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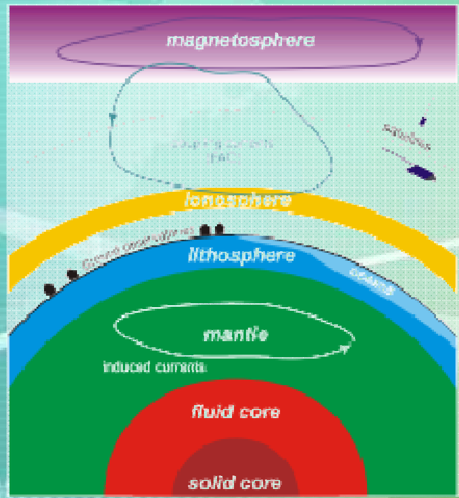

Absolute vector magnetometers for spaceborn and ground observatories

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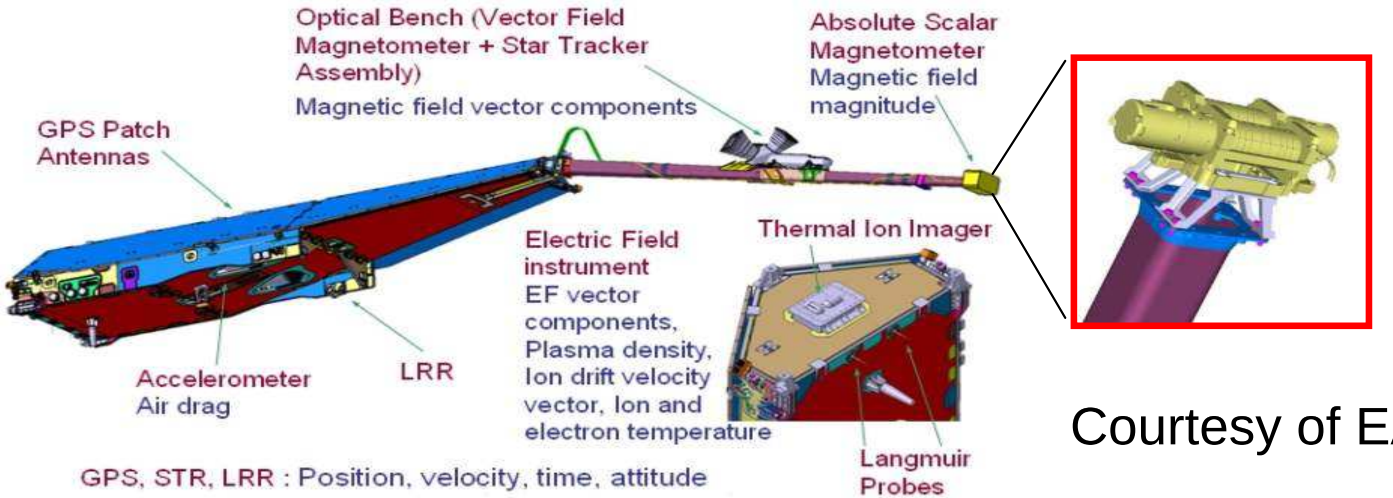
Motivations for absolute vector measurements

Traditional combination of scalar & vector instruments

- Scalar measurements are used both to calibrate the vector instrument and compensate its long term drifts (mostly offsets & transfer functions)
- Vector instruments are then operated as variometers (for which precision is the most relevant feature), while the scalar magnetometers ensure the stability measurements (accuracy being here the key parameter)



