USING SMALL SATELLITES TO ANSWER BIG QUESTIONS IN SOLAR-TERRESTRIAL SCIENCE

Lara Waldrop
University of Illinois at Urbana-Champaign
Department of Electrical and Computer Engineering
There is no shortage of big questions in solar-terrestrial research

For example:

- What are the effects of solar variability on the solar-terrestrial environment, including changes on decadal timescales?
  - Radiative vs. non-radiative impacts
  - Distinguish from lower atmosphere variability
  - Response to geomagnetic storms

- How are small-scale structures produced in the ionosphere and thermosphere? How do they affect global dynamics?
  - Equatorial plasma bubbles
  - Gravity waves
  - Polar cap patches

adapted from HAO Strategic Plan 2011-2015
Many space weather investigations benefit from space-based observations

- **in-situ sampling**
  - solar wind speed and composition
  - magnetospheric ion density
  - precipitating electron flux

- **large-scale earth observation**
  - \([O]/[N_2]\) via UV airglow emission
  - geocoronal density via H Lyman alpha emission
  - auroral boundary localization

- **stereoscopic remote sensing**
  - solar coronal emissions
  - ring current via ENA imaging
Small satellites are a low-cost platform for space deployment

<table>
<thead>
<tr>
<th>100 kg - 10 kg</th>
<th>10 kg - 1 kg</th>
<th>&lt;1 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsatellite</td>
<td>Nanosatellite (CubeSat)</td>
<td>Femto- and Picosatellite</td>
</tr>
</tbody>
</table>

**CubeSat protocol:**

Standardized size and mass:
- one unit (U) = 10x10x10 cm, < 1.33 kg
- can combine as 2U, 3U, 6U, etc.

Standardized deployment as secondary payloads on existing launch vehicles
Sensor and hardware development continues to push size and performance limits

PAYLOAD:
- photon detectors (spectrograph, polarimeter, photometer, ...)
- particle detectors (ion/neutral mass spectrometer, ...)
- field detectors (magnetometer, electric field probe, ...)

SATELLITE BUS:
- power systems
- attitude determination and control systems
- communication systems
- electronics
Science requirements can drive sensor development and mission design

For example, knowledge of neutral atmospheric composition is required for numerous space weather investigations, such as:

- thermospheric response to geomagnetic storms
- ion-neutral coupling and \( \text{H}^+ \) continuity: \( \text{H}^+ + \text{O} \rightleftharpoons \text{H} + \text{O}^+ \)
- tides, gravity waves
- Joule heating
- photochemical and charge exchange reaction rates
- photoelectron flux calculation

To date, long-term, global measurements are notoriously sparse. Direct sensing has not been available since the era of Dynamics Explorer...
The NSF EXOCUBE mission was inspired by a novel sensor for *in-situ* density measurement.

**PI:** John Noto, Scientific Solutions, Inc.  
**Team:** NASA/GSFC (sensor), CalPoly (bus), UIUC, ERAU, Arecibo, Univ. of Wisc.

**PAYLOAD:** dual-aperture, gated time-of-flight mass spectrometer  
mass = 560 g, size = 1.5 U
The NSF EXOCUBE mission was inspired by a novel sensor for \textit{in-situ} density measurement

\textbf{OBSERVABLE:} density of all major ion and neutral species in the upper thermosphere: \(\text{H, H}^+, \text{He, He}^+, \text{O, O}^+, \text{N}_2, \text{N}_2^+\)

\[
\frac{M}{q} = 2 \frac{E}{q} \sqrt{\frac{\text{TOF}^2}{d}}
\]

- peak power = 1.6 W (full filament),
  \(= 0.6\) W (ions only)

- mass resolution: \(M/dM \sim 12\)
  is limited by uncertainties in energy dispersion, time resolution and time of flight path.

- ionizing filament voltage governs sensitivity to neutral density
Use of COTS hardware enables rapid, low-cost fabrication and allows for student-led development

**POWER:**
Lithium-ion batteries at start-up
8 solar panels generate 2.6 W per orbit

**ATTITUDE DETERMINATION AND CONTROL:**
+/- 5° pointing knowledge along ram direction
Solar array sensor on nadir panel + magnetometer
Gravity gradient booms provide passive control
Sinclair momentum wheel on pitch axis
Magnetotorquer coils on each axis
Kalman filter control

**COMMUNICATION:**
Monopole antenna deployed via burn wire
437 MHz amateur band (one receiver initially)
~2 MB per day downlink capability
Mission design must optimize science operations within communication and power limits

- Power budget and downlink accommodates ~ 600-1000 samples/day

- Sampling period of 1 s chosen to ensure sufficient spatial resolution for science goals

- Maximizing science return demands onboard processing, target-of-opportunity sampling, and duty cycling

- Operational design must be flexible and responsive to launch opportunity once known
EXOCUBE served as a valuable proof-of-concept for direct neutral sensing...

