Optimal Download Scheduling for Satellite Missions

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Motivations

Flock 1: 28 Dove Satellites launched on Feb 11th, 2014

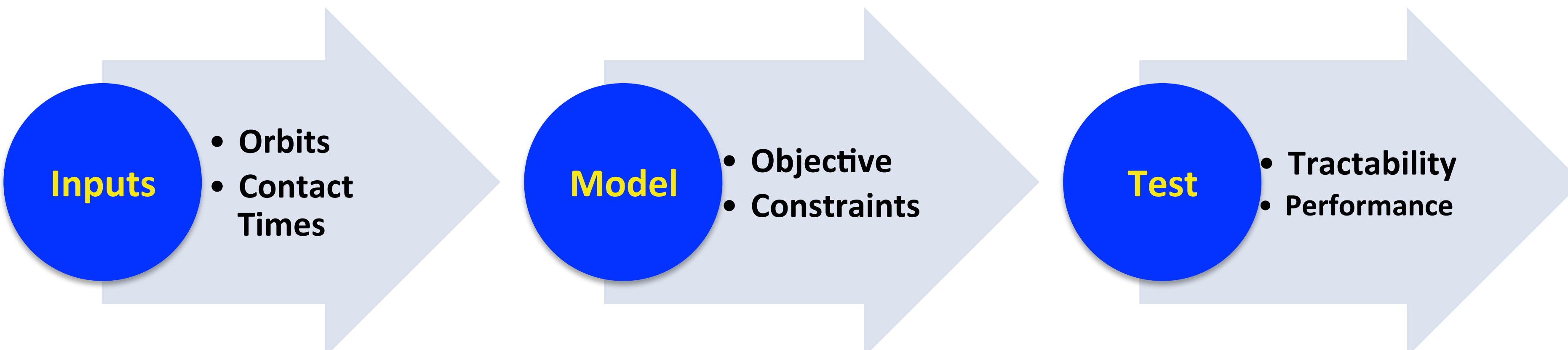
1 - 50 kg Satellite Launches [1]	
Year:	**Approx. Launches Per Year:**
2006-2012	25
2013	92
2014	140 (estimated)

Some ground station antennas

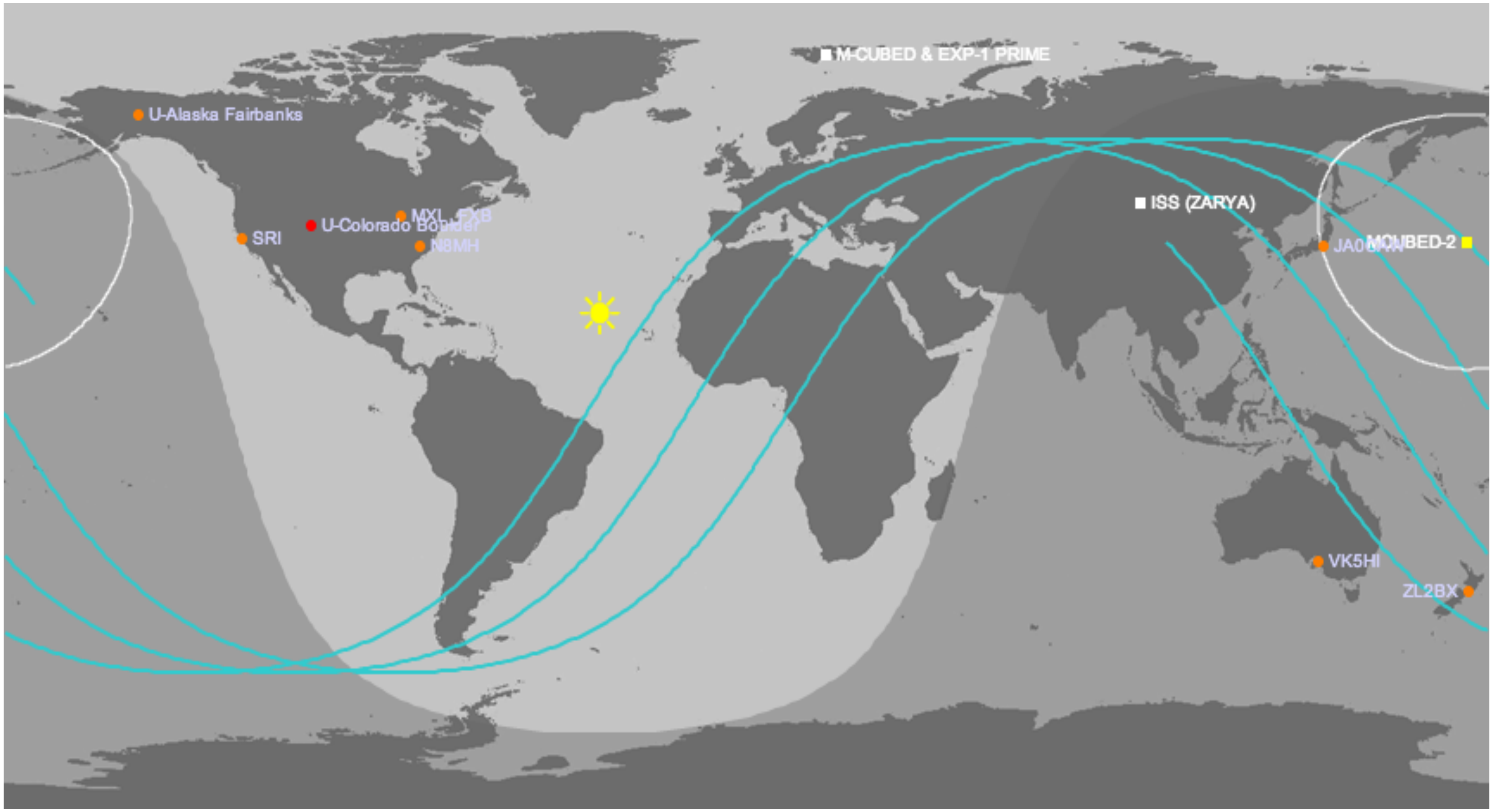
[1] Elizabeth Buchen and Dominic DePasquale. Nano/Microsatellite Market Assesment. SpaceWorks Enterprises, Inc. 2014

Goal and Outline

- Schedule downloads during a multi-satellite, multi-ground station system.