Courtesy of EADS

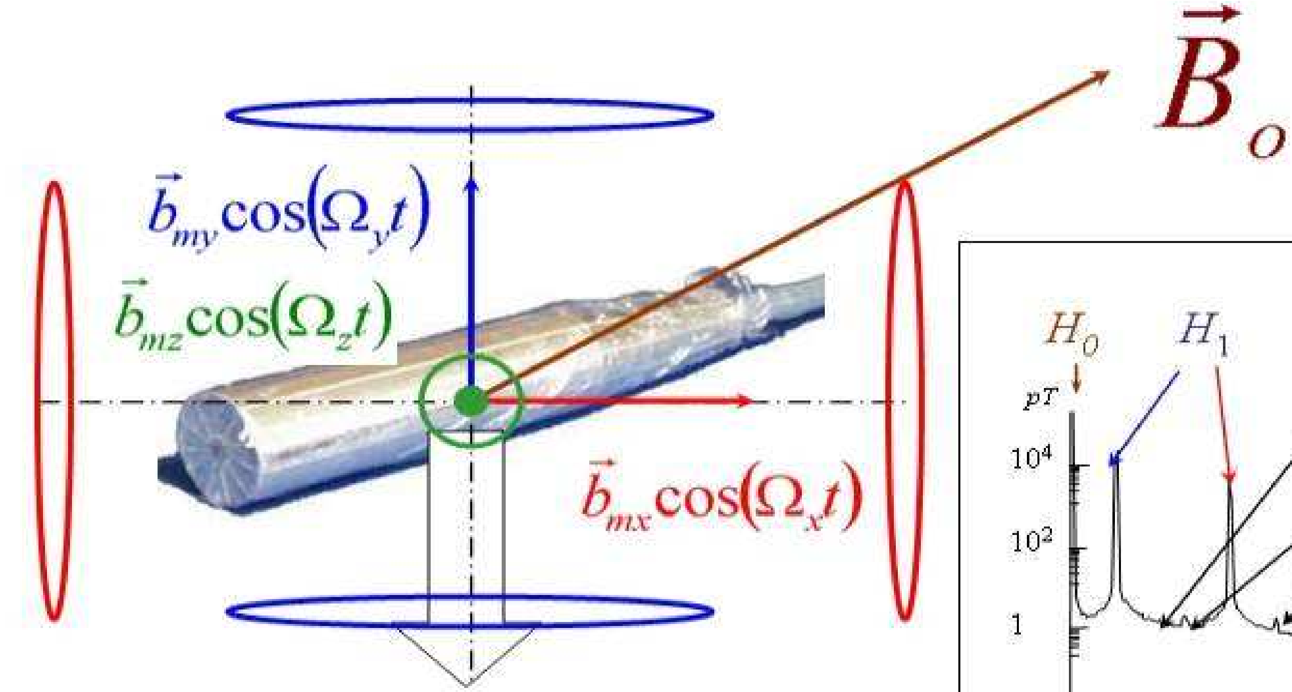
Swarm nominal magnetic payload: CSC -fluxgates- & ASM -resonance scalar sensor-

⇨ Interest to derive absolute CW vector measurements thanks to an intrinsically scalar instrument

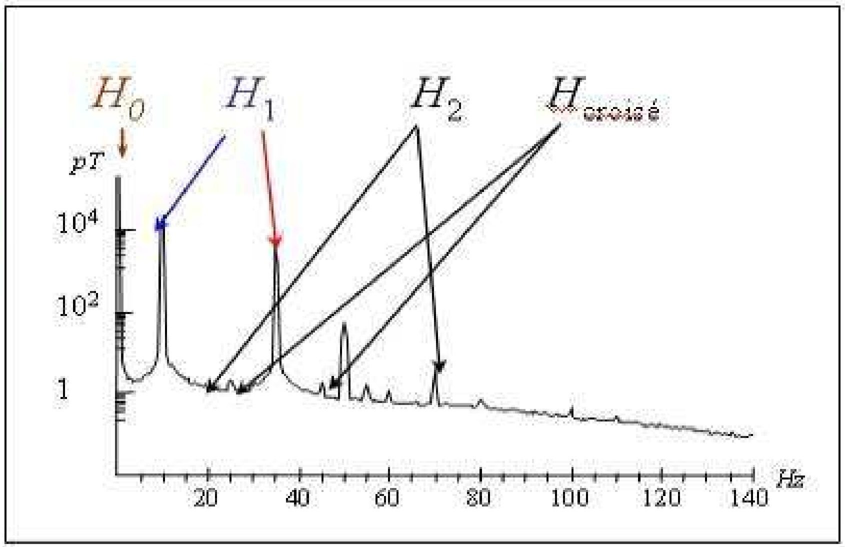
Absolute CW vector magnetometer architecture

Based on an atomic resonance scalar magnetometer (^4He sensor in our case)

Superposition of 3 ac modulations along 3 orthogonal directions



$$s = \left\| \vec{B}_{tot} \right\| = \left\| \vec{B}_o + \sum_{i=x,y,z} \vec{b}_{mi}\cos(\Omega_i t) \right\|$$



Real time analysis of the scalar output

Main specificities of such instruments

- No offsets ⇒ only six unknown parameters to be determined
  (3 transfer functions and 3 angles -deviations from orthogonality-)

