Enabling the Next Generation of Small Satellite Missions by Optimization of Communication Networks

Sara Spangelo (saracs@umich.edu)
James Cutler (jwcutler@umich.edu)

*Michigan eXploration Labs (MXL)*
Dynamics & Control
Aerospace Engineering
University of Michigan, Ann Arbor

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Communication is major constraint for small satellites!

Growing satellite community science missions

- Downloading large amounts of data limited by infrastructure.
- Small satellites are highly constrained by mass, size, power, cost, risk.

Limitations of existing ground station infrastructure

- Systems are complex, non-standardized, and have reliability issues.
- Existing systems are monolithic and designed for single missions.
- Existing ground stations are largely underutilized!

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Image Credit: Allison Craddock
How can we use federated ground networks to solve this problem?

**Proposed Solution:**
Federated Ground Station Networks

**Stages of problem:**
1. Micro-scale: spacecraft dynamics
2. Macro-scale: satellites and ground station dynamics
Why is the FGSN scheduling problem hard?

1. Maximizing total/spacecraft network capacity
   *Scientist: Get me more data!*

2. Sharing of resources for multi-satellite constellations
   *Satellite Operators: Share resources according to needs/priorities*

3. Complex satellite dynamics
   *Limited ability collect/store data/energy*

4. Ground Station Networks:
   *Limited capacity/capability*
So what ingredients are needed to take advantage of FGSNs?

1) Ground Station Model
2) Satellite Model
3) Simulation Tools
4) Representative Data
5) Optimization Tools
1) We need a ground station model which captures diverse networks.

**Capacity:** Amount of information exchanged across the network\(^1\)

\[
C_i = \sum_{j=1}^{m} \int_{0}^{T} a_{ij}(t) \cdot r_{ij}(t) \cdot l_{ij}(t) \cdot \eta_{ij}(t) \, dt
\]

- **Availability**
- **Data rate**
- **Link feasibility**
- **Efficiency**


\(i: \text{satellite}\)

\(j: \text{ground station}\)
2) The satellite model needs to capture on-board dynamics.
3) Ground Station Survey has provided info on over 100 stations!

CubeSat Ground Station Community

Fill out the survey here: http://gs.engin.umich.edu/gs_survey/
3) Satellite Survey has provided info on over 15 satellites.

Representative Satellites from Survey

Estimated orbits based on survey results

Satellites from Survey: F-1, XSAS, Explorer-1 [Prime], FIREBIRD, KySat-1, DICE, myPocketQub, 391, NPS-SCAT, Aalto-1, PACE, Trailblazer, RAMPART, STRaND-1, Draco/GragonSat-1, Inklajn1, CCSWE

Fill out the survey here: http://gs.engin.umich.edu/sat_survey/
3) Here are some interesting statistics on the satellite survey.

![Bar Graph: Maximum Allowable Time Between Downloads]

- **≤1 day**
  - Number of Satellites: 3

- **>1 day to ≤1 week**
  - Number of Satellites: 2

- **>1 week to ≤4 weeks**
  - Number of Satellites: 4

*Preliminary survey results*

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- Results
- Conclusion
3) Here are some interesting statistics on the satellite survey.

**Expected Data Downlink Rate**

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Number of Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1200 bps</td>
<td>5</td>
</tr>
<tr>
<td>&gt; 1200 - 9600 bps</td>
<td>5</td>
</tr>
<tr>
<td>100 kbps</td>
<td>1</td>
</tr>
<tr>
<td>1.5 Mbps</td>
<td>1</td>
</tr>
</tbody>
</table>

Preliminary survey results
4) The simulator first identifies the inputs to the satellite scheduler.
4) Next we model/simulate the on-board energy and data dynamics.
5) So what exactly are we optimizing?

