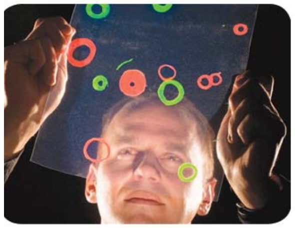
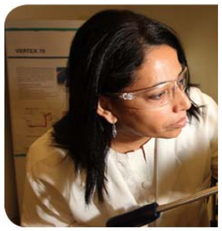

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Constellation Scheduling Under Uncertainty: Models and Benefits

GSAW 2017

Securing the Future

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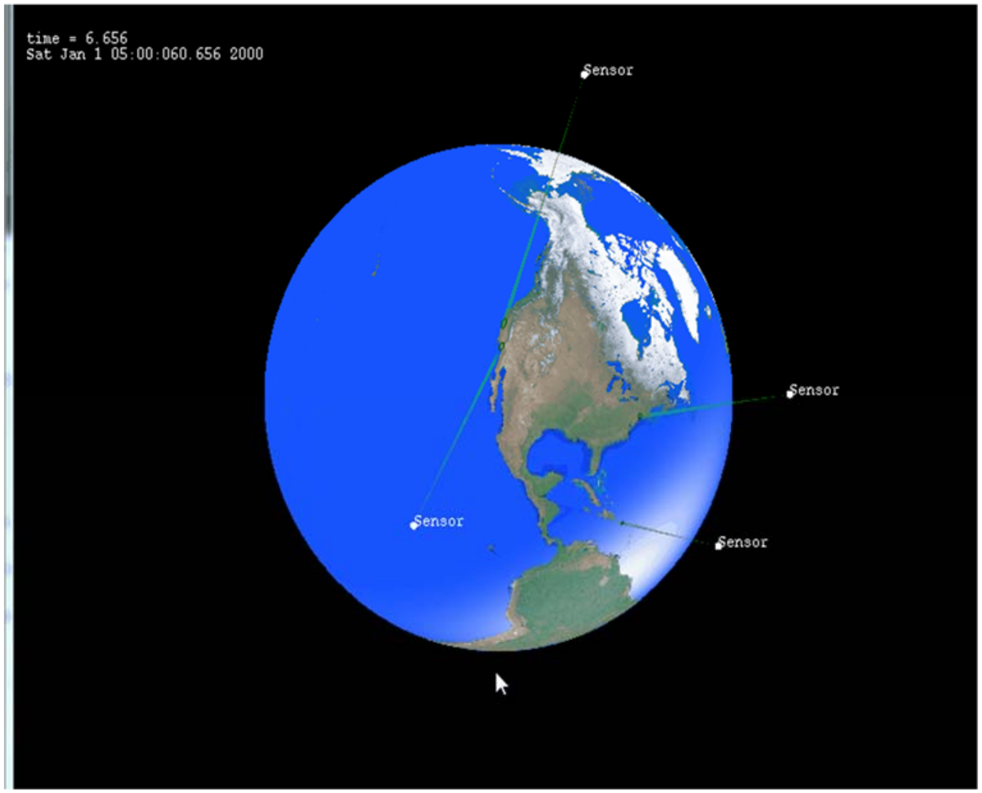
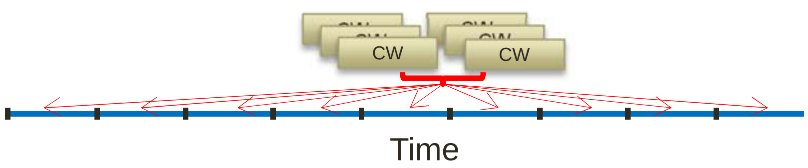
Overview

- **A remote sensing constellation scheduling problem**
- A Mixed-Integer Program (MIP) for constellation scheduling
  - Results
- Stochastic scheduling models
- Computational results
- Ongoing and future research



The Constellation Scheduling Problem

- Problem:
  - Manage a collection of **satellites** scheduled to monitor physical locations in space and time
- Challenge:
  - Sensors have **highly flexible capabilities**, not captured in current scheduling models and technologies
  - Schedules underutilize **expensive sensors**
    - Missed collection opportunities can impact national security
  - Evolving events and uncertainties necessitate:
    - Efficient consideration of alternative schedules
    - Timely schedule generation



- Assumption:
  - The performance of the constellation will be evaluated w.r.t a **fixed set of** *collection windows*

How is a Collection Window Defined?

- **Start time**
  - **Time window:** list of potential collection start times
  - **Duration:** fixed and known before building schedule

- **Configuration**: sensor configuration needed for collection
  - **Physical location**:
    - The location that needs to be observed; precise requirements depend on the sensing technology

- **Performance**: predicted observation quality. Impacted by sensor, sun, target geometry, weather, physical location scene, etc.

- **Priority**: importance relative to other collection windows
- **Category:** hierarchical importance (required, essential, desired)

Collection Window Categories

- **Category 1 (required):** Unique to a given sensor. Sensor's schedule must include all corresponding category 1 collection windows
  - Example: collection windows scheduled for the safety and proper operation of a specific sensor; other collections a planner can *force* onto the sensor schedule

- **Category 2 (essential):** In general, of high priority. In some cases, preempted by higher priority Category 3 collection windows
  - Example: periodic sensor calibration activities

- **Category 3 (desired):** The vast majority of collection windows to be scheduled. Most often lower priority than Category 2 collection windows
  - Example: weather collections, reconnaissance, scientific measurement (vegetation cover, sea currents), etc.