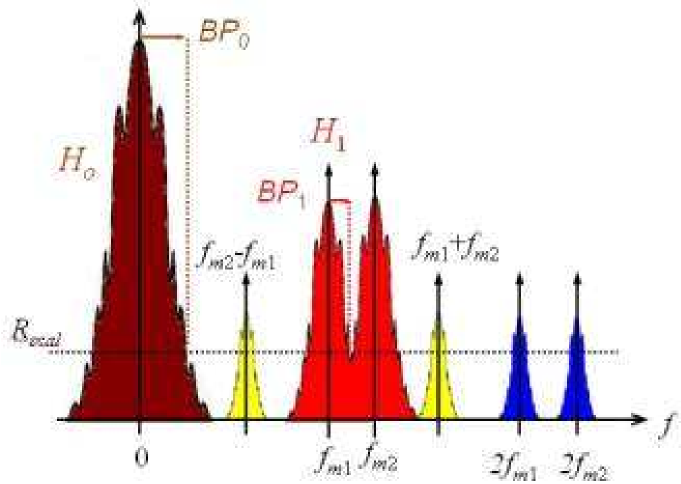
- Open loop operation
  - Easier mechanical realization (field homogeneity & temperature stability) ☺
  - High requirements on instrument operating conditions ☹

- Synchronous scalar and vector continuous measurements, taken at the same spatial point
  - Auto-scaling capabilities and permanent measurement quality assessment
  - Reduced interfaces wrt the traditional scalar/vector instruments combination
  - Perfect time synchronization (and exactly same filtering)
  - Simplified EMC (but high constraints on Low Frequency ambient noise)

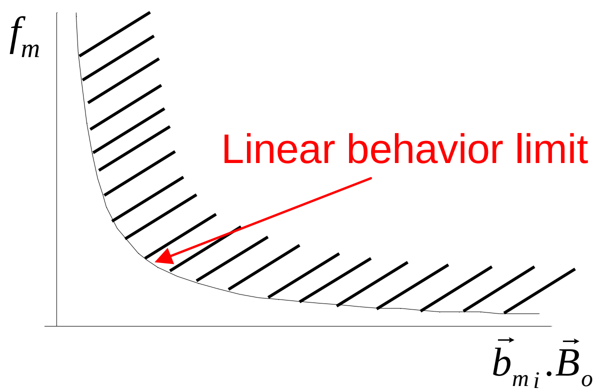
- Vector precision is proportional to B_0* R_{scal} , i.e better @ low fields (constant angular resolution)

Operational constraints

- Modulations frequencies must be chosen to avoid spectrum overlaps (limited bandwidth)
- Adiabatic conditions must be respected ⇨ $F_{m_i} * b_{m_i} * P_i \leq C^{te} (T_R, \gamma)$ (impact on precision)
- Transfer functions stability directly affects the vector measurements accuracy



- Vector resolution is degraded wrt scalar one by a factor b_{m_i} / B_0
- Ambient field noise must be below the scalar resolution at the modulation frequencies (high susceptibility to VLF magnetic environment, main instrument limitation)



Depending on the application specificities, these constraints lead to different optimizations

Mobile applications : the Swarm ASM-V

- Since all attitude configurations might be met, the worst case drives the design (modulation parallel to the magnetic field, $|P_i| = 1$)

- Modulation frequencies shall be high enough to avoid any spectrum overlap due to satellite motion (8 km/s) in the Earth field

- ^{4}He relaxation time ≈1ms

  ⬄resonance linewidth ≈ 70 nT

  ⇨ Modulation amplitude ≈ 50 nT_p (conservative)

  ($\mathfrak{M}_t$ # 14 µA.m² & $\mathfrak{M}_l$ # 8 µA.m² ⇨ < 1 pT_p @1,5 m -VFM location-)

Swarm ASM-V targeted performances

- Sampling scalar frequency 1 Hz ⇨ bandwidth ≈ 0,4 Hz

- Vector accuracy # 1 nT @ 60 µT
  - Transfer functions stability (electronics, excitation coils dimensions, atomic system response to the AC excitation) of the order of 15 ppm absolute…

- Vector precision $\sigma < 1\ nT_{rms}$ @ 60 µT (0,25 nT @ 15 µT)
  - Improvement of the modulation amplitude at the risk of non-linearities in the atomic system response to AC modulations, which would result in accuracy degradation