Two goals in optimizing communication capacity:
1. Maximizing total network capacity
2. Sharing of resources for satellites

Decisions (for each satellite):
1. When/what ground stations?
2. What rate/amount to downlink

Constraints:
1. Satisfying minimum downlink requirements
2. Limited availability for communication
3. On-board satellite dynamics (data, energy)

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5) Don’t forget about all those constraints…

Only a single communication link

Data restricted by time/rate

Energy balance within bounds

Data balance within bounds

Initial/final conditions

Power difference

\[ 1 \geq \sum_{s \in s_i} x_{ij} \quad \forall j \in J, i \in I_j, \]

\[ 1 \geq \sum_{j \in J_i} x_{ij} \quad \forall s \in S, i \in I_s, j \in J_i \]

\[ q_{ij} \leq t_i \cdot r \cdot x_{ij} \quad \forall s \in S, i \in I_s, j \in J_i \]

\[ e_{i+1} = e_i + \delta_i^e - \sum_{j \in J_i} \sum_{k \in K_j} \alpha_{jk} q_{ijk} - h_i, \]

\[ b_{min} \leq e_i \leq b_{max}, \]

\[ d_{i+1} = d_i + \delta_i^d - \sum_{j \in J_i} \sum_{k \in K_j} q_{ijk} - f_i, \]

\[ 0 \leq d_i \leq d_{max}. \]

\[ e_{start} = e_{end} \]

\[ \delta_i^e = (p_{sol} - p_m - p_{pr})t_i \]
So how big of a network do I need to support my mission?

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So how much power do I need to support my mission?

Single Satellite Mission

Data Downlinked, MBytes/day

Power, Watts

Satellite Time Utilization, %

10 Ground Station Network

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Realistic Multi-Satellite, Multi-Ground Station Scenario

Data Download, Mbytes/day

Representative Missions

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Realistic Multi-Satellite, Multi-Ground Station Scenario

- Requirement
- 2 GS, UHF (9600 bps)

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Data Download, Mbytes/day

Representative Missions
Comparison of Requirements and Optimal Solutions

Realistic Multi-Satellite, Multi-Ground Station Scenario

Data Download, Mbytes/day

Representative Missions

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Realistic Multi-Satellite, Multi-Ground Station Scenario

Representative Missions

Data Download, Mbytes/day

- Requirement
- 2 GS, UHF (9600 bps)
- 2 GS, S-band (115.2 kbps)
- 8 GS, UHF (9600 bps)

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Data Download, Mbytes/day

Representative Missions

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Applications of our work on *optimal* mission and vehicle design.

**Model, simulation and optimization enable:**

- Enhanced satellite operational schedules
- Improved satellite vehicle designs

**Future Work**

- More complex networks
- Different approaches to optimization:
  - Strategic objective functions/problems
  - Different decision variables
Acknowledgments

- National Science Foundation (NSF)
- Radio Aurora eXplorer (RAX) Team
- Survey Participants & CubeSat Community
- Amy Cohn and Kyle Gilson, Operations Research, University of Michigan
- University of Michigan Aerospace Engineering Department
- National Science and Engineering Research Council of Canada (NSERC)
BACKUP SLIDES
There will be big scheduling challenges in the near future for small satellites.

**Rainbow colors:** Data satellite missions want to download

**Lines:** What ground station networks can support
Federated Ground Networks are proposed for future missions.

Federated Ground Station Networks (FGSNs)
Synergy of autonomous, globally distributed ground stations

Internet-enabled communication system where ground stations are independently owned + loosely cooperative to enable constellation missions.

Advantages

• Communication opportunity
• Dynamic, flexible framework
• Reduced latency
• Higher data throughput

C. Optimization Solver

The optimization problem is solved using the IBM ILOG CPLEX Optimization Studio (CPLEX) software package [27]. CPLEX is a high performance solver from IBM for linear programming (LP), mixed integer programming (MIP), and quadratic programming (QP/QCP/MIQP/MIQCP) problems. With both integer variables ($x_{ij}$) and continuous variables ($q_{sij}$), our problem is a MIP. The computations are performed on an Intel Core i7 2.8 GHz processor with 8 GB of memory using CPLEX 12.1 C++ API. The code is able to accommodate variable number of ground stations, satellites, and different data and energy rates.
Mission Scenarios

1. **Focused data collection and downlink mode:** Deterministic and scheduled

   Ex. Radio Aurora eXplorer (RAX) dedicated science mission with dedicated ground stations\(^1\)

2. **Opportunistic mode:** Data collection occurs when triggered by an event (which may be stochastic), satellite must process/downlink according to satellite constraints and mission objectives.

