ElectroScience Lab, Department of Electrical and Computer Engineering

Software Library for Simulation of Collaborative Sensor Networks for Navigation and Remote Sensing

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Objective

Next-generation sensor networks inhabit a complex decision space involving autonomous optimization for resource management and hardware reconfiguration. These advanced systems must collaborate through wireless links to succeed, in the interest of maximizing the value of measurements. An open-source software library is under development for modeling and analysis of collaborative networks of adaptive sensors on spaceborne platforms.

Problem Statement

- Autonomous spaceborne remote sensor webs are an emerging technology
- Current observing system simulators do not support these capabilities:
  - Dynamic observation geometry, communications, collaboration, and sensor adaptation
- System must quantify and forecast science value of sensor measurements
- Satellites must communicate collaboratively (and efficiently)
- Code must have free license and public distribution

Software Library Features

Collaborate is a Linux software package containing a C++ simulation development library and Python visualization and analysis modules. Code is published to a Git repository under the LGPLv3.0 license.

Satellite Physics

Attitude Frames
Linear algebra support for *Orbit*, *Body*, and *Accessory* frame transformations

Communication & Sensing Interfaces
- *Modems* to model UHF and Globalstar links
- *Sensors* as an interface to the truth data

Antennas
Define directional RF power and sensor resolution

Solar Panels
Receive the Sun's energy with realistic physical constraints

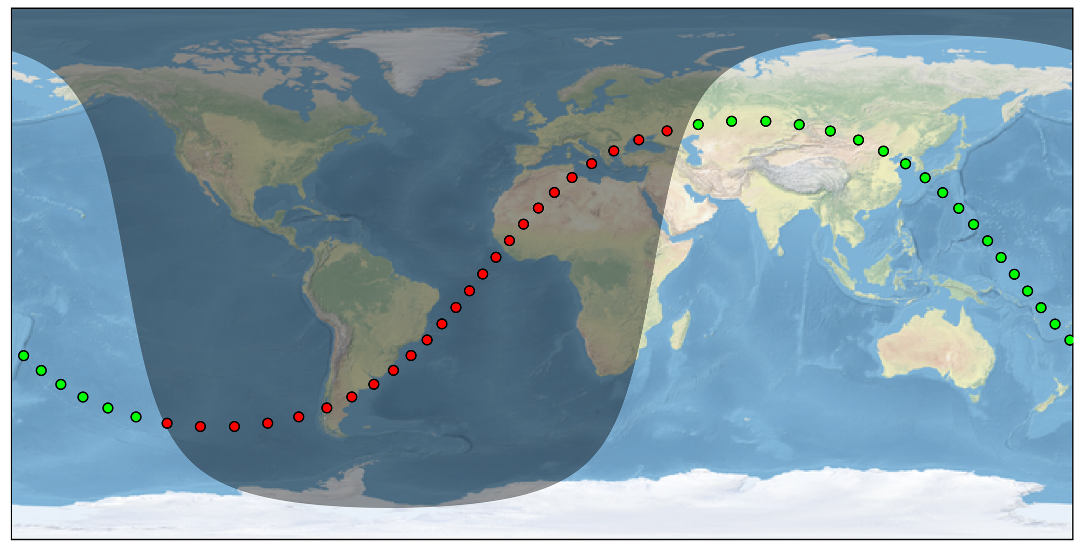

Figure 1: *Solar Panel* power for one complete orbit: Green → $\theta_{LOS} > 0$

Batteries
Store energy for all satellite activities

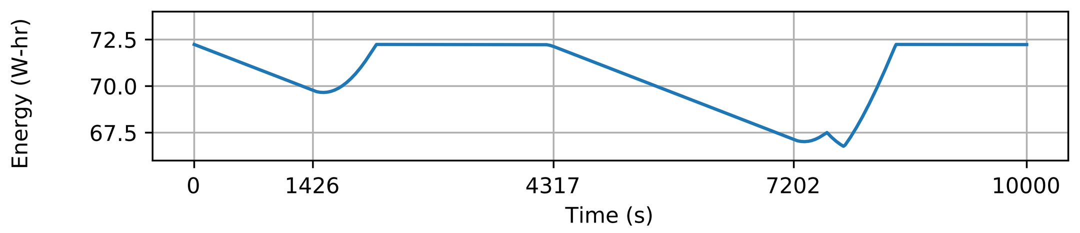

Figure 2: *Battery* energy stored in time for two complete orbits.