Swarm ASM-V calibration

Principle derived from the Oersted/Champ fluxgates calibration procedure

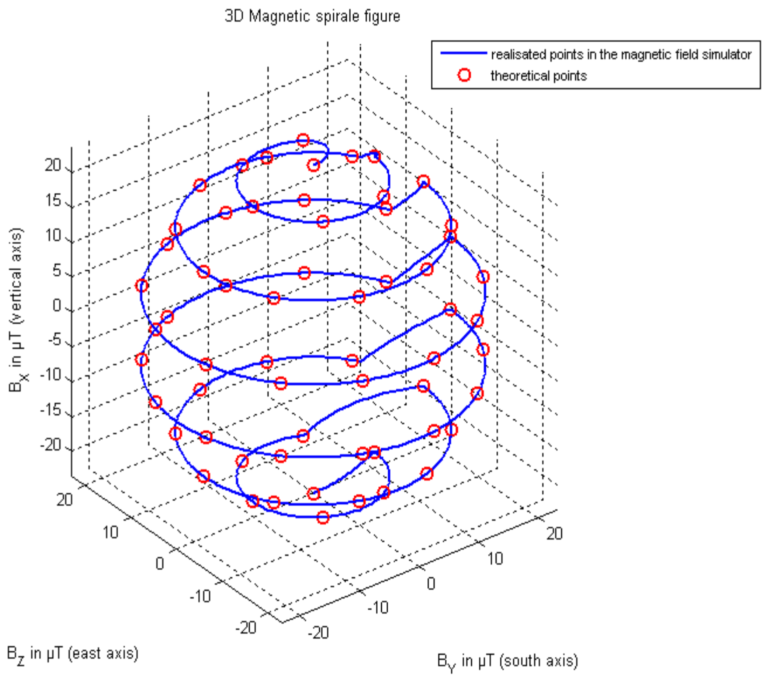
- The DC field modulus is measured by the scalar sensor B_{0scal}

- The vector measurements lead to an independent estimation $B_{0vect} = \sqrt{\Sigma_{i=x,y,z} B_{0i}^2}$

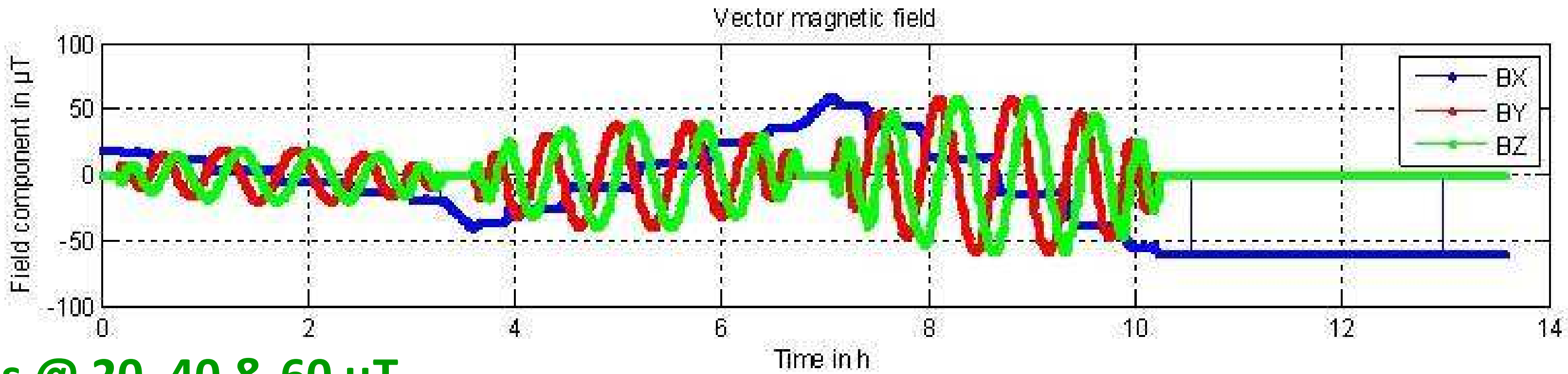
- The 6 calibration parameters (3 transfer functions and 3 angles) are obtained by minimizing the expression

$$\chi^2 = \left\langle \left(B_0\big|_{scal} - B_0\big|_{vect} \right)^2 \right\rangle$$