   Ex. QB50 Project: multi-point, *in-situ* measurements collected as triggered by atmospheric behavior\(^2\)

3. **24/7 mode:** Collecting data or performing testing on a continual basis.

   Ex. Disaster Monitoring Constellation provides constant and reliable global coverage\(^3\)

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Introduction

What’s a nanosatellite?

• Small satellite with mass <10kg

Why nanosatellites?

• Fast, cheap, easy access to space (secondaries)
• Educational opportunities
• Ability to perform novel missions

Applications

• Distributed science missions
• Technology demonstrations
• Forerunner/precursor mission

Highly Constrained

• Size, Mass, Power, Cost, Delivery Time
• Example: CubeSat form factor (1U=10cm³, <1 kg)

RAX, the first NSF funded nanosatellite and built by MXL
Current small satellite developers face the challenges of complex communication systems, the restrictions of on-board satellite power and data constraints, and competition for ground station resources. We are motivated to enable scientists to perform missions that have conventionally been impossible with single spacecraft missions. Our vision is to support multiple satellites performing science missions in concert, collecting data, communicating, and downlinking.

For example, consider the proposed Armada Project, consisting of 48 CubeSats whose goal is to set up and coordinate a nanosatellite science network collecting multi-point, in-situ atmospheric measurements. The science goal is to study the interplay between local, regional and global scales in defining the thermospheric response to magnetospheric input with a satellite constellation which distribute to achieve global coverage. Existing ground station infrastructure does not offer the capacity or capability to support this type of dynamic satellite constellation.

This work presents analytic models for both the spacecraft and ground station. From the satellite perspective, we include mathematical descriptions of the spacecraft needs and requirements. We consider dynamic ground station networks, in particular federated networks that are composed of geographically diverse and independent stations that loosely collaborate to provide increased satellite connectivity. We’ve developed novel network capacity mapping techniques showing satellite energy and downlink needs and ground station potential for downlink. These tools enable spacecraft and ground station operators to visualize network capacity to aid in network scheduling and understanding the sharing of capacity across missions and ground networks.
Capacity Assessment: Example Satellites and Ground Stations

CubeSats

- Low cost, standardized access to space
- Miniaturized satellite (nanosatellite)
- Each Cube (1U): 10cm cube, 1 kg

Radio Aurora Explorer (RAX)

Example launcher: Poly Picosatellite Orbital Deployer (P-POD) standard interface between CubeSat and Launch Vehicle

Ground Stations

CubeSat Ground Station Community

Air Force Satellite Control Network (AFSCN)

Images Credit: CalPoly Website, University of Michigan CubeSat Survey, US Air Force Portal Website
Radio Aurora eXplorer (RAX)

Developed by Michigan eXploration Lab (MXL) and SRI International, funded by NSF*

**Mission objectives**

- Study field-aligned plasma irregularities (FAIs)
- Collect backscatter from FAIs from radar stations

**Constraints**

- 650 km, 72° inclination orbit (Minotaur IV)
- 3U CubeSat form factor (3x10cm³, <3 kg)
- Passively-magnetically stabilized
- Short delivery timeline (start: Fall 2008, launch: Fall 2010)

*NSF: National Science Foundation*
Effect of Ground Station Latitude and Satellite Inclination

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Clustered Satellite P-POD Launch

3 satellites from P-POD TacSat3 launch vehicle from Minotaur I
Ann Arbor Ground Station (Latitude: 42.27 N, Longitude: 83.74 W)

Individual and Total Network Capacity

Separation of Satellite Pairs

AeroCube3, CP6, HawkAat
Orbital Parameters

i = 40.5°

$e_{avg} = 0.003$

$a = 6.83 \cdot 10^3 km$
Ground Station Network to 3 CubeSats

Full Air Force Satellite Control Network to 3 Satellites in P-POD from TacSat3 launch vehicle from Minotaur I

