Sub-Mesoscale Imaging of the Ionosphere with SMAP

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Overview

Baseline Mission – Soil Moisture

- **Global High-Resolution Soil Moisture:** Addresses critical science questions in water and energy cycles and enhances systems for forecast and mitigation of flash-floods, severe storms, and regional droughts
  - Extending the predictability of processes influenced by surface moisture states and fluxes
  - Supporting civilian and DoD operational agencies and decision-making

**Societal Benefits:**

- Water, Energy & Carbon Cycles
- Water and Food
- Water Quality and Human Health
- Water and the Environment
- Weather & Climate Prediction
- Severe Storm Forecasts

SMAP is not an InSAR system
SMAP Instrument Measurement Concept

Orbit: 670 km, sun-synchronous, 6 pm LAN
Antenna: ~6 m, 14.6 RPM, 35.5° off-nadir

- **“Low res” radiometer measurements:**
  - 40 km resolution, ~1000 km swath
  - Made over 360 deg of scan
  - Collected continuously; AM/PM, over land and over ocean

- **“Low res” radar measurements:**
  - 30 km x 6 km resolution “slices”
  - Made over forward 180 deg of scan only (optional 360 deg collection possible)
  - Form full contiguous swath of ~1000 km
  - Collected continuously, AM/PM, over land and over ocean

- **“High res” radar measurements:**
  - (HH, HV) and (VV, VH) polarizations
  - Used to generate 1 km gridded product can be averaged up to 3 km and 10 km.
  - Made over forward 180 deg of scan only (optional 360 deg collection possible)
  - ~1000 km swath with nadir gap of 300 km astride spacecraft ground track
  - Collection programmable; baseline to collect over land during AM portion of orbit only

Nadir gap for 180 deg radar scan: 235-300 km
Nadir gap for 360 deg radar scan: 185 km
Estimating Faraday Rotation from SMAP Multi-pol data

• For SMAP we don’t have fully polarimetric data, but…

• Measurements in nominal multi-pol (HH, HV and VH, VV) mode (ignoring system distortion terms):

\[ M_{hh} = S_{hh} \cos^2 \Omega - S_{vv} \sin^2 \Omega \]
\[ M_{hv} = S_{hv} + (S_{hh} + S_{vv}) \sin \Omega \cos \Omega \]
\[ M'_{vh} = S'_{vh} - (S'_{hh} + S'_{vv}) \sin \Omega \cos \Omega \]
\[ M'_{vv} = S'_{vv} \cos^2 \Omega - S'_{hh} \sin^2 \Omega \]

• Prime notation denotes offset in bandwidth. In general,

\[ \langle S_{pq} S_{xy}^* \rangle = 0 \text{ for any polarizations } p, q, x, y \]

• But \( \langle S_{hh} S_{hh}^* \rangle = \langle S'_{hh} S'_{hh}^* \rangle, \langle S_{hv} S_{hv}^* \rangle = \langle S'_{vh} S'_{vh}^* \rangle \) and \( \langle S_{vv} S_{vv}^* \rangle = \langle S'_{vv} S'_{vv}^* \rangle \)

• Also assume reflection symmetry \( \langle S_{xx} S_{xy}^* \rangle = 0 \) for any polarizations x, y

[Another possible approach is to use Compact Polarimetry]
How to turn SMAP into a Faraday Polarimeter

• Key Assumptions:
  1. Polarimetric system distortions (f’s and δ’s) for SMAP can be ignored or corrected (stable system)
  2. Reflection symmetry for scatterers within footprint
  3. FR and TEC related via:

\[ \Omega = \frac{K}{f^2} \int_{r_t}^{r_f} n_e B_0 \cos \theta ds \]