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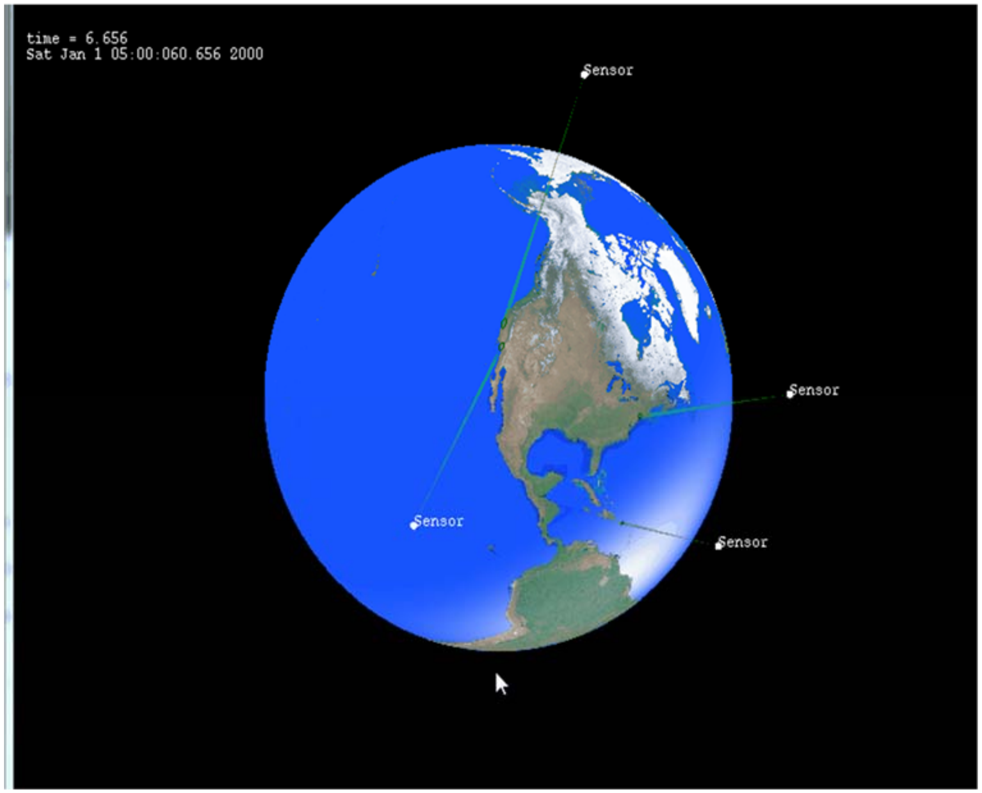


Our Approach

- Scheduling problems can be notoriously **hard** to solve (NP-Hard).
- We are using **Operations Research based heuristics**:
  - Apply a MIP solver using an optimality tolerance (e.g. 1%)
  - Final solution **guaranteed** to be near-optimal or optimal
  - Small tolerances can significantly reduce time to solution
- MIPs facilitate **rapid exploration of alternate formulations and solution methods** and disambiguate the solver from the model
  - Quickly assess different formulations
    - Objective functions, constraint equations
    - Readily extensible to incorporate uncertainty
- Sensitivity analysis
  - Determine active/limiting constraints
  - Rigorously determine the effects of changing objectives, adding/removing constraints and decision variables

Related Work

- Satellite scheduling algorithms favor custom rule-based techniques
  - Feasible schedules produced quickly, but without rigorous solution confidence

Artist's rendering of GOES-R
Credits: NASA

- Academic research is divided into two camps
  - Heuristics and metaheuristics
    - Comparisons of satellite scheduling (Globus et. al 2004)
    - Genetic algorithms (Lining et. Al 2009)
    - Simulated annealing (Peng et. al 2011)
    - Greedy local (Dungan et. al 2011)
    - Ant colony optimization (Wang et. al 2009)

Artist's rendering of Sentinel-1A
Credits: ESA

  - Exact methods (less research)
    - Integer programming (Liao, 2007) – small model size

Constellation Scheduling Mixed-Integer Program

$$\max \quad \sum \frac{\alpha \delta_{i,k,t} p_k d_k q_{k,t}}{\sum_{k \in K} p_k d_k q_k^*}, i \in I, k \in K, t \in T$$

$$w_k = \sum_{i \in I, t \in T} \delta_{i,k,t}, \forall k \in K$$

$$s.t. \quad w_k = 1, \; \forall k \in K_1$$

$$w_k \leq 1, \; \forall k \in K \setminus K_1$$

$$\sum_{k \in K} \delta_{i,k,t} \leq \quad 1 - \sum_{k \in K, \bar{t} \in C(k,t)} \delta_{i,k,\bar{t}}, \forall i \in I, t \in T$$

$$\delta_{i,k,t} \in \{0,1\} \; i \in I, k \in K, t \in T$$

- Objective: schedule as many activities as possible with rewards for high priority, high quality, high duration collections
- Convenience variable denoting whether or not a collection window was scheduled
- Category one collection windows must be scheduled
- Other collections can be scheduled at most once
- Collections can not be scheduled concurrently on a single sensor