Orbital Parameters

- $i = 40.5^\circ$
- $e_{avg} = 0.003$
- $a = 6.83 \cdot 10^3 \text{km}$
**Satellite Model**

**Link Equation**

\[
\frac{P_{dl} G_t G_r L_l L_s L_a}{k T_s r} \geq SNR_{min} \quad \forall t \in [t_o, T] \quad [11.1]
\]

Assume:

\[
\alpha(t) = \frac{G_t G_r L_l L_s L_a}{(SNR_{min}) k T_s} \quad [8.2]
\]

\[
r(t) \leq \alpha(t) P_{dl}(t) \quad [8.3]
\]

\(\alpha(t)\) is dynamic throughout a communication pass.
Satellite Model

Data Dynamics

\[ D(t) \leq D_{\text{cap}} \quad \forall t \in [t_0, T] \quad [12.1] \]

\[ D(t) = D_o + \int_{t_0}^{t} r_{\text{col}}(t) \, dt - C_i \quad [12.2] \]

\( D(t) \): data stored on-board at time \( t \)
\( t_0 \) and \( T \): start and end of timespan
\( D_{\text{cap}} \): data storage capacity
\( D_o \): data stored in the buffer at time \( t_0 \)
\( r_{\text{col}}(t) \): data collection rate
\( C_i \): capacity of satellite \( i \)
Existing Literature

Spacecraft Models

- Operations and data handling for FAST\(^1\) mission (McFadden)
- Dynamics *(Schlanbusch, Rawashdeh, Waydo)*, Propulsion *(Rackemann)*

Simulation Tools

- Commercially available software (MATLAB, Simulink, CommTax\(^2\), AGI\(^3\))
- NASA’s ASPEN\(^4\): planning and scheduling for large aircraft and spacecraft

There is a definite need for:

- Multi-disciplinary models and simulation tools
- Flexible multi-subsystem models based on visible analytic structure

---

\(^1\) FAST: Fast Auroral Snapshot Explorer

\(^2\) CommTax: Communications System Taxonomy

\(^3\) AGI: Analytical Graphics, Inc.

\(^4\) ASPEN: Automated Scheduling/Planning Environment
Satellite Model

Energy Dynamics

\[ E(t) \geq E_{min} \]

\[ E(t) \leq E_{bat} \quad \forall t \in [t_0, T] \]

\[ E(t) = E_{in}(t) - E_{out}(t) \]

\[ \eta_s \int_{t_0}^{t} P_{sol} \, dt + E_0 - \eta_x \int_{t_0}^{t} (P_{op} + P_{pr}(t) + P_{dl}(t)) \, dt \]

\textbf{Energy Collected} \quad \textbf{Energy Consumed}

\( E(t) \): energy stored in battery at time \( t \)
\( t_0 \) and \( T \): start and end of timespan
\( E_0 \): available energy stored in the battery at time \( t_0 \)
\( P_{sol} \): power collected from the solar cells
\( P_{op} \): power for nominal operations
\( P_{pr}(t) \) and \( P_{dl}(t) \): power for data processing and data downloading
\( \eta_{sol} \) and \( \eta_{dl} \): fraction of timespan collecting energy and downloading
Satellite Model

Link Equation

\[ \frac{P_{dl} G_t G_r L_l L_s L_a}{k T_s r} \geq SNR_{min} \quad \forall t \in [t_0, T] \] [10.1]

SNR_{min}: minimum required signal-to-noise ratio required for communication

\( P_{dl} \): power for data downloading

\( G_t \) and \( G_r \): gains of the transmit and receive antennas

\( L_l \) and \( L_s \): transmitter-to-antenna line and space losses

\( L_a \): transmission path loss

\( k \): Boltzmann constant

\( T_s \): temperature noise

\( r \): rate of data downloading

\( t_0 \) and \( T \): start and end of timespan
Future Work

- CubeSat Survey to identify spacecraft needs and operations
- Develop optimal scheduling tools to balance utilization and satellite needs
- Exploit analytic models to augment spacecraft and mission design
- Dynamic optimization techniques for tactical scheduling

