D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions

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Background: Motivation

- Multi-payload, multi-spacecraft constellation scheduling for spatio-temporally varying science observations
- Small Sat constellation + Full-body reorientation agility + scheduling autonomy = More Coverage, for any given number of satellites in any given orbits
- Ground scheduling algorithm allows 2-sat, 1-imager constellation over 12 hours to observe 2.5x compared to the fixed pointing approach. 1.5x with a 4-sat constellation
- Onboard scheduling algorithm allows 24-sat, 1-rainradar constellation to observe ~7% more flood magnitude than ground scheduling

Published Use Cases:
1. Land coverage and coral tracking (COSPAR ASR)
2. Cyclone tracking (IEEE TGRS)
3. Urban Floods (J.Hydrology)
D-SHIELD Proposal

**ANALYZER (Input)**

**INPUTS**
- Constellation orbits
- Ground network specs
- Instrument specs (multiple per satellite, heterogeneous possible)
- Satellite specs
- User case requirements

**OPTIMIZER**

Value as \( f(\text{grid point, time, instrument}) \), Model parameters as \( f(\text{obs}) \)

**SCIENCE SIMULATOR**

- **Measurement Value Model**
  - Nature Run (w/ synthetic observations)
- **Data Assimilation**
  - Value, params from other satellites in DSM
  - Heterogenous, agile measurement data
- **3rd Party Sensors**
  - 3rd party measurement data
  - E.g.: CYGNSS, SMAP, UAVs

**SCHEDULER**

- **Orbital Mechanics Module**
- **Attitude Control System**
- **Instrument Module**
- **Inter-Sat Comm. Module**
- **Power/ Data Module**
- **Ground Module**

Schedule = (grid point/satellite, time, instrument/radio)

**ANALYZER (Output)**

- **User's DSM** (propagated inputs + OM)
- **Natural Phenomena** (variation of Nature Run)
- **LOG Obs, Value**

**OUTPUTS**

- Overall Performance/Value
- Trade-Offs b/w Onboard and Ground Execution
**Science Relevancy Scenario: Soil Moisture**

**Goal:** Use a combination of spaceborne radar, radiometers, reflectometers to make spatio-temporal measurements that will reduce soil moisture uncertainty.

**Traditional Solution:** Design a single or constellation of instruments (size, altitude) to address spatio-temporal trade-offs *(underscored in conflict with all others)*.

<table>
<thead>
<tr>
<th><strong>Radiometric:</strong> Noise sigma Speckle Kp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial Metrics:</strong></td>
</tr>
<tr>
<td>Resolution =&gt; Static Uncertainty</td>
</tr>
<tr>
<td>Coverage =&gt; Global Understanding</td>
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<tr>
<td><strong>Temporal Metrics:</strong></td>
</tr>
<tr>
<td>Revisit =&gt; Dynamic Uncertainty</td>
</tr>
<tr>
<td>Revisit =&gt; Global Understanding</td>
</tr>
</tbody>
</table>

**Alternative Comparison:** SMAP Conical Scanning:
-30dB sigNEZ; 450m along track (AT) resolution; 3 day global coverage+revisit.

**Alternative Solution:** Science-based Intelligent Planning of Stripmap SAR:
-30dB sigNEZ; optimized* spatial resolution at the cost of speckle, coverage, revisit ~ to be addressed by more looks + measurements using constellation + intelligent agility.

* ~7m AT and >250m CT resolution
Goal: Measure to reduce Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:
1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

International Geosphere–Biosphere Programme (IGBP) 16 classes distilled into 5 relevant for Soil Moisture: Forest, Shrubland, Cropland, Grassland, Bare

Ignoring water, wetland, urban, frozen
Sources of variation over the global 9km tile grid:
1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

Will be accounted for in the speckle noise model of the science simulator

Time Series radar cross section (RCS) prediction for Walnut Gulch at L:1.57GHz, P:430MHz, VWC = 0.29kg/m², 40deg incidence, 0.02m roughness
Sources of variation over the global 9km tile grid:
1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

Hourly precipitation forecast from GEOS FP in Cubed-sphere grid C720 resolution (12 km) and ~30 km lat-lon. Using PRECTOT - Total precipitation (kg m-2 s-1) …

Ideal measurements are after long periods of dryness followed by rain, no rain after a long period of rain, etc.