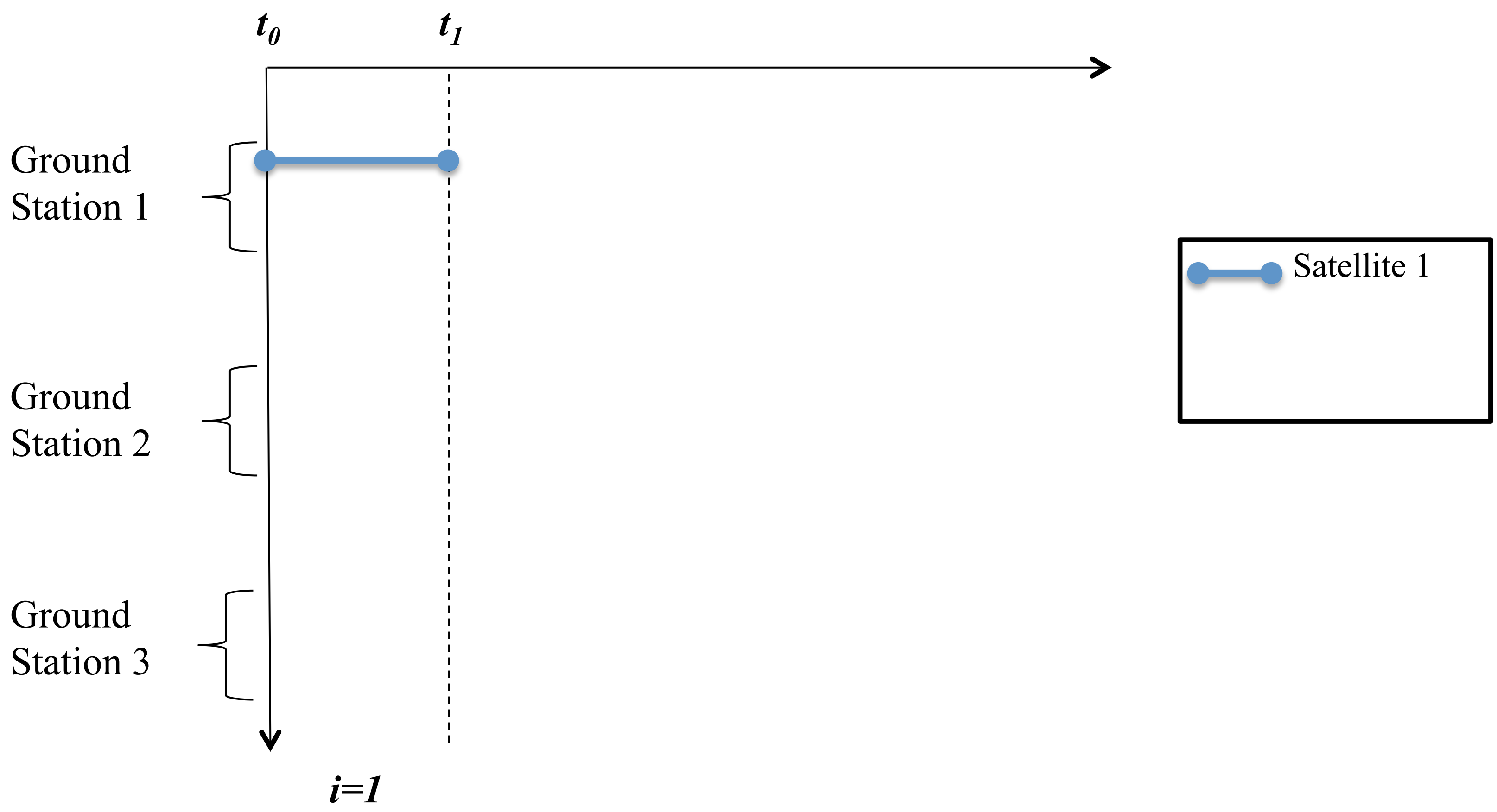


Orbits and Ground Stations



<u>Tracking satellites using the *"Retrotrack"* web-application</u>

Abstract Representation of Contact Times



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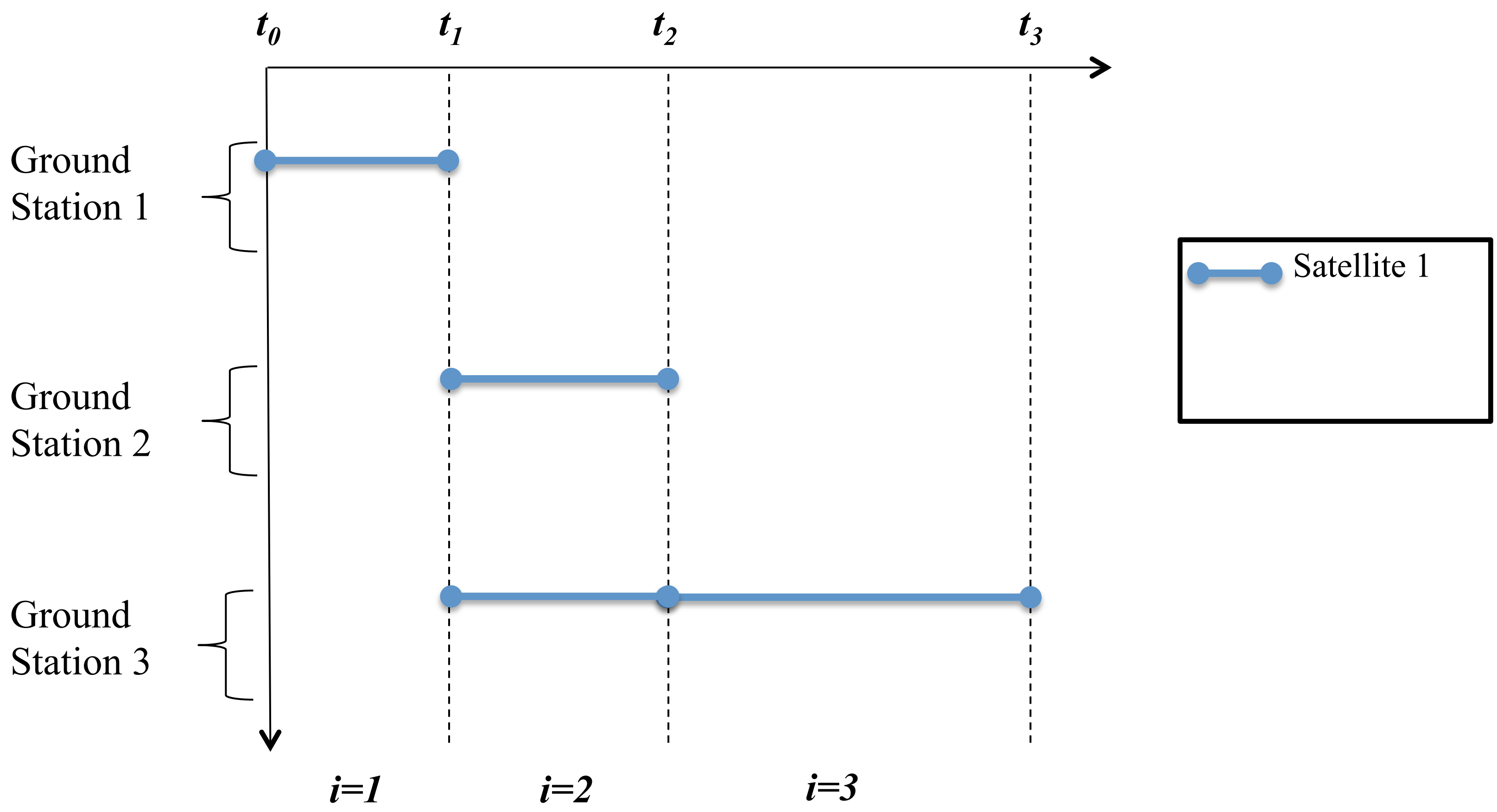