Where:

- $\delta_{i,k,t}$: whether collection window *k* starts at time *t* on sensor *i*
- $q_{i,k,t}$: quality of starting collection window *k* at time *t* on sensor *i*
- d_k, p_k : duration and priority of collection window *k*
- $C(k,t)$: set of feasible start times for collection window *k* before time *t*
- α : scaling constant (e.g. 100)

Predicted Observation Quality: $q_{i,k,t}$

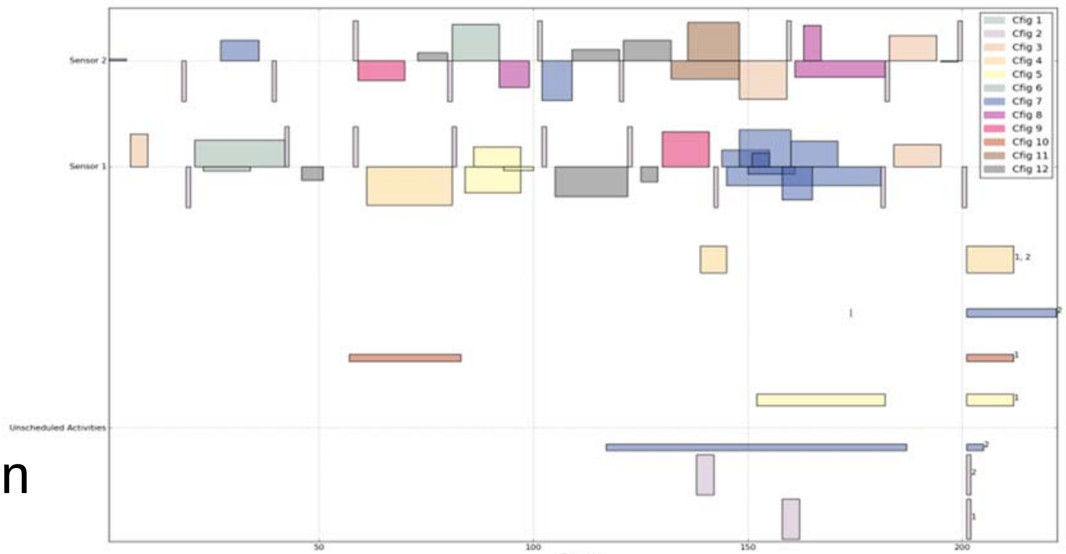
- Using a medium- or high-fidelity physics based simulation, build a performance score normalized between 0 and 1, composed of the following metrics:
  - Geometric access
  - Coverage
  - Probability of detection (PD)
  - Closely Spaced Objects (CSO)

- These scores depend on:
  - Weather, collection window scene background, sensor optics, etc.

- Predicted observation quality is calculated off-line, in advance of scheduling for all sensor, collection window, and start time combinations

Results – Constellation Scheduling MIP

- Solutions within **99%+ of optimal in minutes** using untuned *Gurobi* solver
  - Solving to provably optimal usually occurs within one hour
  - Linux machine with:
    - 64 cores, 1 TB RAM
- Models implemented using Sandia's Pyomo optimization software library
  - www.pyomo.org
- Typical problem scale:
  - Two sensors
  - 1440 timesteps
  - 450 collection windows



Example schedule with model modified to allow collection windows sharing configurations to run concurrently.

Notes on Constellation Scheduling MIP

- Established a set of benchmark problem instances
  - Differing numbers of satellites [1,10]
  - Large time-windows (w/ majority spanning the entire planning time horizon)
  - Competing priorities
  - Time-varying predicted observation quality

- Benchmark instances aim to be applicable for model extensions
  - All collection windows include a set of feasible configurations

- The model assumes prescience. In reality, after planning:
  - Collection windows are added to the queue
  - Predicted weather is or is not realized
  - Collection fails to reveal desired information