---


FGSN: Federated Ground Station Network
Multi-Scale Satellite Capacity Models

- **Maximum Model**
  - Constant ideal Link

- **Topological Model**
  - Line-of-sight Constraints

- **Scheduled Model**
  - Operational Constraints

- **Actualized Model**
  - Off-nominal Constraints

Ellipse Area: Network Capacity, decreases with increasing model fidelity
Architecture

- Satellite Tool Kit (STK)® and Matlab®
- STK/SGP4 Propagator for orbit maneuver and trajectory analysis
- Models ideal P-POD deployment ($\Delta V$, plunger)
- Computes separation, contact times
Network Capacity Model

**Availability**

\[ C_j = \sum_{i=1}^{n} \int_{t=0}^{t=T} a_{ij}(t) r_{ij}(t) l_{ij}(t) \eta_{ij}(t) dt \]

Line-of-sight between ground station and satellite

\[ a_{ij}(t) \in \{0,1\}, \ 1 \leq i \leq n, \ 1 \leq j \leq m \]

Example: Satellite visible from ground station when above horizon:

\[ a_{ij}(t) = 1 \text{ if } 0 < e \leq \pi \]
\[ a_{ij}(t) = 0 \text{ if } \pi < e \leq 2\pi \]

Satellite Image Credit: Falling Pixel Website
Earth Image Credit: noaa.gov Website
Network Capacity Model

Data Transfer Rate

\[ C_j = \sum_{i=1}^{n} \int_{t=0}^{T} a_{ij}(t) r_{ij}(t) l_{ij}(t) \eta_{ij}(t) dt \]

Link Equation:\(^1\):
- antenna diameters, gain patterns
- system efficiencies
- frequency, transmitter power

Optimal elevation, data rate to maximize data throughput\(^2\)

Example 1: constraint of a single data rate throughout pass, set design time/ update

Example 2: flexible communication system, variable data rate

---

Space Mission Analysis and Design (SMAD)

Link Feasibility \[ C_j = \sum_{i=1}^{n} \int_{t=0}^{t=T} a_{ij}(t)r_{ij}(t)l_{ij}(t)\eta_{ij}(t)dt \]

Is communication link desired due to scheduling constraints of system?

Example: constraint of single link from ground station to satellite feasible for a given ground station \( j \),

if \( l_{ij}(t) = 1 \) when \( i = p \),

then \( l_{ij}(t) = 0 \) when \( i \neq p \)
Network Capacity Model

Efficiency

\[
C_j = \sum_{i=1}^{n} \int_{t=0}^{t=T} a_{ij}(t)r_{ij}(t)l_{ij}(t)\eta_{ij}(t)dt
\]

- Time losses: slewing, keyholing, pointing inaccuracies
- Ground station failures, downtime, dropped packets
- Ground Station Stable/ Mobile
- Example, satellite operates 80% of time:

\[
\eta_{ij}(t) = 0.8 \text{ for all } t \in [0, T] \text{ for all } i
\]

The arrows show the round "keyhole" as the base of the cone due to elevation constraints of the gimbal. Green volume=visible space by keyhole problem.

# CubeSat Survey Ground Stations

## Summary Station Locations

Total Number of Stations: 97.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>9w2qc</td>
<td>3</td>
<td>101</td>
<td>50</td>
</tr>
<tr>
<td>AA2TX</td>
<td>42.7</td>
<td>-71.15</td>
<td>27</td>
</tr>
<tr>
<td>AJ1O</td>
<td>35.4197</td>
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<td>1825</td>
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<td>amsatsbs</td>
<td>46.453</td>
<td>9.201</td>
<td>1660</td>
</tr>
<tr>
<td>amsatsbs</td>
<td>46.133</td>
<td>8.858</td>
<td>1890</td>
</tr>
<tr>
<td>ANSAT - Norwegian Student Satellite Program</td>
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<td>16.1308</td>
<td>5</td>
</tr>
<tr>
<td>Auburn University</td>
<td>32.6097</td>
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<td>216</td>
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<tr>
<td>BUTE</td>
<td>47.4769</td>
<td>19.0575</td>
<td>106</td>
</tr>
<tr>
<td>Cal Poly</td>
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<td>-120.665</td>
<td>100</td>
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<td>CUSat, Cornell University</td>
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<td>dcherba_wz8t</td>
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<td>250</td>
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<td>DD1US</td>
<td>49.225</td>
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<td>190</td>
</tr>
<tr>
<td>DK3WN</td>
<td>49.43</td>
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<td>EI7IG</td>
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<tr>
<td>FK1 FR</td>
<td>46.2003</td>
<td>31.5000</td>
<td>600</td>
</tr>
</tbody>
</table>
CubeSat Survey Ground Stations