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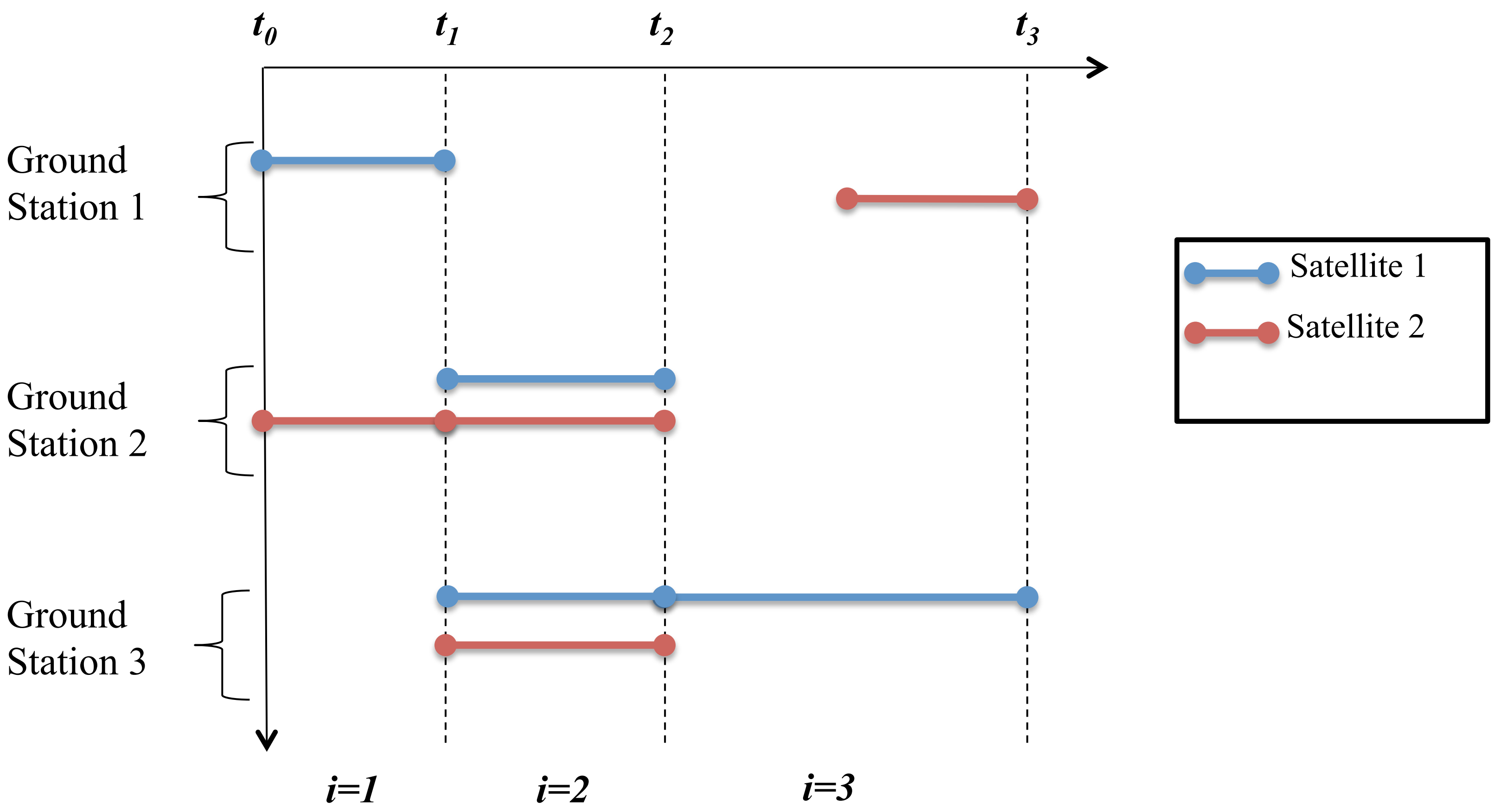