**ORBIT:**
Launch on Jan. 31, 2015, via ELaNa-X SMAP Delta II
inclination = 98°
sun-synchronous (dawn/dusk)
elliptical (440-675 km)

---

*First flight spectrum of ions*

*Flight spectrum of neutrals (during outgassing)*
EXOCUBE served as a valuable experience for “lessons learned”...

Next time:

- De-scope dependence on curriculum-based student involvement
- Prioritize more testing in the development timeline
- Incorporate component redundancy everywhere possible
- Prepare a ground-station contingency plan in the event of communication problems
- Better prepare for potential launch delays
Mission design can also be inspired by the launch opportunity itself

*For example*, the **Exploration Mission 1** is the first planned flight of the Space Launch System and the second uncrewed test flight of the Orion spacecraft.

- Launch projected to occur in September, 2018
- Orion spacecraft will perform a circumlunar trajectory
- EM-1 will host several secondary CubeSat payloads for deployment along the sun-earth line near 5.5 Re into translunar, heliocentric orbits (assuming no propulsion)

The **EM-1 CubeSat trajectory is ideal for investigating the Earth’s neutral hydrogen geocorona**...
What drives the distribution, energization, and transport of atomic hydrogen?

- Ionization of neutral H is the primary source of TEC in the topside ionosphere.

- H readily escapes from Earth due to thermal evaporation and solar wind pickup.

- Charge exchange between H and H\(^+\), O\(^+\) ions generates energetic neutral atoms (ENAs), which dissipate magnetospheric energy after solar storms and enhance gravitational H escape.

- Solar radiation pressure perturbs gravitationally bound H and creates an extended “geotail”.

Figure 1: Flow diagram for hydrogen in the exosphere.
Sparse empiricism limits our understanding of the thermospheric and exospheric H population

Routine estimates are limited to ~90 km and from 3-8 \( R_E \)

- The low altitude estimates (via NASA/TIMED/SABER) depend on assumptions regarding MLT chemistry and are insufficient for establishing the exospheric H source

- The high altitude estimates (via NASA/TWINS/LAD) are typically derived by assuming a parametric form for the exospheric distribution and require knowledge of the solar source emission brightness and interplanetary background emission

Available data are not accurate or comprehensive enough to resolve data-model discrepancies or to advance physics-based model development

(derived from Bailey and Gruntman [2011] and Zoennchen et al. [2013])
Multi-directional measurement of H airglow emission intensity enables H density estimation

The Tomographic Hydrogen Emission Observatory (THEO)

Team: UIUC, SRI, SSI, UC Berkeley, ERAU, Arecibo

PAYLOAD: H 121.6 nm (Lyman alpha) photometer whose FOV scans in 3D via controlled rotation and nutation of satellite bus
Spinning/rotating platforms are well-suited for model-independent tomographic sensing

- Singly scattered (optically thin) emission intensity from a given vantage in a given line-of-sight direction is proportional to the underlying emitter density along the column:

\[
I[r, \hat{n}] = g \int_{r}^{r_{\infty}} [\hat{n}] \cdot N[r'] \cdot \Phi[r, \hat{n}] \, dr'
\]

- Model-independent estimation of unknown density requires sampling the emission intensity along many distinct, overlapping lines-of-sight, casting the integral equation is cast in matrix form:

\[
I = Lh + w
\]

then inverting to solve for \( h \)
Spinning/rotating platforms are well-suited for model-independent tomographic sensing

- Multi-path viewing geometry avoids need for detector calibration
- This tomographic approach is also appropriate for photometric sensing from low-earth orbit (e.g., NSF IT SPINS CubeSat)
- For O/N2, significant global improvements in assimilated Ne emerge with 6 coplanar S/C orbiting in constellation formation

Alex Chartier JHU/APL
Dynamical model: TIEGCM, High-lat model: AMIE, Solar flux: TIMED/SEE observations, Assimilation: DART (80 members of each)
As always, mission operations must balance science goals with power and communication capabilities.

Science → sampling rate → data generation rate → transmission strength and duty cycle → power requirements → instrument operation → sampling rate

Programmed transmission rate resets are designed to occur when the link margin falls below a minimum threshold.

Trade-offs between power margin, data generation margin, and communication quality must be evaluated.
Small satellites will play a big role in solar-terrestrial research for years to come

- Advancing performance in power generation, ADCS precision, subsystem efficiency, and communication links will support an increasing diversity of payloads (e.g., imaging systems)

- Development of low-power propulsion systems along with enhanced navigation and communication capabilities will enable solar system exploration

- Ongoing miniaturization of sensors and bus hardware will advance development of pico- and femto-satellites

- Widespread incorporation of deployment infrastructure and increased launch availability will enable low-cost orbit insertion for distributed or constellation missions