• To estimate FR:
  - Find a minimum for the following function by plugging in a range of trials for \( \Omega \) between zero and \( \pi/2 \) [Freeman and Saatchi, IEEE TGRS 2004]:

\[
\left\langle M_{hv}M_{hv}^* \right\rangle + \left\langle M_{vh}'M_{vh}'^* \right\rangle + \tan 2\Omega \left[ \left\langle M_{hh}M_{hv}^* \right\rangle + \left\langle M_{vv}'M_{hv}'^* \right\rangle \right]
\]

\[ \Rightarrow 2\left\langle S_{hv}S_{hv}^* \right\rangle \text{ for correct value of } \Omega (\pm n\pi/2) \]
  - PalSAR results indicate that the precision achievable is <0.5 deg which results in TEC estimates of order 1 TECU

• Results are FR rotation correction for SMAP data and a 2-D ionospheric imager with unprecedented spatial resolution (few km) and reach (global)
Simulation of Faraday Rotation Estimates from a small segment of SMAP data

- Recall that FR depends on TEC and the angle the radar look vector makes with the local magnetic field, $B_o$
- SMAP’s 360 degree scan capability means that FR will be non-zero for a wide range of scan angles (when TEC is non-zero)
- This is in contrast with most SARs, which generally have a fixed, side-looking geometry
- Note that FR values for forward and backward scan directions are different
SMAP will resolve Faraday Rotation variations (and hence TEC variations) at sub-mesoscale spatial scales within each 40x40 km footprint.
Simulation of Faraday Rotation Estimates from One Orbit of SMAP Data (forward scan)
Simulation of TEC along the Line of Sight (forward scan) for One Orbit of SMAP Data
• Space-based GPS (COSMIC) offers improvements over oceans compared with ground-based GPS but spatial resolution is still poor
• COSMIC data can be used to generate vertical profiles of TEC
Ground-based GPS networks provide GPS data that can be used to produce global ionospheric maps (GIM).

Resolutions of typical GIM are at a few hundred kilometers.
Polar Ionospheric Features Captured in PalSAR Polarimetric SAR images

- Multiple strips of enhanced Faraday rotation aligned with magnetic inclination contours are observed in a single path over polar region by PALSAR in a polarimetric mode.
- FR structures as small as 0.1~0.2 degrees are identified after smoothing to reduce noise.
- FR Discontinuity between the images raise possible calibration (by JAXA) or processing issues.
Anticipated SMAP Measurements over the Polar Region

- Sketch of SMAP annual coverage of polar cap area. The grids are in the geomagnetic coordinates. The auroral oval is estimation for medium-low geomagnetic and auroral activity.

- A-year SMAP scan can cover the entire polar cap and auroral zone

Image of auroral arcs by DMSP. [windows2universe.org]
Traveling ionospheric disturbances measured using about 1200 GPS receivers of GEONET in Japan. [Courtesy of Akinori Saito, Kyoto University; Pi et al., 2011]

Mid-latitude ionospheric disturbances measured using a GPS receiver onboard CHAMP satellite during a geomagnetic storm. [Mannucci et al., 2005.]
Figure 3. Vertical TEC anomalies at three time epochs, (a) 1 hour, (b) 20 minutes, and (c) 1 minute before the earthquake, observed at GEONET stations with the satellite 15. Positive anomalies (red color) are seen to grow near the focal region.

[Heki, 2011]
Summary:

- SMAP is a NASA Earth Science mission scheduled for launch in Spring 2014.
- It uses L-Band (λ = 24 cm) active and passive microwave instruments to infer the dielectric and surface roughness properties of the Earth’s surface.
- From these measurements, global soil moisture estimates will be derived every 2-3 days at 3-10 km resolution.
- We have developed (and validated) a new technique to estimate and correct for Faraday rotation using L-Band radar measurements.
- Applied to SMAP, this new technique will allow sub-mesoscale resolution mapping of 2-D spatial variations in TEC in the ionosphere, at 2-3 day repeat globally, and ~1-day repeat intervals in the auroral and polar zones.

A new tool to tackle space weather, Earth activities, and climate linkage questions at sub-mesoscale resolutions.