Satellite Constellation Design

Constellations are formed using orbit models defined by the standard two-line element (TLE) set.

```
CUBERRT
1 43546U 98067NU  19051.50068816  .00005646  00000-0  73930-4 0  9999
2 43546  51.6373 215.9656 0005459  50.2329 309.9144 15.60284412 34513
```

These models can be modified and duplicated for the design of complex constellations. Patterns are formed by adjusting orbit parameters.

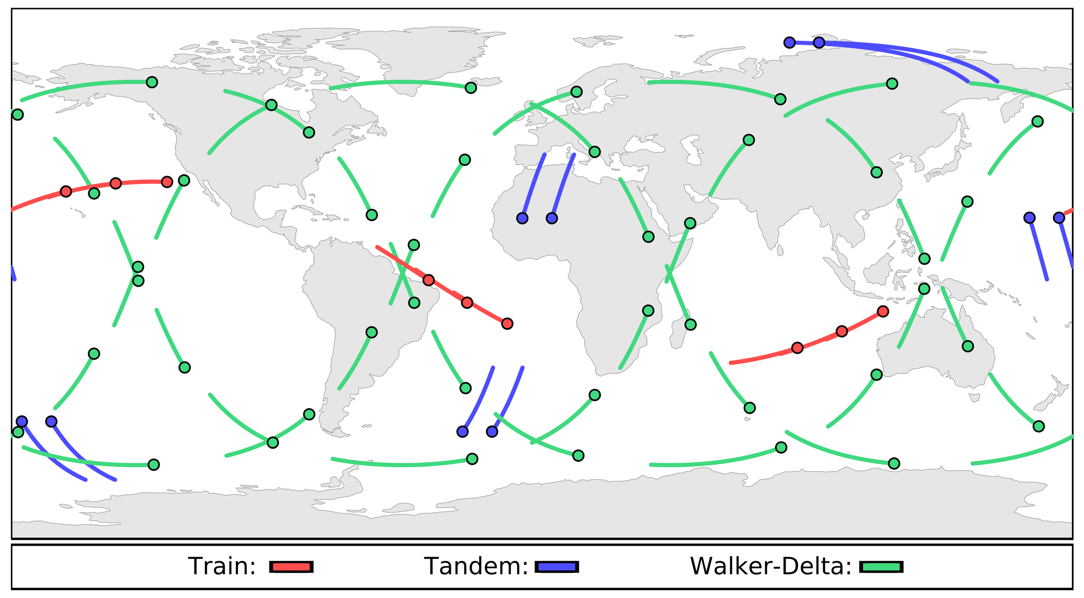

Figure 3: Constellation design by duplicated and modified TLE sets

Network Structures and Algorithms

Graphs
Weighted and *Unweighted Graphs* capture communication parameters and the existence of viable line-of-sight wireless links among individual satellite nodes.