Website: https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php
Forecast data: https://fluid.nccs.nasa.gov/weather/
Sources of variation over the global 9km tile grid:
1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

SMAP saturated pixel product globally available every 3 days. Interesting pixels are those that are not saturated and there has been rain recently...

Output = SM and Variance as a function of space and future time
Addressing Temporal Resolution / Science Needs

Temporally close measurements (just as neighboring pixels) can be combined to reduce speckle noise. Use inverse modeling to find maximum $\Delta T$ up to which SM dynamism does not prevent meaningful integration => $\Delta T=2$ hours

1000+ rows of combinatorics for 2 sats
Planning Ops using dynamic knowledge and forecast of soil moisture and precipitation. Season, vegetation, soil types are known constants.
Planner: Optimizing the Observation Schedule

Search space size for a single satellite:
- 24 hours (4 x 6-hour plans), 1-s increments (86.4k s)
- 2 instruments (L-band, P-band)
- 62 viewing angles/instrument
- 41,500 Access Time Points (TP)
- 1,662,486 Ground Positions (GP)

Pre-processing for choice flattening (reduces space by 65%)
Uses Constraint Satisfaction Problem (CSP) Algorithm to find solution

Science value = 1-retrieval error/0.04 as a %
Over 24 hours by single sat:
Interesting land cover GPs = 1.662m
Rainy, unsat. GPs = 307.9k-309.8k
Total observed GPs = 53.4k (3.2%)
Rainy, unsat. observed GPs = 15.6k (~5%)

For 1 horizon of 6h:
Interesting land cover GPs = 637k
9.8k variables, 3.8mins to solve
Adding all constraints and heuristics
~16k GP, 3.2k variables, 43s to solve

Very prelim Planner: Single Sat has 15% SMAP temporal coverage at 60x AT spatial resolution

Video: https://sreejanag.github.io/Videos/eosim_demo_5x.mp4
Extending the Constellation

**Initial Constellation:**
Single Plane, 3 sats, 2 radars on each

**Extended Constellation:**
Single Plane, 6 sats, heterogeneous distribution of instruments with shared antenna
Minimized Cost and Revisit time of every instrument using **VASSAR Tool**, w/ spacecraft sizing applied to custom instrument

<table>
<thead>
<tr>
<th>ID</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L-band SAR</td>
</tr>
<tr>
<td>2</td>
<td>P-band SAR</td>
</tr>
<tr>
<td>3</td>
<td>Antenna (sized for P-band)</td>
</tr>
<tr>
<td>4</td>
<td>P-band Reflectometer</td>
</tr>
<tr>
<td>5</td>
<td>L-band Reflectometer</td>
</tr>
<tr>
<td>6</td>
<td>FMPL-2 (L-band radiometer)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>True Anomaly</th>
<th>Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat 1</td>
<td>0 deg</td>
<td>All</td>
</tr>
<tr>
<td>Sat 2</td>
<td>60 deg</td>
<td>ID 3-6</td>
</tr>
<tr>
<td>Sat 3</td>
<td>120 deg</td>
<td>All</td>
</tr>
<tr>
<td>Sat 4</td>
<td>180 deg</td>
<td>ID 3-6</td>
</tr>
<tr>
<td>Sat 5</td>
<td>240 deg</td>
<td>All</td>
</tr>
<tr>
<td>Sat 6</td>
<td>300 deg</td>
<td>ID 3-6</td>
</tr>
</tbody>
</table>

**Reference:** B. Gorr, A. Aguilar, D. Selva, V. Ravindra, M. Moghaddam, S. Nag, “Heterogeneous Constellation Design for a Smart Soil Moisture Radar Mission”, IGARSS 2021
Extending the Planner

- To multiple satellites with follow-up observations within $\Delta T$ and beyond
- Time constraints to slew between observations
- Ensure image lock for strip-map image
- Constraints for energy consumption by the instruments and slewing ADCS module
- Constraints for energy budget for given battery size and eclipse times