### University of Michigan Ground Station Survey

There are 97 stations that have been entered into the database.

There are 205 antennas that have been entered into the database.

**Details on all the institutions sorted by antenna type.**

<table>
<thead>
<tr>
<th>Institution</th>
<th>Lat.</th>
<th>Lon.</th>
<th>El.</th>
<th>Antenna Type</th>
<th>Frequency</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UniWuerzburg</td>
<td>49</td>
<td>9</td>
<td>310</td>
<td></td>
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<tr>
<td>INPE</td>
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<td>-53.8</td>
<td>488</td>
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<td>190</td>
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<td>dish</td>
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<td>Goonhilly New Ventures</td>
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<td>354.8</td>
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<td>dish</td>
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<tr>
<td>Goonhilly New Ventures</td>
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<td>354.8</td>
<td>100</td>
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<td>6</td>
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<tr>
<td>University of Alaska Fairbanks</td>
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<td>147</td>
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[http://gs.engin.umich.edu/gs_survey/]
**Mercury** is a software system for commanding and controlling satellite ground stations via the Internet. Our motivations for developing Mercury are to reduce the cost of operating space missions and to increase mission yields and capabilities. We seek to make accessing space systems as easy as searching [Google](https://www.google.com). We are developing an opensource software platform, currently based on Linux, Apache, MySQL, and Java, to build a network of Internet enabled ground stations.

Currently, Mercury is deployed to support university satellite missions. As an example, a Mercury-enabled OSCAR station at Stanford University is the primary access point for the [QuakeSat](https://quake.sas.upenn.edu) satellite, a first generation CubeSat designed to measure low frequency magnetic field emissions from Earth that are believed to be earthquake precursor signals. Other satellites supported by Mercury include [Sapphire](https://sapphire-space.org) and [Opal](https://www.opal-forcespace.org).

Core ground station services are captured in Mercury, ones that are shared across multiple missions. We divided these services along autonomy lines into three hierarchical layers which permit low level hardware commanding, contact automation for a single station, and peer cooperation among ground stations teams to enhance globally distributed contacts. The *virtual hardware level* captures the fundamental capabilities of low-level ground station components and enables generic commanding of heterogeneous hardware. The *session level* captures typical automation tasks and services of a single ground station system. The *network level* captures the services of a ground station network enabling cooperate teams of ground stations to optimize satellite contacts.
Global Educational Network for Satellite Operations (GENSO) is an educational project initiated by the International Space Education Board (ISEB). This board consists of the Education Departments of the Canadian Space Agency, the European Space Agency, the Japan Aerospace Exploration Agency and the National Aeronautics and Space Administration.

The project is managed by the Education office of ESA and the AMSAT Radio Amateur Community. A set of development teams from America, Europe and Japan are working on GENSO. GENSO has the following objectives:

unparalleled near-global levels of access to educational small spacecrafts in orbit, allow remote access for operators to real-time mission data, even in cases of technical difficulties of local groundstation has or if it is under maintenance, provide partially remote control of the participating ground stations, optimise uplink fidelity by calculation of real-time link budgets and uplink station selection, perform downlink error-correction by comparing multiple data streams, redundancy check define and implement a global standard for educational ground segment software, mission control software interfaces define and instantiate an optional well-defined standard solution for educational ground-segment hardware support a common interface for applying for frequency allocation and coordination.