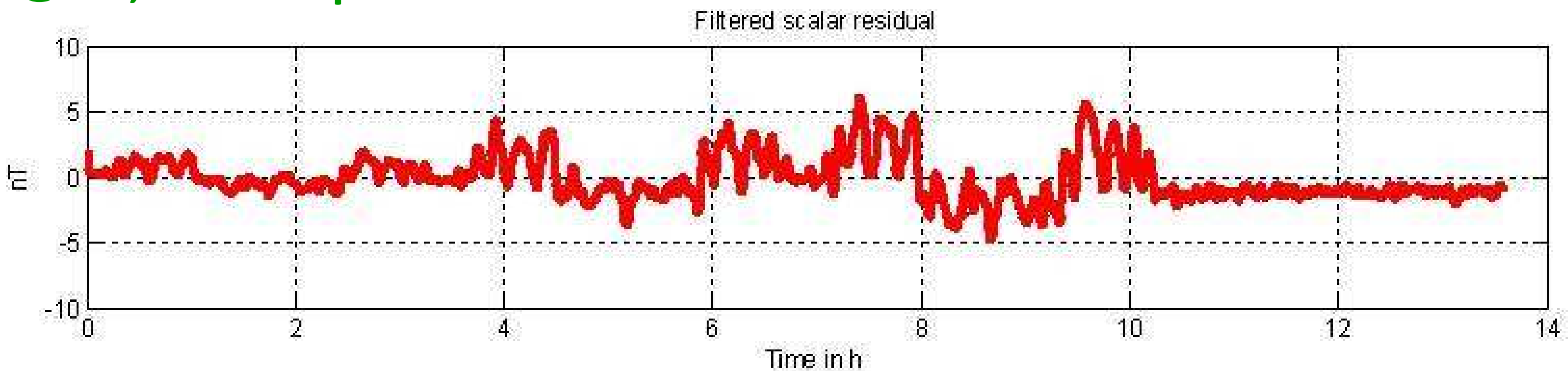
for a set of different directions (thin shell measurement)



FM1b vector calibration results



Thin shells @ 20, 40 & 60 µT



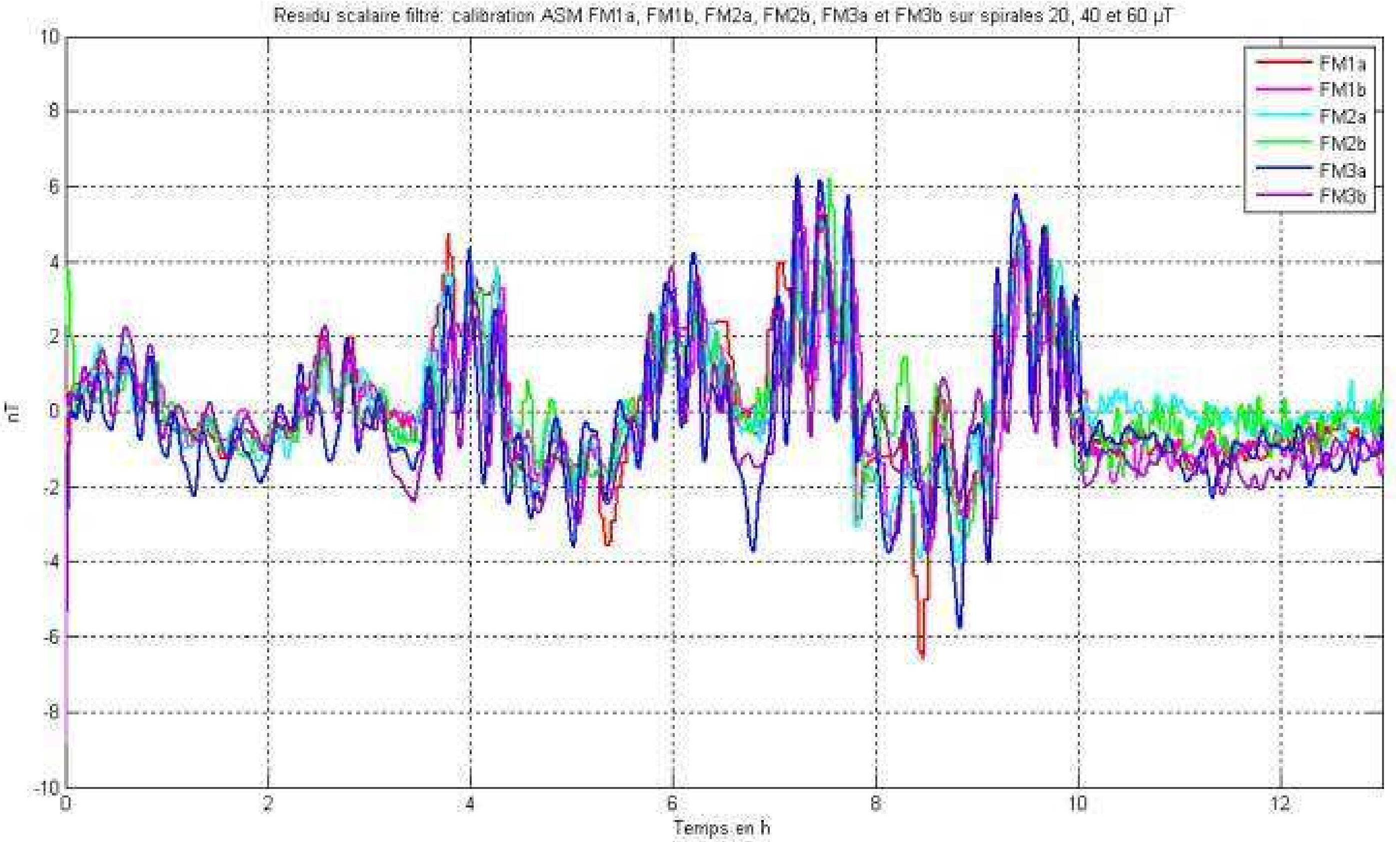
Angles of deviation from orthogonality : $\{\alpha, \theta, \gamma\}$ = {0.016° -0.130 -0.097°}