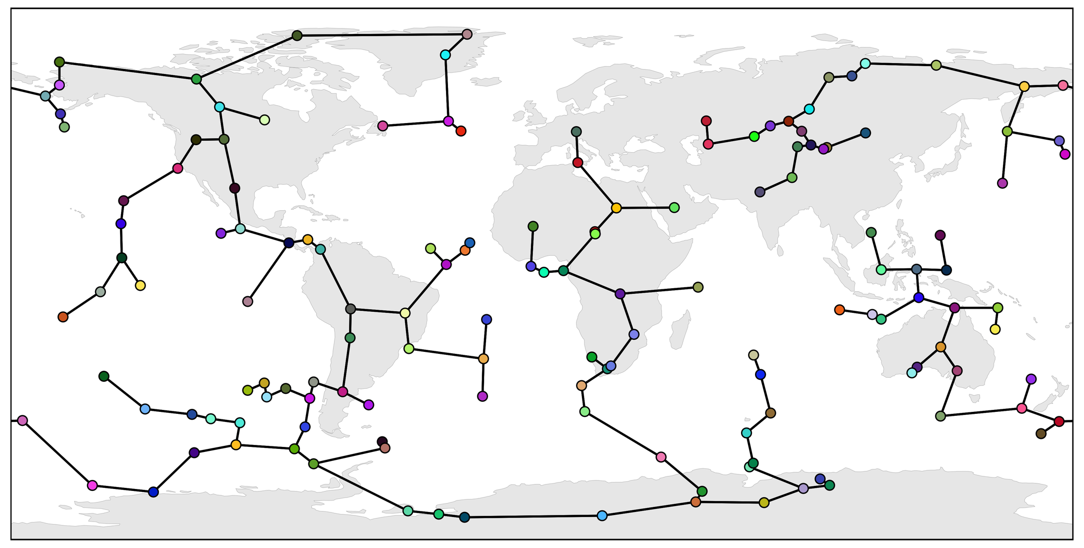

Figure 4: Prim's minimum spanning tree - based on line-of-sight RF parameters (gain, etc.)

Trees
Network algorithms use *Trees* to compare alternate communication routes. These sensor networks are fully dynamic (nodes are in motion and limited in resources), so tree nodes store identities and timestamps.

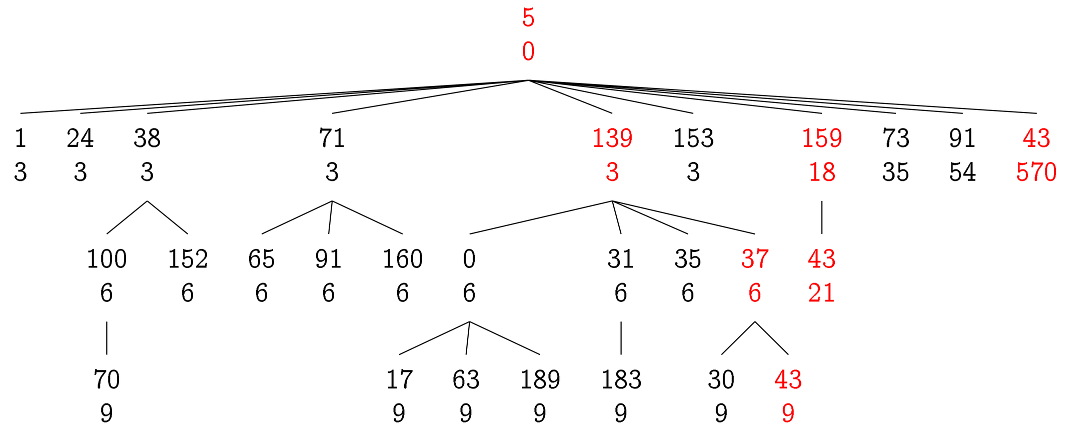

Figure 5: *Tree* storing possible communication routes - nodes store identity and timestamp

Collaborative Remote Sensing

The model illustrated below generalizes adaptive hardware and resource management for satellites capable of processing and communication.

Collaborative Sensing Model

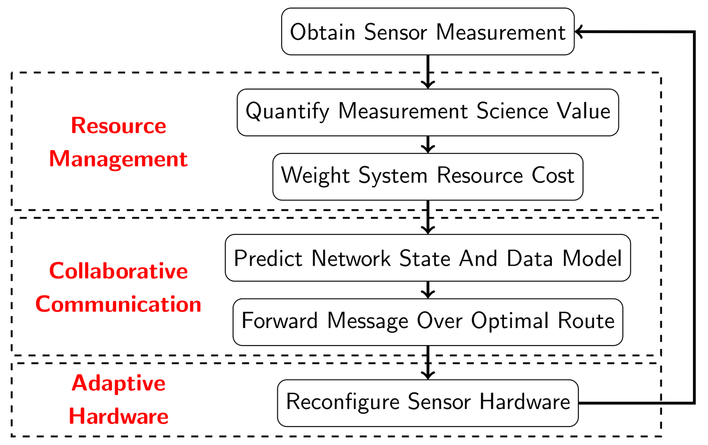

Figure 6: Collaborative sensing model highlighting the role of communication

Truth Data

Satellites measure atmospheric NetCDF data from NASA's Ganymed GEOS-5 Nature Run. Variables of interest include *optical cloud depth* and *precipitation*.

