s} \)

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 $\implies$ we are disarmed

What we usually have

$$x^e = f^e_i (y^i)$$

What we need

$$x^{e,\tau} = f^{e,\tau}_{i,\nu} (y^{i,\nu})$$

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

\[
\begin{align*}
\dot{x}^e &= v^e \\
\dot{v}^e &= R_b^e f^b - 2\Omega_{ie}^e v^e + g^e(x^e) \\
\dot{R}_b^e &= R_b^e (\Omega_{ei}^b + \Omega_{ib}^b)
\end{align*}
\]

- INS mechanization equations - Difference Equation model

\[
\begin{align*}
x_{k+1}^e - x_{k-1}^e &= \delta t \cdot v_k^e \\
v_{k+1}^e - v_{k-1}^e &= \delta t \cdot (R_b^e f^b_k - 2\Omega_{ie}^e v_k^e + g^e(x_k^e)) \\
[R_b^e]_{k+1} - [R_b^e]_{k-1} &= \delta t \cdot [R_b^e]_k \left(\Omega_{ei}^b_k + \Omega_{ib}^b_k\right)
\end{align*}
\]
MU 5: INS/GPS AND THE KALMAN-FILTER SOLUTION APPROACH

- a particular case of dynamic networks (general Gauß-Helmert formulation)
  \[ 0 = f(\ell + v, x) \] classical [static] observation equation
  \[ 0 = f(\ell + v, x, \dot{x}) \] 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

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)

GROUND CONTROL OBS

△ horizontal
• vertical
▼ full 3D

AERIAL CONTROL OBS

△ 3D full
△ 3D full + attitude
MU 6: WHAT INTEGRATED SENSOR ORIENTATION IS

GROUND CONTROL OBS
△ horizontal
• vertical
△ full 3D

AERIAL CONTROL OBS
△ 3D full
△ 3D full + attitude

IMAGE PHOTOGRAM. OBS

6 photogrammetric measurements
MU 6: WHAT INTEGRATED SENSOR ORIENTATION IS

GROUND CONTROL OBS
△ horizontal
• vertical
▲ full 3D

AERIAL CONTROL OBS
△ 3D full
▲ 3D full + attitude

IMAGE PHOTOGRAM. OBS
x photogrammetric measurements
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 $R_{cb}$ 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

\[
\ell_{X^l} + v_{X^l} = X^l + R_{c}^l(\omega, \varphi, \kappa)A^c + S^l
\]

\[
R_{c}^l(\omega, \varphi, \kappa) = R_{vl} \cdot R_{vl}'(\ell_{\psi} + v_{\psi}, \ell_{\theta} + v_{\theta}, \ell_{\gamma} + v_{\gamma}) \cdot R_{bl}' \cdot R_{c}^b(\gamma_x, \gamma_y, \gamma_z)
\]

• **New relative** position and attitude (tPA) aerial control observation equations

\[
\ell_{X_2^l} + v_{X_2^l} - (\ell_{X_1^l} + v_{X_1^l}) = X_2^l - X_1^l + (R_{c}^l(\Omega_2) - R_{c}^l(\Omega_1)) A^c
\]

\[
R_{c}^l(\Omega_2) \cdot R_{c}^l(\Omega_1) = R_{vl} \cdot R_{vl}'(\ell_{\psi_2} + v_{\psi_2}) \cdot R_{vl}'(\ell_{\psi_1} + v_{\psi_1})^T \cdot R_{vl}'
\]

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

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

MU 10: ISO AND NON-OPTICAL SENSORS

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


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 \( \{(X, Y, Z, x, y), \ldots\} \)

\[
X^l \left( (E, N, h)^T \right) = X^l \left( (E_0, N_0, h_0)^T \right) + \mu r_i^l x^i
\]
MU 11: COMPUTATIONAL vs. MAPPING COORD. REF. FRAMES

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

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

\[X^l \left( (E_0, N_0, h_0)^T \right) + J \cdot (\Delta E, \Delta N, \Delta h)^T + (\Delta E, \Delta N, \Delta h)K(\Delta E, \Delta N, \Delta h)^T + \ldots\]

\[= X^l \left( (E_0, N_0, h_0)^T \right) + \mu r_i^l x^i\]

\[J \cdot (\Delta E, \Delta N, \Delta h)^T + (\Delta E, \Delta N, \Delta h)K(\Delta E, \Delta N, \Delta h)^T = \mu r_i^l x^i\]

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

<table>
<thead>
<tr>
<th>Data Type</th>
<th>E (cm)</th>
<th>N (cm)</th>
<th>h (cm)</th>
<th>E (um)</th>
<th>N (um)</th>
<th>h (um)</th>
<th>E (ppm)</th>
<th>N (ppm)</th>
<th>h (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS ABS</strong></td>
<td>3.8</td>
<td>2.7</td>
<td>3.0</td>
<td>3.2</td>
<td>2.7</td>
<td>3.0</td>
<td>3.5</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>GPS REL</strong></td>
<td>4.7</td>
<td>3.4</td>
<td>3.8</td>
<td>4.0</td>
<td>3.4</td>
<td>3.8</td>
<td>4.4</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>INS/GPS ABS</strong></td>
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<td>22</td>
<td>25</td>
<td>27</td>
<td>22</td>
<td>25</td>
<td>29</td>
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<tr>
<td><strong>INS/GPS REL</strong></td>
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Note: RMS values are given for 24 check-points. Units are in centimeters (cm), microns (um), and parts per million (ppm).
A [MORE] ROBUST INS/GPS CONTROL MODEL - 2 - RELATIVE

PAVIA BLOCK

CHECK POINTS
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