Vector coil transfer functions: $\{\beta_1, \beta_2, \beta_3\}$ = { 51.5041 nT 48.8995 nT 51.0794 nT }

Model	20 µT	40 µT	60 µT
FM1b	0,7nT/√Hz	1,1 nT/√Hz	1,7 nT/√Hz

Resolution # OK, but scalar residuals are still above targeted values (1 nT)

Comparison of FMs vector calibration results



Strong correlation for the 6 Swarm FMs tested,

comforting the hypothesis of experimental bias

(magnetic gradients on thin shell settings)

⇨search for an alternative coil facility

(low AC noise - < 1 pT/√Hz - & homogeneous field -gradients << 1 nT for ϕ 5 cm-)

Ground observations specifities

- Fixed operation ⇨ instrument installation can be accordingly optimized to achieve the best performances

- To enhance the vector resolution of these magnetometers implies to amplify the modulation excursion

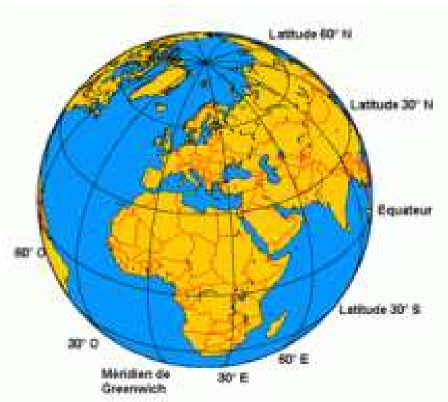
- In order to respect the maximum scalar modulation depth (related to the resonance linewidth), one can apply vector modulations only along two directions almost perpendicular to the magnetic field ($P_{i,j} \approx 0$)

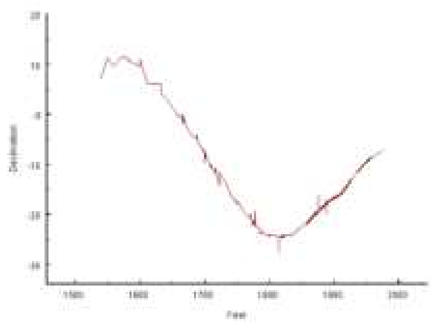
- This also directly relaxes constraints on transfer functions stability and deviations from orthogonality

Performance goals for ground measurements

- Derived from Intermagnet observatories specifications:
  - Sampling frequency: 0,2 to 1 Hz (bandwidth DC to 0,1 Hz)
  - Thermal stability: 0,25 nT/°C
  - Long term stability < 5 nT/year
  - Dynamic range < 6 µT (auroral & equatorial zones)
  - Precision: 0,1 nT
  - Accuracy: 1 nT

- Maintenance-free operation for one year achievable provided declination & inclination variation rates < 1°/yr (seems OK)





Future outlooks for ground measurements

- Design evolutions of the ASM-V architecture to adapt it to the new objectives have been finalized
  - precision enhancement ≈ * 30, i.e. $\sigma < 30\ pT_{rms}$
  - accuracy better than 0,1 nT

- Instrument qualification @ LETI premises in 2011
  (precision, environment susceptibility, short term stability)

- Stability measurements @ IPGP Chambon la Forêt observatory beginning of 2012 (comparison to reference sensors / Swarm ASM-V?)

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Thanks for your attention