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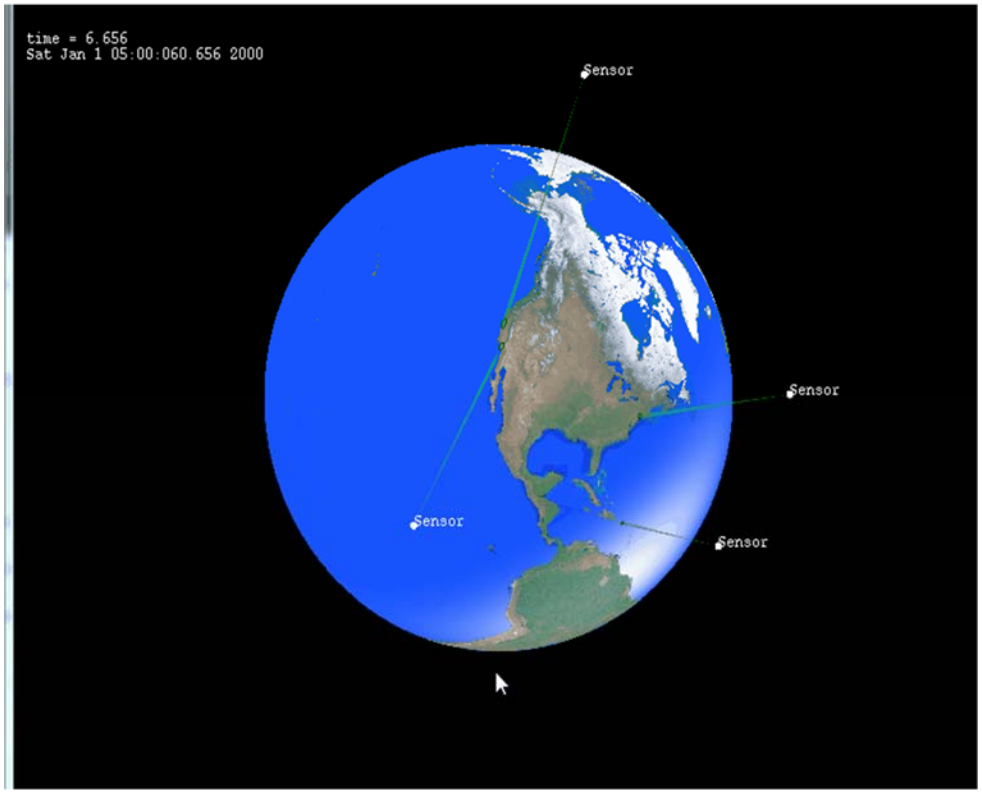


Stochastic Scheduling Models

- Developed distinct scenario-based stochastic MIP models to address the following areas of sensor scheduling uncertainty:

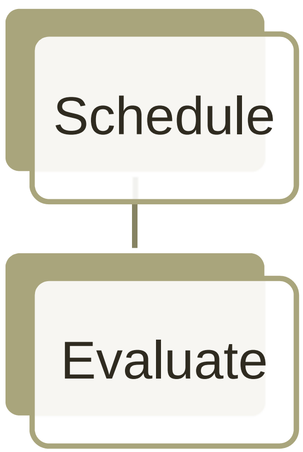
  - *Ad hoc* **collection windows**
    - Described by scenarios modeling collection windows with uncertain start times and durations
      - *Ad hoc* collection windows assume **highest** priority
    - Produced schedules will be resilient to disruptions and include a plan for "getting back on schedule"

  - **Weather**
    - Uncertain performance of scheduled collection windows based on weather (cloud-cover) scenarios
    - Produced schedules will be resilient to performance effects caused by weather

