Sustainable land imaging requirements to monitor surface soil moisture with HyspIRI-like data

Michael Ramsey\textsuperscript{1} and Stephen Scheidt\textsuperscript{2}

\textsuperscript{1}Dept. of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA
\textsuperscript{2}Center for Earth & Planetary Studies, Smithsonian Institution, Washington, DC
Outline

• **Background**
  – importance of soil moisture
  – relevant HyspIRI science questions
  – what is TI/ATI and how is it measured?
    ▪ examples

• **Sustainable Measurements?**
  – HyspIRI-specific possibilities
  – limitations/synergies with other sensors (e.g., SMAP, Landsat, ...) and modeling approaches (e.g., ET/PET)
• Importance in a Changing Climate
  – soil moisture only represents ~0.05% of the global water budget
    ▪ however, it has an disproportionate influence to its volume
    ▪ fundamentally affects a variety of global climatic conditions
      ➢ e.g., vegetation, ET, soil organic matter, aridity
  ▪ in semi-arid landscapes soil moisture changes can be more impactful and can increase the mobilization and entrainment of dust, for example

White Sands, NM (MODIS: 14 March 2008)
HyspIRI Relevant Science

- **TQ3: Water Use and Availability**
  - *TQ3c:* How can we improve early detection, mitigation, and impact assessment of droughts at local to global scales?
    - as a *T-question*, the description focuses only on ET/PET

- **CQ5: Surface Composition and Change**
  - *CQ5c:* How is the composition of exposed terrestrial surface responding to anthropogenic and non-anthropogenic drivers (*e.g.*, desertification, seasonal/yearly climate change, weathering, disturbances)?
    - this *C-question* focuses only on the spectral mapping
Soil Moisture Content (SMC)

• **Measurements in Semi-Arid Lands**
  - soils experience rapid drying following precipitation
    - importance of diurnal TIR measurements
  - low vegetation makes calculation of ET more reliant on soil emissivity/composition
  - field measurements over a large geographical region
    - are difficult and expensive
      - sensitive sensors to measure low water/high salinity soils
  - influence of SMC on soil mobility/erosion
One Approach

**Thermophysical Properties**

- function of temperature differences and albedo
- able to interpret diurnal to seasonal weather-related processes:
  - soil moisture content (SMC) → *link to future SMAP data?*
  - soil erosion potential in arid/semi-arid lands
  - consolidated vs. rocky soils, soil density/cohesion

- thermal inertia: resistance of a material to change in temperature, \( I = (\kappa \rho c)^{1/2} \)

- **ATI:** apparent thermal inertia, \( ATI = NC(1-A)/(T_d - T_n) \)
  - a measure of the magnitude of the daily thermal curve moderated by albedo (A) and changes in solar flux with latitude and solar declination (N and C)
TI Modeling Approach

\[ P = \frac{(1-a)S_0C_t}{\Delta T \sqrt{\omega}} \left\{ A_1 \left[ \cos(\omega t_2 - \delta_1) - \cos(\omega t_1 - \delta_1) \right] \right\} + \frac{A_2 \left[ \cos(\omega t_2 - \delta_1) - \cos(\omega t_1 - \delta_1) \right]}{\sqrt{1+\frac{1}{b} + \frac{1}{2b^2}}} + \frac{A_2 \left[ \cos(\omega t_2 - \delta_1) - \cos(\omega t_1 - \delta_1) \right]}{\sqrt{2+\frac{\sqrt{2}}{b} + \frac{1}{2b^2}}} \]

• **Data Inputs**

  \( a = \text{albedo} \)
  \( \Delta T = \text{temperature difference} \)
  \( t_n = \text{day (n=1) and night (n=2) time} \)
  \( S_0 = \text{solar constant} \)
  \( \omega = \text{angular velocity of Earth} \)
  \( C_t = \text{atmospheric transmissivity} \)
  \( \delta_n = \text{phase difference}^* \)
  \( A_n = \text{coefficient of Fourier series}^* \)