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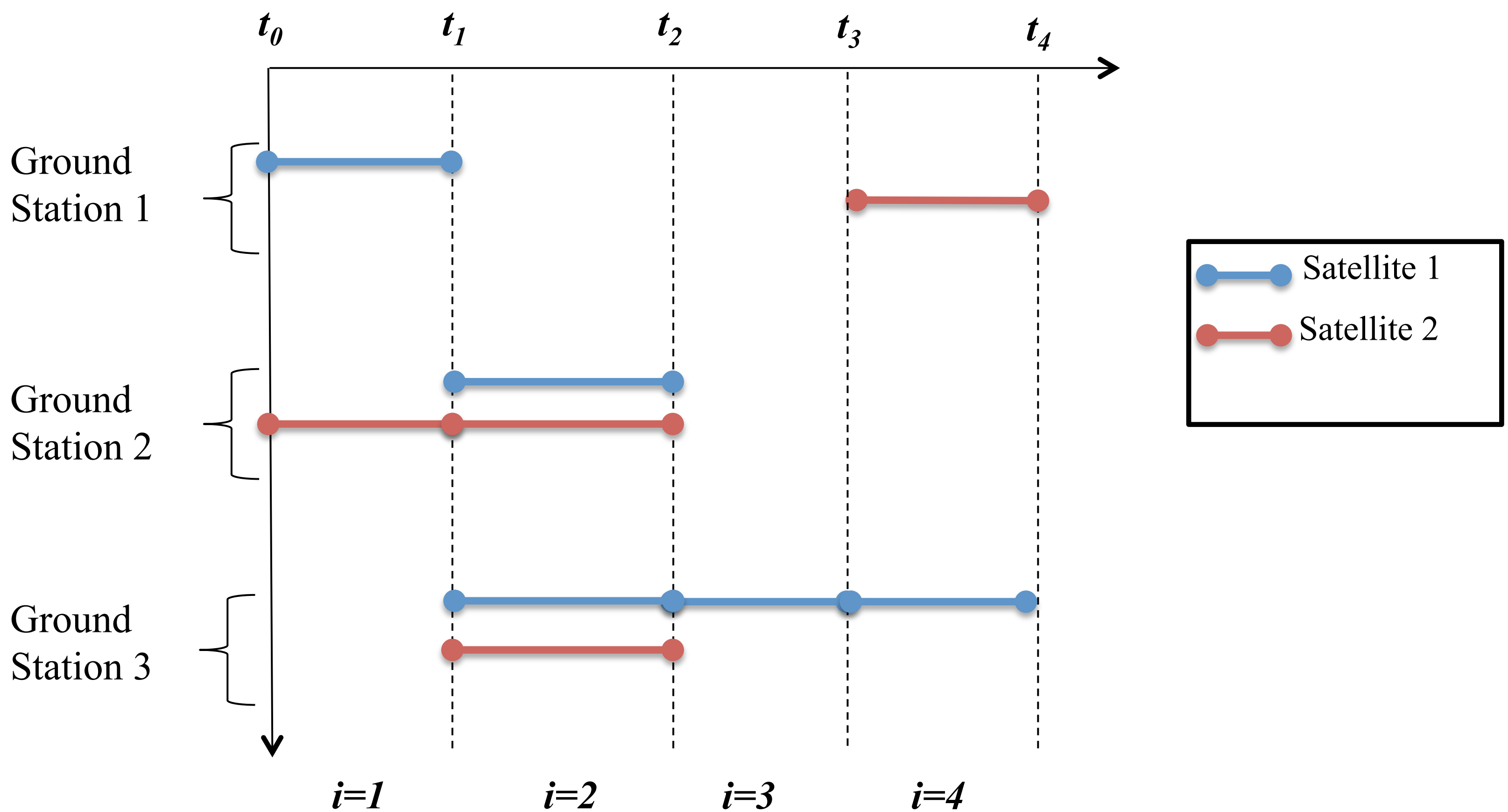

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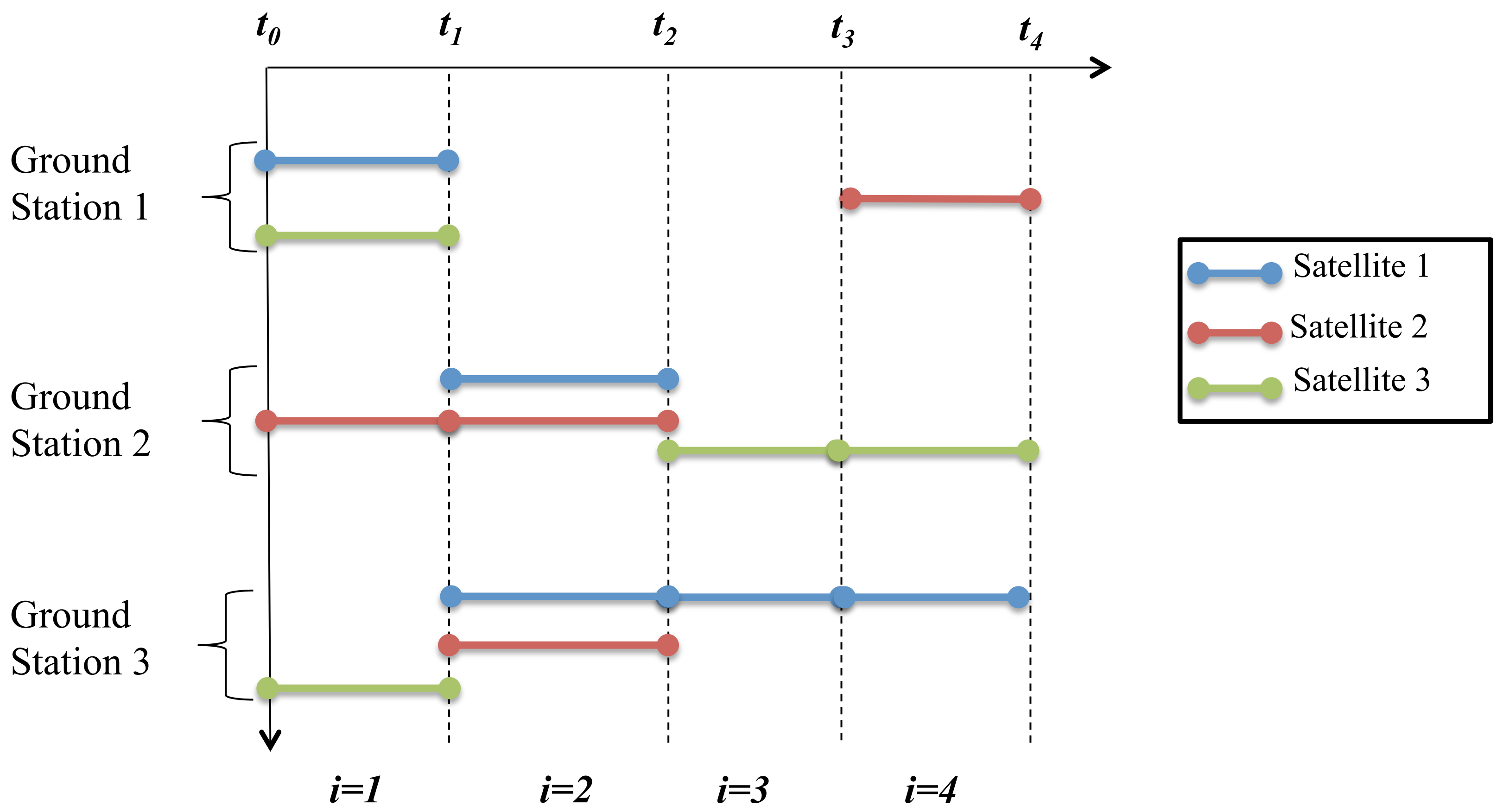