MIP vs. Stochastic MIP Comparison

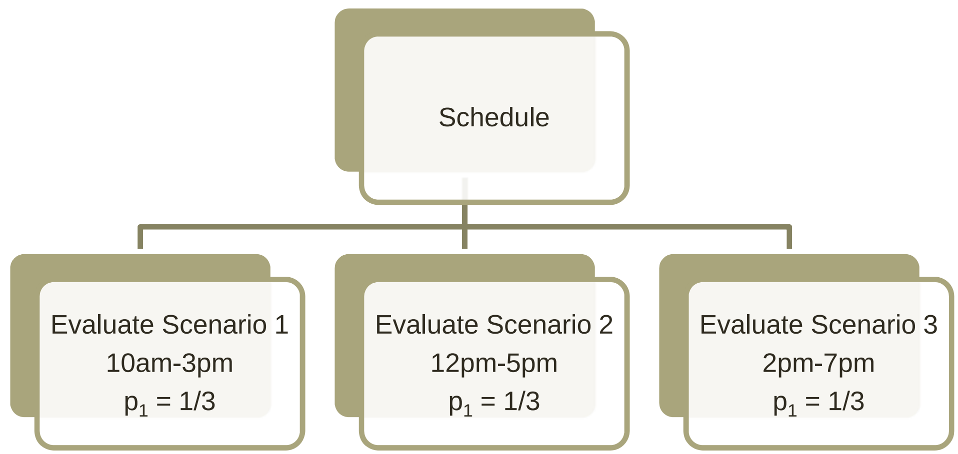
MIP

$Max\ f(x)$



Stochastic

$Max\ \mathbb{E}[f(x)]$



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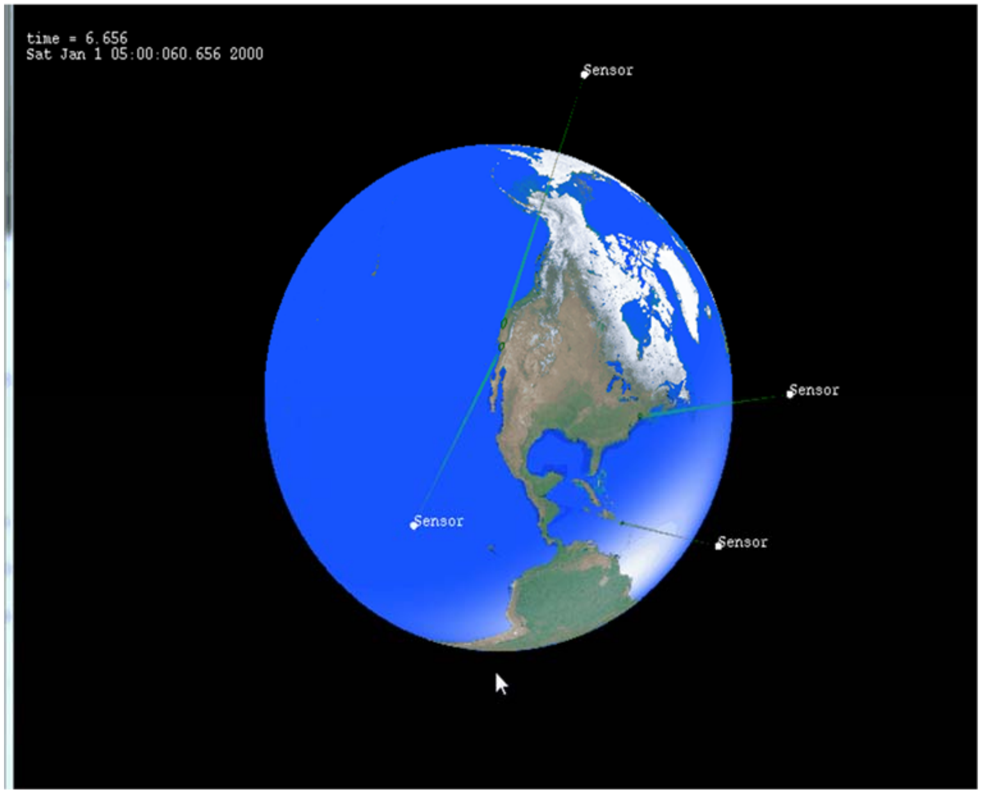
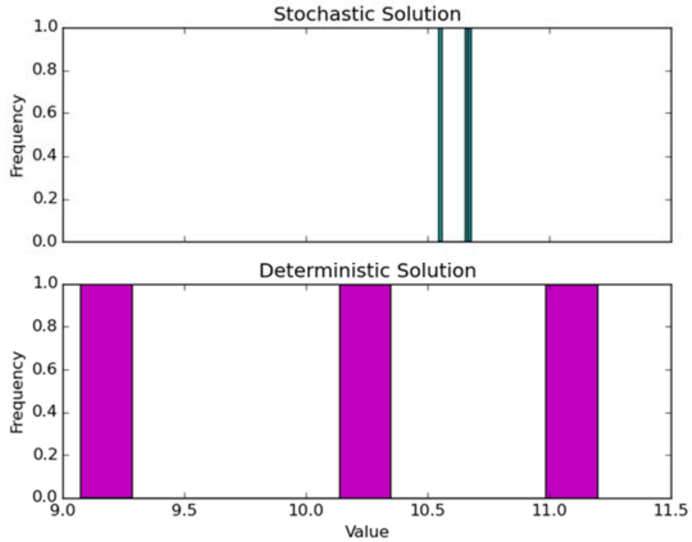


Results – Stochastic MIPs

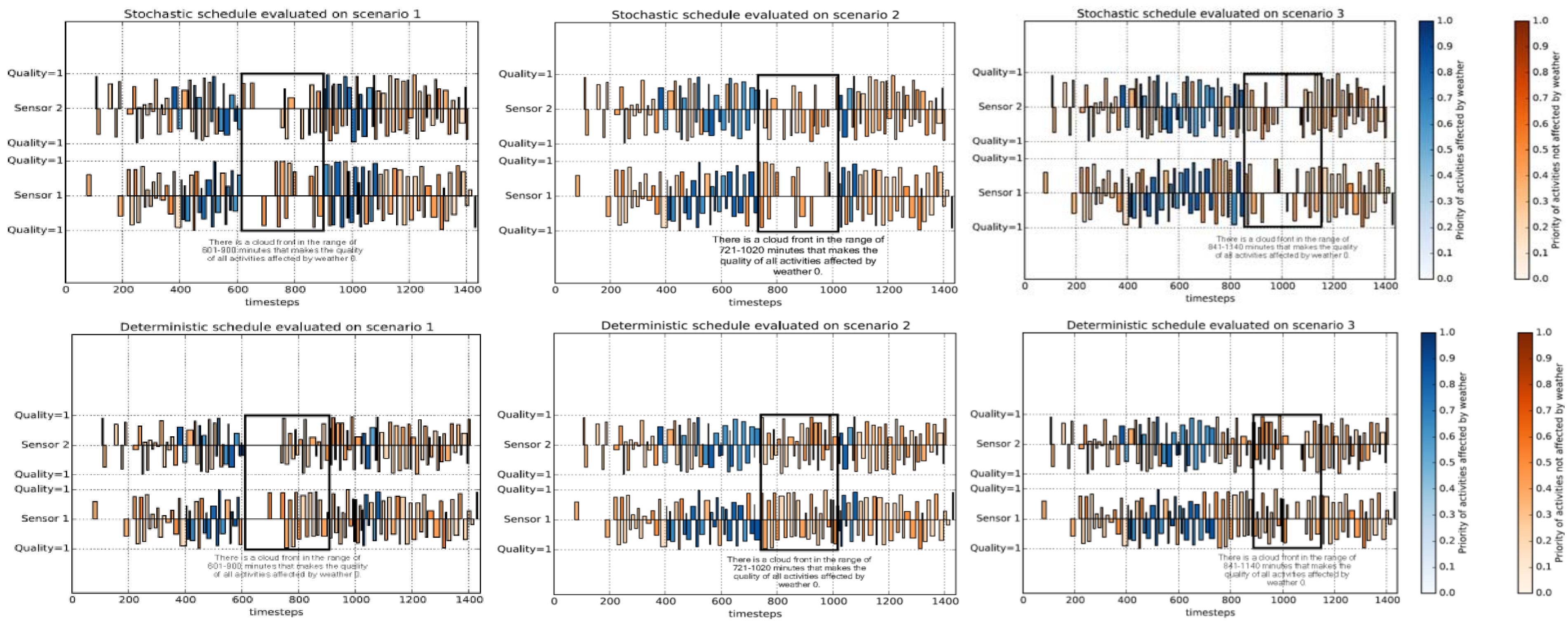
- Exploring the value of stochastic solution
  - Current models are giving a ~5% Value of Stochastic Solution (VSS)
- We are solving the extensive form (EF)
  - Generate a larger MIP with decision variables for each scenario
  - Modify original MIP objective function
- Typically solves to optimal within one hour
- We can use Pyomo's PySP Progressive Hedging (PH) metaheuristic to solve problems with many scenarios



