Laser-pumped atomic magnetometers for space

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( Jie Qin, Visiting Scientist, 2008)
Contents

- Magnetometry requirements in science missions
- Magnetometer types
  - Flux-gate
  - Optical, He-atom cell, lamp-pumped
- Laser-pumped magnetometers
Mag-Fields measured in science missions

<table>
<thead>
<tr>
<th>Mission type</th>
<th>Dynamic range (T=Tesla)</th>
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- Other requirements:
  - Lander missions, delivery of soil into shielded environment
  - Ground-testing, shielding of geo-magnetic field, variations are ~ 10-100 nT
Space: Scalar and Vector magnetometry

- Vector magnetometry for magneto-sphere mapping
  - E.g. flux-gate type, tri-axial
  - Magnitude of field is also important
  → pointing knowledge needed
    ~ +/- 1 degree for ~ 1 % field accuracy

- This level of pointing knowledge is not trivial, affected by…
  - Spacecraft pointing knowledge
  - Location axes; magnetometer on boom

- Also, Environment stray-fields, EM interference, timing effects
  → in-flight Calibration
    - Use of scalar magnetometry
      - e.g. Cassini, both vector & scalar magnetometers
      - use of solar-wind (Interplanetary)
Space magnetometer types

• Imperial College Fluxgate Magnetometer (0 - 20Hz)
  – Highly accurate three axis fluxgate design
  – Accuracy – Better than 0.1nT
  – Targeted at space plasma and planetary missions
  – Cluster, Double Star, Cassini, Ulysses, Rosetta…
  – 40 years of in-flight experience in:
    space plasma physics and building magnetometer instruments
    (Earth and planetary magnetospheres, Heliospheric observations)

• Limitations
  – Accuracy dependent on core size, power,
  – Resource overhead
    Mass 200g, Power ~0.4W, Magnetic Cleanliness
  – Current space plasma S/C use two fluxgates on long boom
  – Alternative sensing technology needed for very small sats
  → Magneto-resistancce (MR) magnetometers being developed
Space magnetometer types

Optical magnetometer (lamp-pumped He emission spectra)

Larmor precession of atomic-spin states, radio-frequency

Absolute calibration possible:

\[
\text{frequency} = \Omega \cdot \text{field}
\]

\[
\Omega = \text{gyro-mag constant}
\]

e.g. Ulysses (US), adapted for Cassini (Imperial College)

- Vector & scalar combined
- Range/resolution
  - Vector: <250nT/5pT
  - Scalar: <16,400nT/36 pT
Laser-pumped magnetometry

- Spectroscopy of atomic lines, sensitive to magnetic field

- As per He lamp devices but:
  - Laser-pumped + heated, rather than lamp-pumped + dis-charge
    → Resonance operation, high % spin polarisation & lifetime~10ms (SERF)
      - Requires zero-field, i.e. Nulling of ambient-field via coils
      - Requires high-temp cell, ~100 deg.C.
    → high sensitivity pico-T → femto-T

Rb hyperfine spectrum (saturated absorption)
Ground-based developments femto-tesla applications

- Magnetic-gradient (Gradiometry) mapping
  - US Navy, NASA SBIR proposal “laser magnetic gradiometer”
  - earth-crust structure, earth-quake, volcanic activity studies
- Medicine (heart and brain electromagnetic)
  - miniaturisation, chip-scale ~ 1cm size (NIST, USA)
  - Mass-production
  - field-applications, arrays, advantages over cryogenic SQUID devices

- 0.1W power consumption, 35g weight
- $1500

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Space Instrument Concept

- Challenges
  - Highest sensitivity requires near-zero field
    → Require use of control system with feedback in Helmholtz coils
    → Need to combine with lower-sensitivity sensor, for dynamic range
    → Several functions in single instrument head
  - EMC
  - Pointing
  - Timing
Sensor head conceptual design

- Challenges
  - Device technologies to be engineered and qualified for space
    - Photonics devices: laser diodes, modulators (e.g. ESA-studies: Lidar, LISA)
    - High temperature cell ~ 100 deg.C
  - Proof-of-concept sensor proposed at RAL

Rb Spectroscopy bench at RAL

Design: opto-mechanical-thermal-electromagnetic...
Conclusions: Summary of Advantages:

- **Sensitivity**, (femto-tesla) for new applications in planetary science
  - requires sensor field environment to be controlled at this level

- Compact and versatile, allows to combine several functions in single head for:
  - Scalar, absolute calibrated
  - Vector, 3 axes
  - Dynamic range/sensitivity combinations

- E.g. Devices or modules of ‘standard’ type for each aspect
  - With much commonality in hardware

- **Spin-out applications**; mini-sensors for medicine, geo-physics
Outlook: femto-Tesla laser-pumped magnetometers

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- Between terrestrial and space applications, what science may drive development of this area?
  - Including the demanding field-control and calibration aspects

- Similar interest by NASA SBIR proposal, gradiometer
- Development to TRL-4

‘Cold atoms and precision sensors in space’ W Ertmer et al, Europhysics news, No.3, Vol.39

Space & Atmospheric Physics Group, Imperial College, London

Beihan Univ. Presentations and discussions, at Co-operation Meeting, BUAA, June 2011