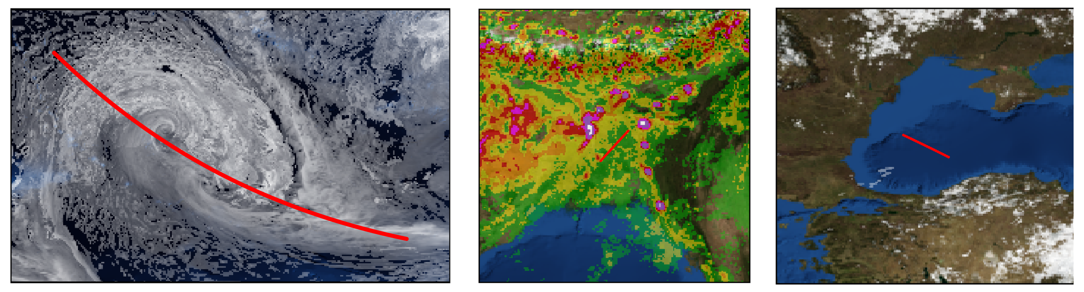

Figure 7: Satellites sensing Nature Run data - (clouds, precipitation, and optical images)

Scheduling Optimal Communication Routes

The *Collaborative Communication* section in Figure 6 involves:

1. Internal data processing and simulation to identify:
   - Potential target satellites
   - Optimal communication route for efficient information transfer
2. Serialization of important data (including the route) into *Packets*

Considerations
- Networks are often sparse, with no direct link possible
- Time constraints exist based on positions and velocities
- Multiple possible routes exist for communication

A *Predictive Route Optimization Algorithm* is implemented and introduced.

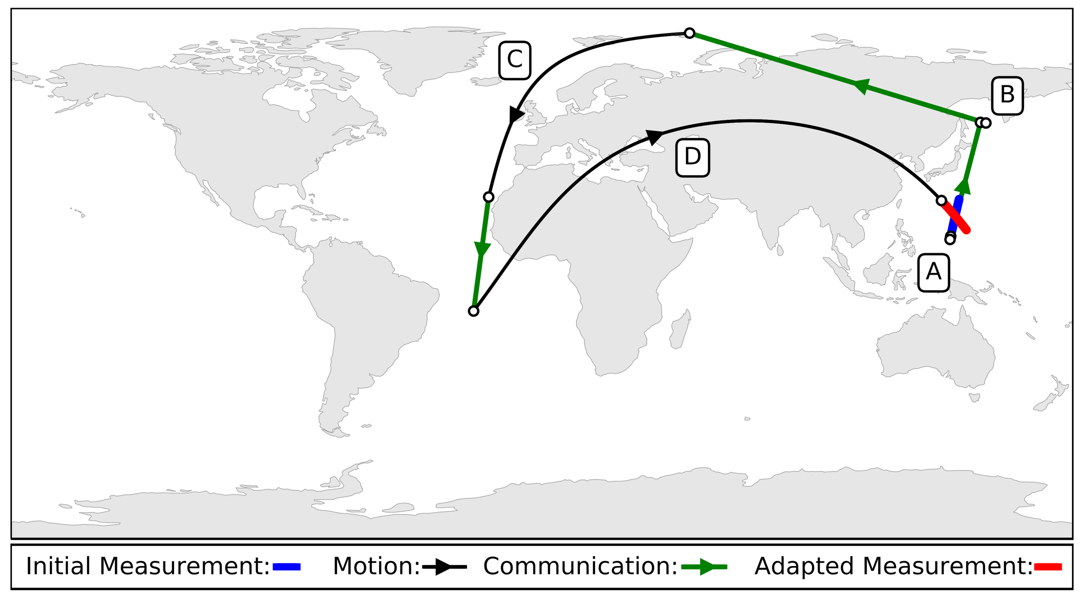

Figure 8: *Collaborative Sequence* - initial measurement, route, and adapted measurement. Algorithm has identified opportunities to delay transmission in anticipation of contact.

Quantifying Benefits of Collaboration

High correlation between cloud depth and precipitation data is visually observed. Precipitation is typically present where clouds exceed threshold α_c.