<table>
<thead>
<tr>
<th>Plan for sat 1:</th>
<th>Time</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[2-4]</td>
<td>P.48</td>
</tr>
<tr>
<td></td>
<td>[5-14]</td>
<td>Idle</td>
</tr>
<tr>
<td></td>
<td>[15-17]</td>
<td>L.48</td>
</tr>
<tr>
<td></td>
<td>[18-36]</td>
<td>Idle</td>
</tr>
<tr>
<td></td>
<td>[37-40]</td>
<td>Slew</td>
</tr>
<tr>
<td></td>
<td>[41-43]</td>
<td>L.44</td>
</tr>
<tr>
<td></td>
<td>[44-45]</td>
<td>Slew</td>
</tr>
<tr>
<td></td>
<td>[46-48]</td>
<td>P.45</td>
</tr>
<tr>
<td></td>
<td>[49-49]</td>
<td>Idle</td>
</tr>
<tr>
<td></td>
<td>[50-51]</td>
<td>Slew</td>
</tr>
<tr>
<td></td>
<td>[52-54]</td>
<td>P.46</td>
</tr>
</tbody>
</table>

**Experiment Results:** Preliminary experiment results are presented below for our example with 3 satellites with a 6-hour planning horizon. We define $\text{maxError} = 0.04$ = our maximum allowable model error. All GP are initialized with a default error $= \text{maxError} = 0.04$.

<table>
<thead>
<tr>
<th>Heuristic</th>
<th># images (makespan)</th>
<th># of GP observed</th>
<th>Avg Err /GP</th>
<th>maxErr %</th>
</tr>
</thead>
<tbody>
<tr>
<td>MinGpChoiceErr</td>
<td>6,445</td>
<td>14,401</td>
<td>.015</td>
<td>0.375</td>
</tr>
<tr>
<td>MinGpChoiceRank</td>
<td>6,459</td>
<td>19,866</td>
<td>.023</td>
<td>0.525</td>
</tr>
<tr>
<td>MaxGpCount</td>
<td>6,452</td>
<td>24,641</td>
<td>.025</td>
<td>0.625</td>
</tr>
</tbody>
</table>

**Figure 7:** Preliminary experiment results comparing three local heuristics.

Other Modules that serve as Input to Planner

https://arxiv.org/abs/2102.07940

Publicly available Source Code on Orbit, Instrument, EO Simulator:
Thank you!

Questions?
Sreeja.Nag@nasa.gov
Backup Slides
Science Relevancy Scenario: Urban Floods

5-42 cities assumed flooded simultaneously over 6 hours

Value Function Snapshot

Data: Dartmouth Flood Observatory (Brakenridge 2012)


Results: S. Nag, et al, "Designing a Disruption Tolerant Network for Reactive Spacecraft Constellations", AIAA ASCEND, Nov 2020
Addressing Spatial Resolution / Instrument Design

- **Instrument Design**: Create potential SARs in L,P band with comparable to SMAP’s \( \sigma_{\text{NEZ}} \) but different operating modes
- **Considerations**: PRF, full or fixed swath, polarization
- **Modes**: StripMap, Scan SAR, spotlight SAR
- Used NSGA II for MOO
- **Variables**: Pulse width, Chirp bandwidth, Antenna beamwidth in Azimuth and elevation
- **Objectives**: Antenna area, swath, \( \sigma_{\text{NEZ}} \), looks per km
- **Future instruments**: Radiometers and Reflectometers can be used from existing missions in the L and P band
Observation Planner: Optimizing the Schedule

Planner-centric View to **decide** what to look at, **when** to look at it and **how** to look at it i.e. Choose command `<instrument, viewing angle>` **for all available viewing times**

Planning Horizon = 6 hrs (representative of commercial sc-gs contacts)
Local and Global Heuristics are ongoing topics of research:
1. Max Coverage maximizes number of GPs seen but does not use science value
2. Choice Score maximizes science value without accounting for GPs seen
3. GPscore maximizes product of GPs and science value (current POR)
4. Other options: max GP choice rank, max RareGP (TBD with improved science simulator)

\[
\text{science value} = \frac{1 - \text{retrieval error}}{0.04} \quad \text{(after ranking for seen, rain, saturation)}
\]