Objective function values for schedules produced with stochastic and deterministic models (three weather scenarios)

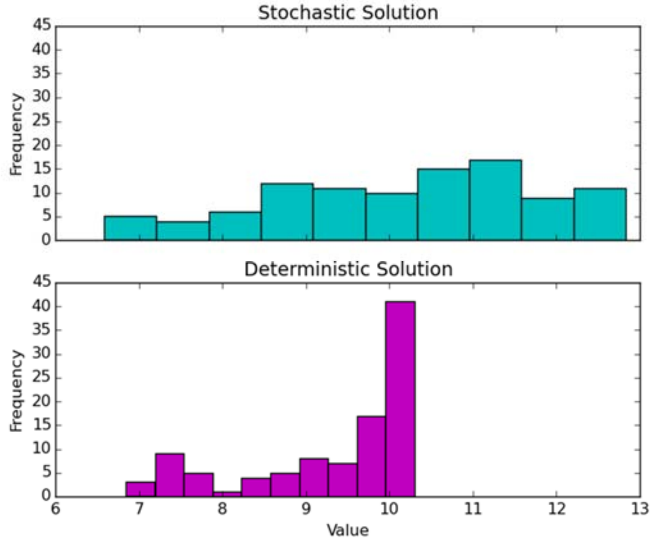
Results – Stochastic MIPs (cont.)

- Collection windows are either affected or unaffected by clouds:
- Three scenarios, each with a different time of cloud arrival
  - Weather front in black rectangles (no value for collections affected by weather)



Results – Stochastic MIPs (cont.)

- Model prevents collection windows below defined quality threshold (q^0) from being considered for scheduling
  - Under different scenarios, collection windows can be above or below q^0 depending on scheduled time and sensor



Objective function values for schedules produced with updated stochastic and deterministic models (100 weather scenarios)

- By updating the model to allow these collections to be scheduled, we are seeing upwards of an 8% Value of Stochastic Solution (VSS)
- We are solving the extensive form (EF) with 100 weather scenarios to optimal on the order of a few hours

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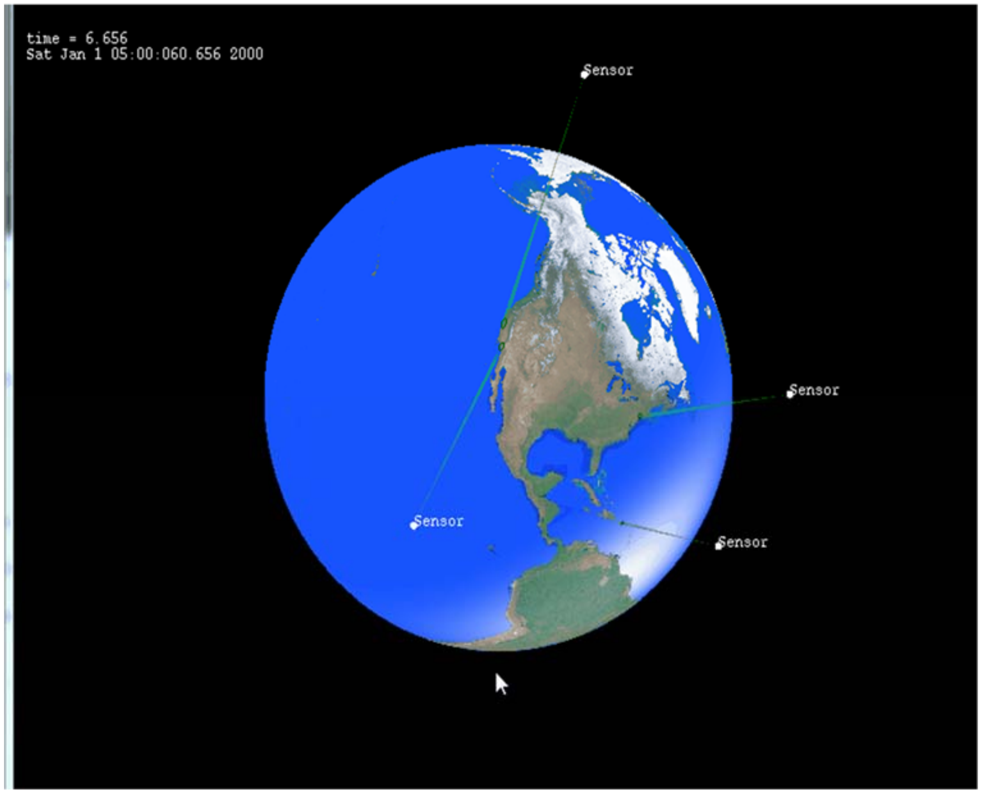