The Multi-Satellite, Multi-Ground Station Scheduling Problem (MMSP)

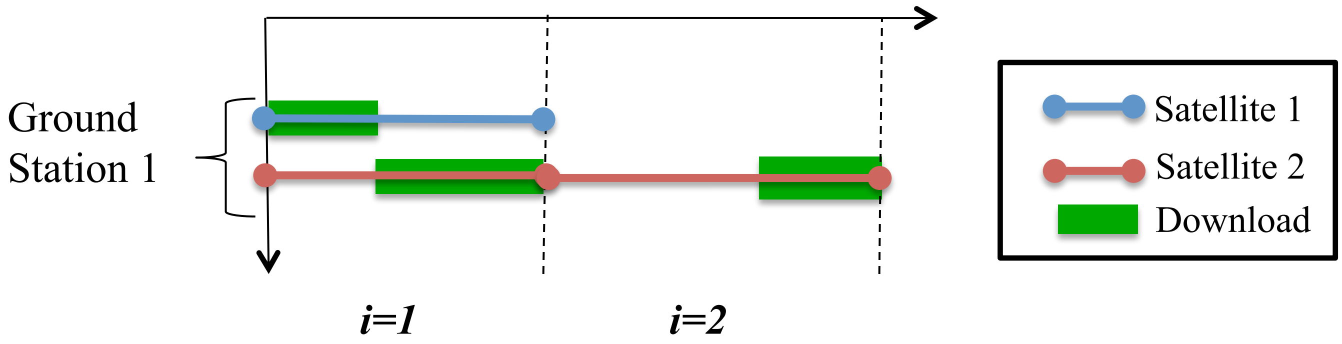
- **Objective** is to maximize the total amount of data downloaded over the planning horizon
- **Subject to**:
  - Download opportunities
  - Conflicts
  - Energy & Data Dynamics
  - Ground Stations Characteristics:
    - Download Rate (bits/sec)
    - Download Cost (joules/bit)
    - Efficiency (percentage of download actually received)

Download Decisions

- x_{sig} – Percentage of interval i that satellite s downloads to ground station g
- q_{sig} – Amount of data downloaded from satellite s during interval i to ground station g

A Simple Schedule

	Ground Station 1			
	Interval 1		Interval 2	
	x	***q***	***x***	***q***
Satellite 1	40%	2 Mb	0%	0 Mb
Satellite 2	60%	3 Mb	30%	1 Mb



The Full Optimization Model

Objective

$$\max \sum_{s\in S}\sum_{i\in I}\sum_{g\in G} \eta_{ig} q_{sig}$$

Constraints

$$
\begin{aligned}
& x_{sig} \le \gamma_{sig} && \forall s \in S, i \in I, g \in G && (1)\\
& \sum_{s\in S} x_{sig} \le 1 && \forall i \in I, g \in G && (2)\\
& \sum_{g\in G} x_{sig} \le 1 && \forall s \in S, i \in I && (3)\\
& q_{sig} \le t_i \phi_{ig} x_{sig} && \forall s \in S, i \in I, g \in G && (4)\\
& e_{s0} = e_{start} && \forall s \in S && (5)\\
& e_{min} \le e_{si} \le e_{max} && \forall s \in S, i \in I && (6)\\
& e_{s,i+1} = e_{si} + \delta^e_{si} - \sum_{g\in G} \alpha_{ig} q_{sig} - h^e_{si} && \forall s \in S, i \in I && (7)\\
& d_{s0} = d_{start} && \forall s \in S && (8)\\
& 0 \le d_{si} \le d_{max} && \forall s \in S, i \in I && (9)\\
& d_{s,i+1} = d_{si} + \delta^d_{si} - \sum_{g\in G} \eta_{i,g} q_{sig} - h^d_{si} && \forall s \in S, i \in I && (10)\\
& 0 \le x_{sig} \le 1 && \forall s \in S, i \in I, g \in G && (11)\\
& q_{sig}, e_{si}, d_{si}, h^e_{si}, h^d_{si} \in \mathbb{R}^+ && \forall s \in S, i \in I, g \in G && (12)
\end{aligned}
$$

Example of Constraints: Energy Dynamics

1) Initialization: energy available at beginning of planning horizon

$$e_{s0} = e_{start} \qquad \forall s \in S$$

$$e_{min} \leq e_{si} \leq e_{max} \qquad \forall s \in S,\ i \in I$$

$$e_{s,i+1} = e_{si} + \delta^{e}_{si} - \sum_{g \in G} \alpha_{ig} q_{sig} - h^{e}_{si} \qquad \forall s \in S,\ i \in I$$

Parameters:

α_{ig}: Download cost (joules/bit)

δ_{si}^{e}: Net amount of energy acquired (joules)

Sets:

S: Satellites

I: Intervals

G: Ground Stations

Variables:

x_{sig}: Percent of interval used for download

q_{sig}: Amount of data downloaded (bits)

e_{si}: Energy available (joules)

h_{si}^{e}: excess energy spilled

Example of Constraint: Energy Dynamics

1) **Initialization: energy available at beginning of planning horizon**
2) **Buffer Size: lower and upper bound on stored energy**

$$e_{s0} = e_{start} \qquad \forall s \in S$$

$$e_{min} \leq e_{si} \leq e_{max} \qquad \forall s \in S,\ i \in I$$

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Example of Constraint: Energy Dynamics

1) **Initialization: energy available at beginning of planning horizon**
2) **Buffer Size: lower and upper bound on stored energy**
3) **Propagation: recursive equation**

$$e_{s0} = e_{start} \qquad \forall s \in S$$

$$e_{min} \leq e_{si} \leq e_{max} \qquad \forall s \in S,\ i \in I$$

$$e_{s,i+1} = e_{si} + \delta^e_{si} - \sum_{g \in G} \alpha_{ig} q_{sig} - h^e_{si} \qquad \forall s \in S,\ i \in I$$

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What do we want to look at?