β_c=225m, α_c=75m β_p=1cm, α_p=1mm

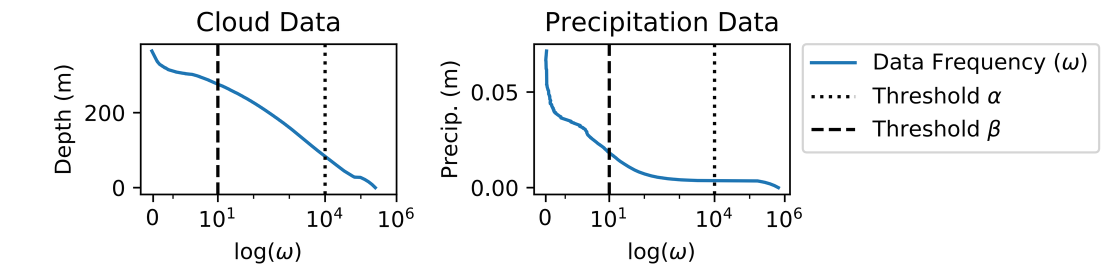

Figure 9: Magnitude thresholds for *low*, *medium*, and *high* cloud-depth and precipation.

Three heterogeneous sensor constellations are formed, inclination ≈ 51°:

Sensor	Goal
Cloud Radars	None
Precipitation Sensors	Maximize precipitation measured
Optical Imagers	Minimize depth of obstructing clouds

Two simulations are performed to measure improved mission science returns

1. Isolated satellites
   - No communication
   - Random measurements and short duty-cycle
2. Collaborative satellites
   - *Source* satellites are the *cloud radars*, which process data internally
   - Identify target regions based on cloud depth threshold (α_c)
   - Calculate optimal routes and formulate packets
   - *Sink* satellites are *precipitation sensors* and *optical imagers*
   - Queue precipitation sensors for medium clouds (depth > α_c)
   - Queue optical imagers for the absense of clouds

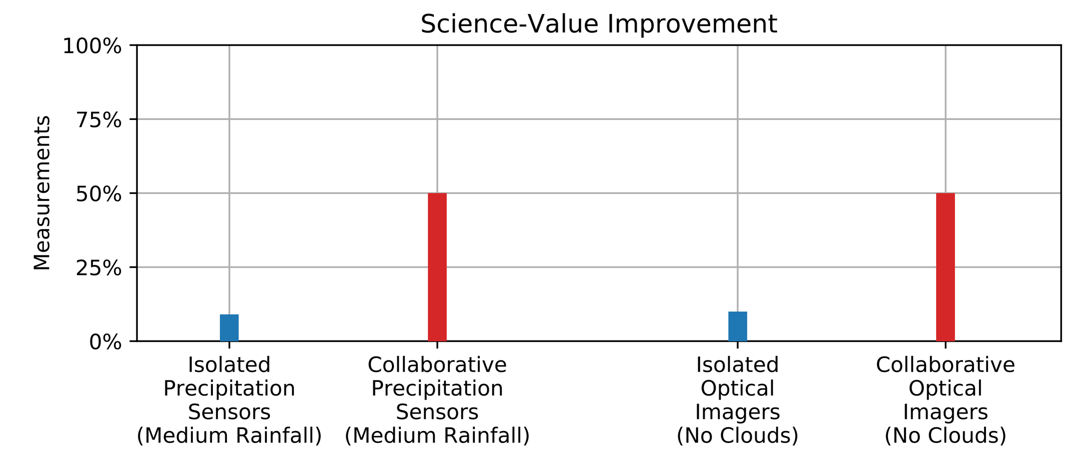

Figure 10: Quantitative improvement in the science-value of sensor measurements.

Publications

"Using Cognitive Communications to Increase the Operational Value of Collaborative Networks of Satellites". NASA Glenn, CCAAW, 2019.

"Multiplatform Mission Planning And Operations Simulation Environment For Next Generation Small Satellite Missions". Utah, SmallSat, 2019.

"Open Source Software for Simulating Collaborative Networks of Autonomous Adaptive Sensors". Yokohama, Japan, IGARSS, 2019.

Conclusion

The Collaborate library offers a number of modeling and analysis capabilities for observing system development: solar power management; realistic sensing platforms; wireless communication interfaces; network algorithms and data structures; and constellation design based on standard orbit models. A model for collaborative networking provides a scheme for network resource management and sensor reconfiguration. The example illustrates increased science return through cloud targeting and avoidance by sensor collaboration.