Ongoing Research and Future Work

- Exploring several alternative formulations
  - Allow concurrent activities subject to constraints
  - Exploiting periodic calibration activities ("knapsack")

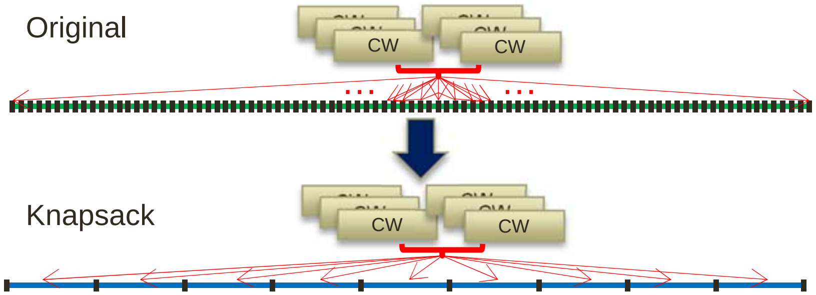


Illustration of the knapsack formulation.

- With Texas A&M, investigating models where collections can choose from multiple configurations

- Soliciting sensor operator expertise to meaningfully define q_{ikt}

- Exploring interrelated coverage optimization problems:
  - Sensor footprint mosaics without gaps, guaranteed properties
  - Sub-footprint placement according to BW constraints

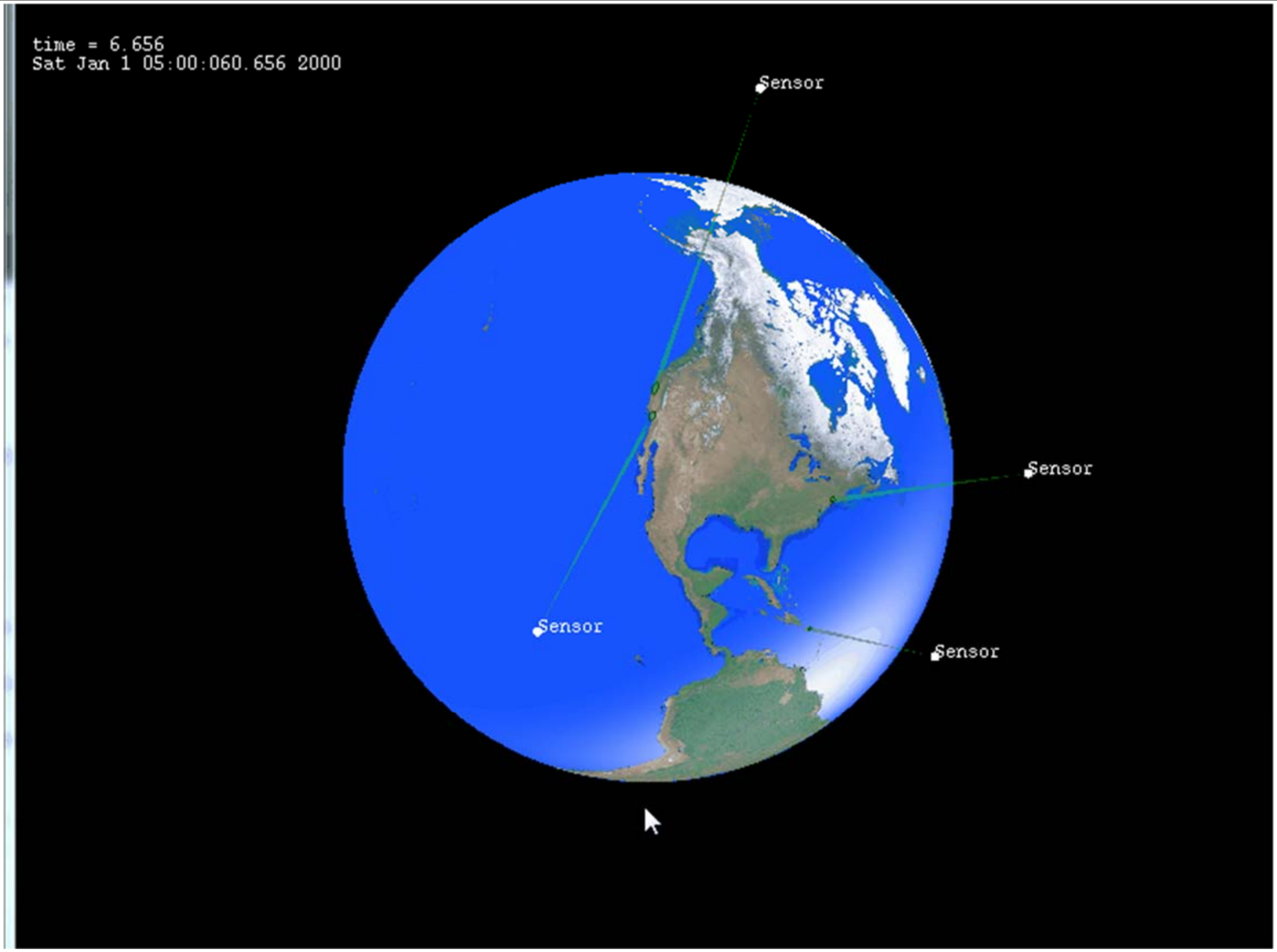
Ongoing Research and Future Work (cont.)