- Assess performance of our optimization model compared to other methods
- Evaluate system sensitivity under various scenarios
  - Number of satellites *VS* Number of ground stations
  - Congestion effects
  - Energy acquisition capabilities

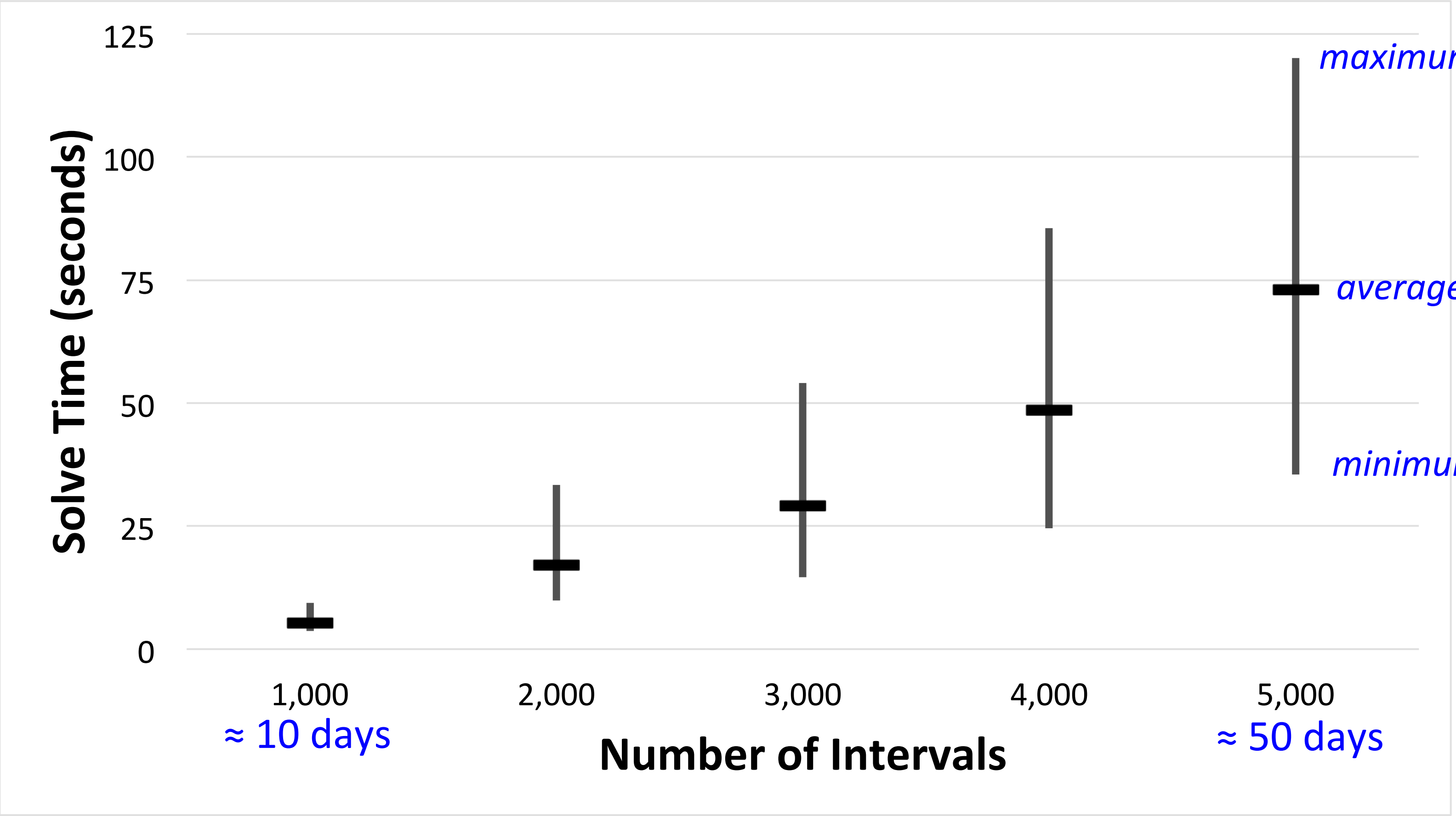
Generating Data for Testing

- Planning horizon is typically one day (100 intervals)
- Contact times are randomly generated
- For each test scenario, 50 random instances are solved and average objective value is computed

Comparison Methods

- Greedy Heuristic
  - At each point in time
    - Identify maximum possible download for each satellite
    - Schedule the maximum download
    - Repeat until no more feasible downloads
- Unrestricted Ground Stations
  - Use MMSP formulation, but allow ground stations to receive data from numerous satellites simultaneously
  - Example: Deep-Space Network (DSN)