  * values are dependent on solar declination, latitude, and maximum daytime temperature

• **Data Output**

  \( P: \text{thermal inertia (J m}^2 \text{ K}^{-1} \text{ s}^{-1/2} \text{ or TIU)} \)
  \( \text{ATI: } (1-a)/\Delta T \)

• **Sources of Error**

  **albedo:** dependent on instrument and calculation
  \( \Delta T: \text{satellite overpasses are not at maximum and minimum diurnal temperatures} \)
  \( C_t: \text{assumed to be constant or corrected} \)
  \( \text{time: overpass time: 36 hours for ASTER} \)
  \( \text{(potential error and in-scene variability, i.e., cloud, rain, etc.)} \)

[Xue and Cracknell, 1995]
Examined ASTER apparent thermal inertia (ATI) at White Sands, NM

- calculated over 8 years
- understand the relationship between
  - ATI ↔ TI ↔ SMC ↔ sediment availability
  - how are the differences in ATI over time explained for the same geographic area?
  - what are the errors in a vegetation-limited system?
  - can this approach determine SMC & sediment mobility?
ASTER Relative Albedo Changes

![Image of satellite images showing albedo changes over time from 2002 to 2008.](image-url)
Derived Thermal Inertia

11-07-2002
11-23-2002
05-04-2004
04-08-2006
04-27-2007
03-12-2008
Derived SMC

range of soil moisture content (9% - 25%)
Derived Threshold Wind Velocity

time-averaged image of the unit less erosion threshold wind velocity ratio \( \left( \frac{u^*_e}{u^*_d} \right) \)
Derived Wind Threshold Velocity

Wind Threshold Velocity

Distance (meters)
White Sands: 14 March 2008
Conclusions: Requirements

• Thermal Inertia $\rightarrow$ SMC:
  – day/night LST (*multispectral TIR ideal*)
    - < 100m spatial, < 36 hour temporal resolution
    - better resolution of LST and surface composition
  – day albedo (*multi – hyperspectral VSWIR*)
    - < 60m spatial, ~ same time as $\text{LST}_{\text{day}}$
    - NDVI assessment for vegetation cover
  – DEM availability
    - assess and remove topographic shadowing
  – can be done with a variety of current/future sensors
  – testing needed over a variety of surface types
Conclusions: *Integrative Approach*

- **Optical Sensors**
  - existing ASTER and new Landsat data
  - use of higher temporal resolution VSWIR data combined with HyspIRI TIR

- **Other Configurations**
  - ISS
    - precludes climate and solid earth science (especially at higher latitudes)
    - significant potential for soil moisture studies at mid-latitudes
      - overpass times would vary over the course of the day
      - allow temperature sampling at times excellent for ATI/TI based SMC studies
Conclusions: *Integrative Approach*

**Microwave Sensors**

- **upcoming Soil Moisture Active Passive (SMAP)**
  - SMC maps at 9 km several times seasonally
    - for example, the White Sands eolian system is ~26 km²
      - equates to ~80 SMAP pixels / ~190,000 HyspIRI pixels
    - limited in areas of steeper topography/higher latitudes
  - a unique synergy exists
    - TIR data captures different scales
    - proposing to carry out cal/val testing of the TIR approach at SMAP calibration targets
Conclusions

- **Retrieved TI, Soil Moisture, and Wind Threshold Velocity**
  - at a high spatial resolution using ASTER
  - for eolian systems
    - soil moisture is the most important parameter where estimating sediment availability
    - values are slightly higher than would be expected for the dunes
      - model needs further refinement and testing in other regions
      - however, the general trends within the dunes and over time are valid
      - detected a dramatic decrease in soil moisture in March 2008
        - several days before the largest dust storm at White Sands in over a decade (used as a monitoring tool with HyspIRI?)
sustainable land imaging notes

– 20 year period starting in 2018