- Interested to partner with satellite planners/operators to create representative *ad hoc* and weather scenarios

- Additional model constraints, objective functions
  - Scheduling of collection windows requiring multiple satellites
  - Exploring the effects of removing duration from the objective
  - Use coarser model over longer timeframe (multiple days) in conjunction with existing model (**time-value of information**)

- Solver tuning
  - Extending OR-based heuristic implementations developed by Texas A&M to stochastic models
  - To date, models produce many similar schedules
    - Produce definitions for “dissimilar” schedules

Questions?


time = 6.656
Sat Jan 1 05:00:060.656 2000
Sensor
Sensor
Sensor
Sensor

Stochastic MIP- *ad hoc* Collection Windows

$$\begin{aligned}&\text{Max } f(x)+\mathbb{E}[g(x,\tilde{\xi})]\\ &\text{s.t. } Ax\le b\\ &\qquad x\in X,\end{aligned}$$

where

$$\begin{aligned}
g(\delta,\xi)= \quad & \text{Max } h(\gamma(\xi),\Gamma(\xi)) & \\
& \text{s.t. } \textstyle\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\Delta^{\xi}_{ikt}-\Omega^{\xi}_{k}=0 & \forall k\in\mathcal{K}_4,\\
& \textstyle\sum_{k\in\mathcal{K}_4}\Delta^{\xi}_{ik\bar{t}}\le 1-\sum_{k\in\mathcal{K}_4}\sum_{t\in\mathcal{C}(k,\bar{t})}\Delta^{\xi}_{ik\bar{t}} & \forall \bar{t}\in\mathcal{T}, i\in\mathcal{I}\\
& \Omega^{\xi}_{k}=1 & \forall k\in\mathcal{K}_4,\\
& y^{\xi}_{ikk_zt}+(1-\Delta^{\xi}_{ikt})\ge\delta_{ik_zt} & \forall i\in\mathcal{I}, k, k_z, \in\mathcal{K}^p_4, t\in\mathcal{T},\\
& (1-y^{\xi}_{ikk_zt})+\Delta^{\xi}_{ik_jt_j}\ge 1 & \forall i, k_j, k_z, t_j, t_z\in\mathcal{K}^p_4,\\
& (1-y^{\xi}_{ik_jt_jk_zt_z})\ge 1-\delta_{ik_zt_z} & \forall i, k_j, k_z, t_j, t_z\in\mathcal{K}^p_4,\\
& \gamma^{\xi}_{ikt}+\textstyle\sum_{k_z\in\mathcal{K}_1}\sum_{t_z\in\mathcal{T}}y^{\xi}_{iktk_zt_z}\ge 1 & \forall i, k, k_z, t, t_z\in\mathcal{K}^p_4,\\
& (1-\gamma^{\xi}_{ikt})+(1-y^{\xi}_{iktk_zt_z})\ge 1 & \forall i, k, t, k_z, t_z\in\mathcal{K}^p_4,\\
& \Gamma^{\xi}_{ik_zt_z}+(1-y^{\xi}_{iktk_zt_z})+(1-\gamma^{\xi}_{ikt})\ge 1 & \forall i, k, t, k_z, t_z\in\mathcal{K}^p_4,\\
& (1-\Gamma^{\xi}_{ik_zt})+\textstyle\sum_{k\in\mathcal{K}_4}\sum_{t\in\mathcal{T}}y^{\xi}_{ikk_zt}\ge 1 & \forall i, k_z, t_z\in\mathcal{K}^p_4,\\
& (1-\Gamma^{\xi}_{ik_zt})+\textstyle\sum_{k\in\mathcal{K}_4}\sum_{t\in\mathcal{T}}\gamma^{\xi}_{ikt}\ge 1 & \forall i, k_z, t_z\in\mathcal{K}^p_4,\\
& \Omega^{\xi}_{k}\in\{0,1\} & \forall k\in\mathcal{K}_4\\
& \Delta^{\xi}_{ikt}\in\{0,1\} & \forall k\in\mathcal{K}_4, i\in\mathcal{I}, t\in\mathcal{T}\\
& y^{\xi}_{ikk_zt}\in\{0,1\} & \forall i, k_j, k_z, t_j, t_z\in\mathcal{K}^p_4,\\
& \gamma^{\xi}_{ikt}\in\{0,1\} & \forall i\in\mathcal{I}, k\in\mathcal{K}_4, t\in\mathcal{T}\\
& \Gamma^{\xi}_{ikt}\in\{0,1\} & \forall i\in\mathcal{I}, k\in\mathcal{K}, t\in\mathcal{T}
\end{aligned}$$