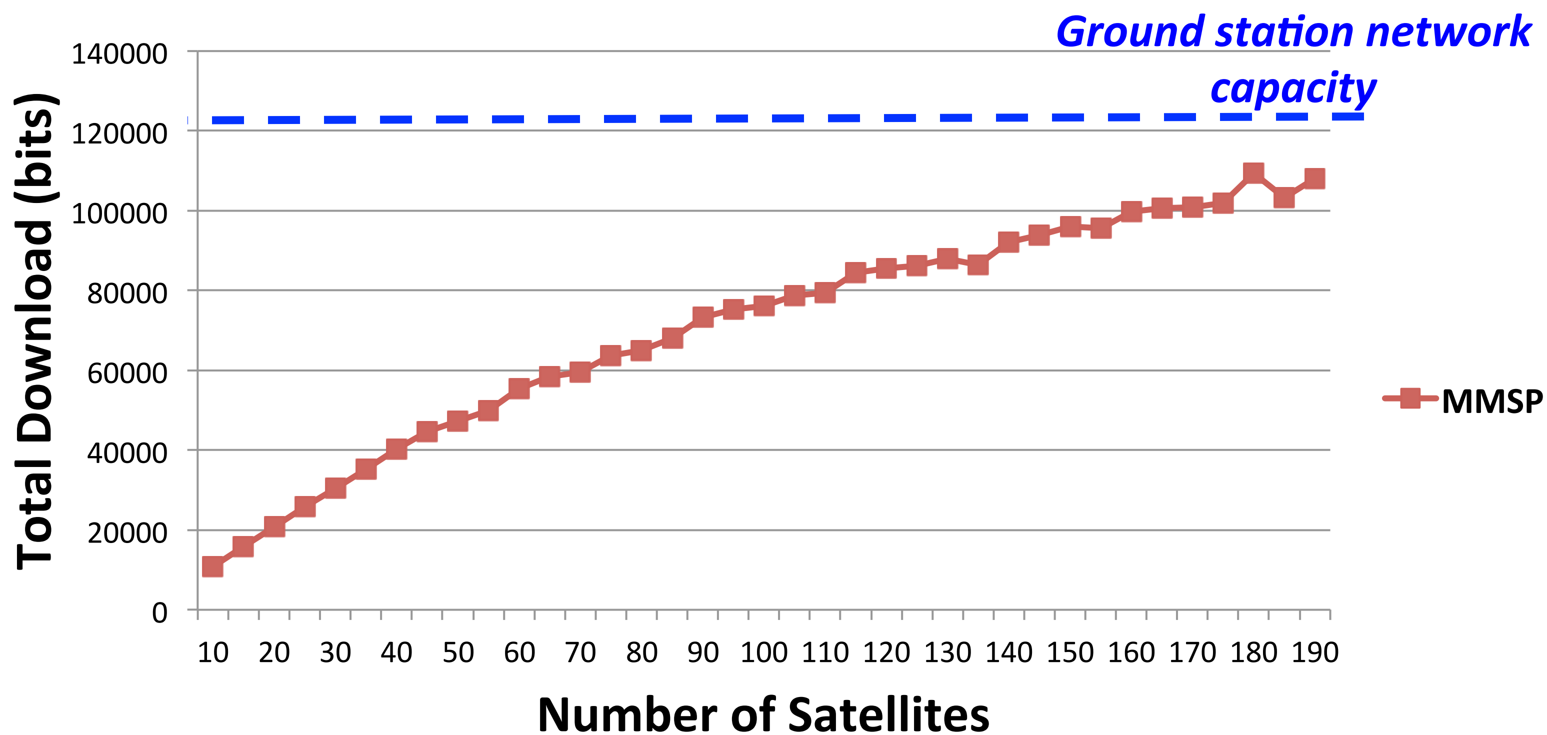
Computational Performance
(20 Satellite, 15 Ground Stations)



MMSP model can be solved quickly even for large instances

Number of Satellites

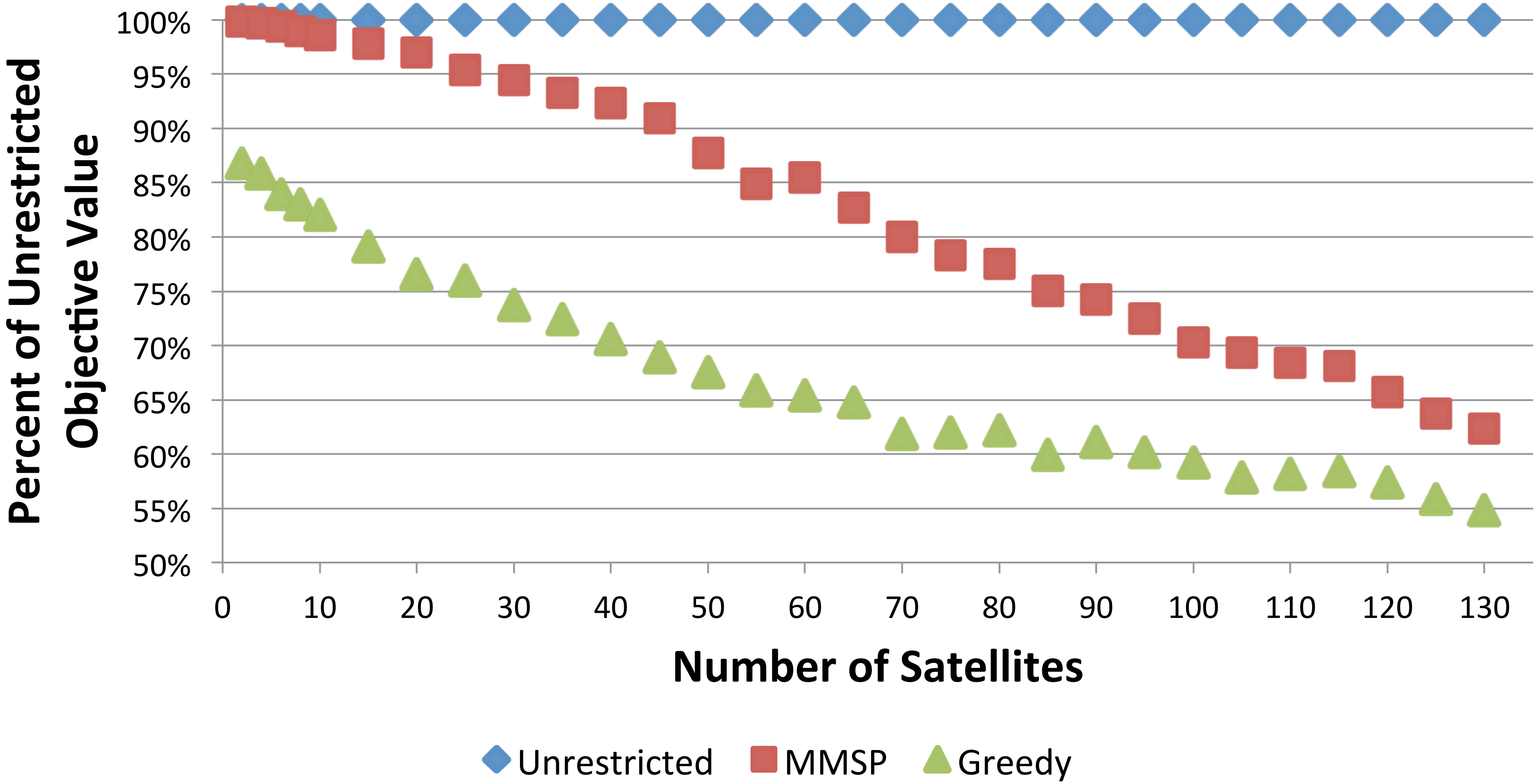
(with 20 ground stations)



