In-flight validation and monitoring of gradiometric GOCE data

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GOCE workshop, Frascati, Nov 2006
Measurements with a real gradiometer have errors due to:

1. different scale factors
2. axes are not perfectly aligned
3. sensitive axes are not mutually perpendicular
4. internal dynamics
5. accelerometers do not occupy their nominal positions
6. origins of the 3 OAGRFs do not coincide and their axes are not aligned
7. gradiometer configuration is time-varying

→ Gradiometer calibration and validation
**Calibration/validation chain**

- Pre-launch calibration → validation
- Internal calibration → validation/monitoring = topic of this talk
- External calibration → validation

**Error on trace**

- At 5 mHz
  - Processing errors, 53%
  - Instrument-satellite coupling errors, 36%
  - Satellite errors, 1%
  - Instrument errors, 10%

- At 100 mHz
  - Processing errors, 7%
  - Instrument-satellite coupling errors, 26%
  - Satellite errors, 6%
  - Instrument errors, 61%
Internal calibration

- Determine Inverse calibration matrices (ICMs) and Quadratic factors in shaking mode(s)

- Apply parameters → internally calibrated accelerometer data

Re-calibration=validation?

- Are the calibration parameters accurately enough determined?
- Do they properly model the systematic effects in the MBW?
- Has the gradiometer configuration changed over time?
- Do we need to re-calibrate?
Validation Concept

1. **Calibration**: Determine Inverse Calibration Matrices (ICMs) and Quadratic factors in shaking mode(s) and apply them → calibrated accelerometer data

2. **Validation**: Estimated calibration matrices should contain zeros/ones
   - a Form 12 condition equations
   - b Adjust the condition equations in LS sense
   - c Determine parameters for validation data window
   - d Check estimated parameters against sensitivity bounds
Example: Condition #1

12 condition equations forming a gradiometer network

\[ a_{c,36,x} - a_{c,14,x} = 0 \]
Validation

\textit{a} Form 12 condition equations in 50-100 mHz frequency band (UMBW)

- Gradients are assumed to be negligible
- Angular rates are determined with star tracker data and gradiometer
- Condition equations are not zero and yield misclosures

\begin{align*}
    a_{c,36,x} - a_{c,14,x} &= 0 \\
    a_{c,36,x} - a_{c,25,x} &= 0 \\
    a_{c,36,y} - a_{c,14,y} &= 0 \\
    a_{c,36,z} - a_{c,14,z} &= 0 \\
    a_{c,36,z} - a_{c,25,z} &= 0 \\
    -2 \frac{a_{d,14,x}}{L_x} - \omega_y^2 - \omega_z^2 &\approx 0 \\
    -2 \frac{a_{d,25,y}}{L_y} - \omega_x^2 - \omega_z^2 &\approx 0 \\
    -2 \frac{a_{d,36,z}}{L_z} - \omega_x^2 - \omega_y^2 &\approx 0 \\
    - \frac{a_{d,25,x}}{L_y} - \frac{a_{d,14,y}}{L_x} + \omega_x \omega_y &\approx 0 \\
    - \frac{a_{d,25,x}}{L_y} - \frac{a_{d,36,x}}{L_x} + \omega_x \omega_z &\approx 0 \\
    - \frac{a_{d,36,z}}{L_z} - \frac{a_{d,25,z}}{L_y} + \omega_y \omega_z &\approx 0
\end{align*}
/b Adjust the condition equations in LS sense

® adjusted accelerations

c Determine 54 parameters

\[
\begin{pmatrix}
    a_{i,x}' \\
    a_{i,y}' \\
    a_{i,z}'
\end{pmatrix}
= K_i S_i R_i
\begin{pmatrix}
    a_{i,x} \\
    a_{i,y} \\
    a_{i,z}
\end{pmatrix}
+ \begin{pmatrix}
    n_{i,x} \\
    n_{i,y} \\
    n_{i,z}
\end{pmatrix}
+ \begin{pmatrix}
    1 + K_{i,x} & \alpha_i + \zeta_i & \beta_i - \varepsilon_i \\
    \alpha_i - \zeta_i & 1 + K_{i,y} & \gamma_i + \delta_i \\
    \beta_i + \varepsilon_i & \gamma_i - \delta_i & 1 + K_{i,z}
\end{pmatrix}
\begin{pmatrix}
    a_{i,x} \\
    a_{i,y} \\
    a_{i,z}
\end{pmatrix}
+ \begin{pmatrix}
    n_{i,x} \\
    n_{i,y} \\
    n_{i,z}
\end{pmatrix}
\]

54=6 accelerometer*(3 scales +3 rotation angles +3 non-orthogonalities)

d Check estimated parameters

® Ideally, the 54 estimated parameters should be zero. If they are not this is due to:

- validation concept not sensitive enough
- calibration/validation parameter model model wrong
- calibration parameters not accurately enough determined
- gradiometer configuration has changed over time
- other reasons
How good is the validation method in the shaking-mode?

- Apply ideal ICMs and then validate = sensitivity of the method

- Dependent on number of measurements used

- Using 1 day of data:
  - scales: $< 10^{-3}$
  - non-orthos: $< 10^{-4}$
  - rotations: $< 10^{-4}$
How good is the method?

Full Variance-Covariance Matrix

When used as a calibration tool it meets the requirements for the trace.
How good is the validation method in the science-mode?

Maximum parameter uncertainty for accelerometer 3

If the validation parameter estimates are within these bounds, the internal calibration is considered to be successful and sufficiently accurate.
Validation result in science mode after calibration with Alenia’s ICMs

Calibration successful.
Validation result in science mode after calibration with Alenia’s ICMs

Artificial scale of 1.001 on accelerometer component $a_{3,z}$

Parameter estimate after validation

→ Calibration successful.
Validation result in science mode after calibration with Alenia’s ICMs

Artificial scale of $1.005$ on accelerometer component $a_{3,z}$

Calibration not successful → Re-calibration necessary
Validation result in science mode after calibration with Alenia’s ICMs

Artificial scale of $1.01$ on accelerometer component $a_{3,z}$

Parameter estimate after validation

Effect on other parameters

→ Calibration not successful → Re-calibration necessary
Summary and Conclusions

• Internal validation/monitoring tool for the gradiometer has been developed for satellite shaking-mode data and the science-mode data
• Sensitivity of the method is about $10^{-3}$-$10^{-4}$
• Method is (almost) complete; but improvements and additional checks are currently under investigation
• Failure cases have to be studied in detail
• Link to external calibration and HPF activities planned