Decreasing marginal benefit of adding new satellites to existing system

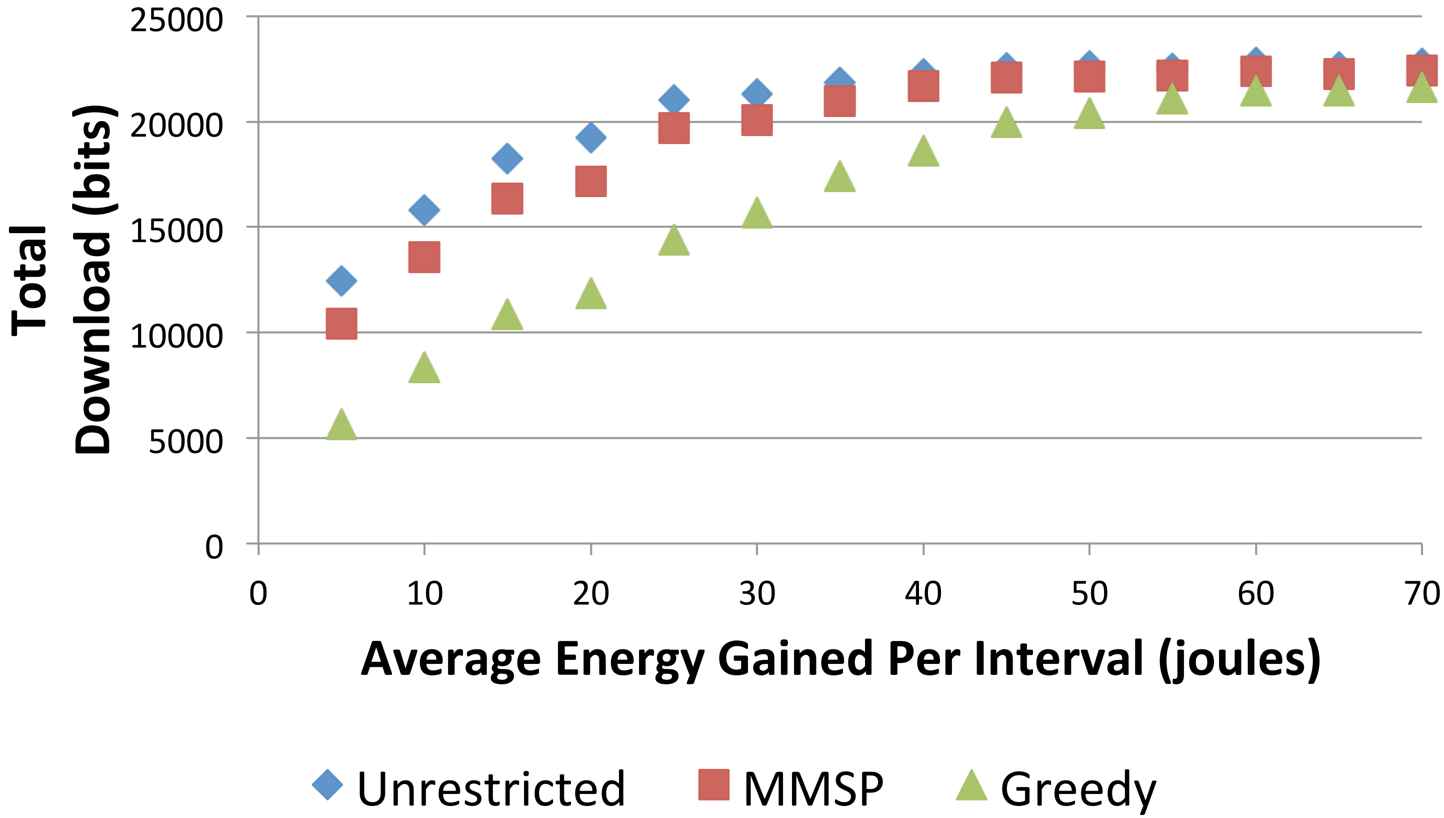
Number of Satellites

(with 20 ground stations)



1) MMSP is better than Greedy
2) MMSP effectiveness decreases in scenarios with very high congestion

Energy Gained Per Interval



MMSP is most beneficial when energy is a limiting resource

Conclusions and Future Work

1. **Operations Research approach – Optimization**
2. **Participate in satellite design and mission development**
3. **Project future mission performance (e.g. QB50)**
4. **Deploy optimization model on operating networks**
5. **Other applications…**

Thank You!

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Generating Data for Testing

Table 1: Base Case Model Parameters	
Description	**Default Value**
Number of satellites	20
Number of ground stations	15
Number of time intervals	100
Time Interval Length Uniform	Uniform (1,30)
Prob (see 0 ground stations)	25%
Prob (see 1 ground station)	25%
Prob (see 2 ground stations)	25%
Prob (see 3 ground stations)	25%
Prob (see 4 ground stations)	0%
Prob (see 5 ground stations)	0%

Table 2: Satellite Parameters	
Description	**Default Value**
Minimum energy level (joules)	0
Maximum energy level (joules)	100
Starting energy level (joules)	e_max
Maximum data level (bits)	100
Starting data level (bits)	d_max
Energy Gain (joules per interval)	Normal (30,15)
Data Gain (bits per interval)	Normal (10,5)

Table 3: Ground Station Parameters	
Description	**Default Value**
Efficiency Percentage	Normal (1,0.2)
Data Rate (bits/sec)	Normal (4,2)
Energy Cost (joules/bit)	Normal (5,2.5)

- Negative values are set to 0, efficiencies greater than 1 are set to 1