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14. ABSTRACT

Need for optimal Tx/Rx analysis capability to analyze AFSCN future architectures. AFOPT needs capability expansion as well as improved solution methodology. Iterative solution methodology outperforms IP solve better on average for harder problems

15. SUBJECT TERMS

Strategic Planning; Satellite Communications; Air Force Operations; Military Planning; Langrangian Iterative Solution Methodology; combinatorial optimization; AFOPT; AFSCN; strategic planning; satellite control network; Air Force Optimization Tool; Air Force

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Strategic Planning of the Air Force Satellite Control Network Using Combinatorial Optimization

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6/19/2019

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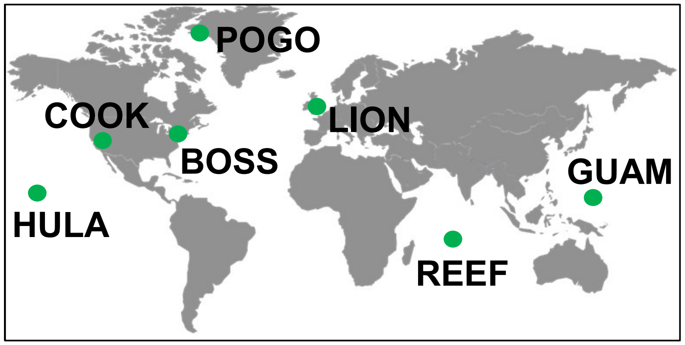
Background

- **Air Force Satellite Control Network (AFSCN)**
  - 22nd Space Operations Squadron operated (Schriever AFB)[1]
- **Problem Statement**
  - Currently a manual scheduling environment
  - Need analysis capabilities to develop objective architecture solutions
- **Current Analytical Capabilities**
  - Systems Tool Kit (STK) scheduling module from Orbit Logic[2]
  - Academia-developed tools (GENITOR, etc.)[3]



Need for <u>optimal</u> Tx/Rx analysis capability to analyze AFSCN future architectures

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Agenda

- **Air Force Optimization Tool (AFOPT)**
  - Origins
  - Construction
  - Lagrangian Iterative Solution Methodology
- **Excursion**
- **Future Work**
- **Conclusions**

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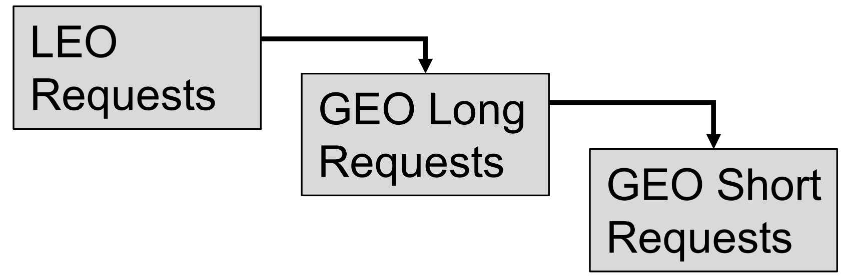
AFOPT - Origins

- **Air Force Optimization Tool (AFOPT)**
  - Original Development:

2003	Col Steven Baker, USAF, Ret Brig Gen Andrew Armacost, USAF Dr. Lee Lehmkuhl Thomas DeLaCruz

Cascade Heuristic:



  - Modern computational solvers can solve AFOPT directly
    - Still 8+ hours
  - AFOPT needs additional capabilities

AFOPT needs capability expansion as well as improved solution methodology

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AFOPT - Construction

- **Variables:**
  - $S_{jrt} \in \{0,1\}$: Scheduling of soft request r on antenna j at time t
  - $H_{jrt} \in \{0,1\}$: Scheduling of hard request r on antenna j at time t
  - $SNOT_r \geq 0$: Number of missed soft requests r
  - $HNOT_r \geq 0$: Missed hard request r
  - $DWN_{dt} \in \{0,1\}$: Scheduling of downtime d at time t

All are linear or binary variables!

Inputs

Hard Requests
Soft Requests
Downtime
Antenna Details

AFOPT

Objective:
- Minimize request missing penalty & hard request start time penalty

Constraints:
- Satellite capacity (w/ min. separation)
- Antenna capacity
- Downtime enforcement
- Antenna time limits

Outputs

Optimal Schedule

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AFOPT - Lagrangian Iterative Solution Methodology

- **AFOPT Facts:**
  - LP and IP solutions have near-zero gap under most operating conditions for provided formulation
    - Exceptions for site/antenna selection and limited antenna availability
  - Binary problem
  - Variables far outnumber number of constraints
    - E.g. 1.2 million variables vs. 0.1 million constraints

Solution methodology based on LP solves appears promising

Solution methodology based on efficiency measures appears promising

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AFOPT - Lagrangian Iterative Solution Methodology

- **Efficiency Measures ($\boldsymbol{e_i}$):**
  - Provides insight into IP solution values based on dual-LP solution [4]
  - In general:
    - Large e_i implies variable i is 1 in IP
    - Small e_i implies variable i is 0 in IP
    - e_i equal or near-zero implies greater uncertainty about IP solution

Coeffient for i in constraint j

Dual LP solution for constraint j

Objective coefficient for i

$$e_i = \begin{cases} \dfrac{\sum_j u_{ij} \cdot \bar{u}_j^{LR}}{c_i} + 1 & c_i \neq 0 \\ \displaystyle\sum_j u_{ij} \cdot \bar{u}_j^{LR} & c_i = 0 \end{cases}$$

Obtaining e_is can help in <u>guessing</u> at IP solution greatly reducing the size of IP solves

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AFOPT - Lagrangian Iterative Solution Methodology

- **Knapsack Example**
  - Select a subset of items with maximum utility $(\sum u_i = U)$ subject to one capacity constraint $(\sum c_i \leq C)$
    - $C = 220$

ITEM #:	2	10	6	8	9	5	3	1	7	4
u_i:	43	52	99	31	36	28	41	19	14	8
c_i:	19	23	98	36	50	44	91	43	69	72
e_i:	2.263	2.261	1.010	0.861	0.720	0.636	0.451	0.442	0.203	0.111
Linear:	1	1	1	1	0.88	0	0	0	0	0
Binary:	1	1	1	1	0	1	0	0	0	0

Core Variables

Efficiency measures tend to group core variables!

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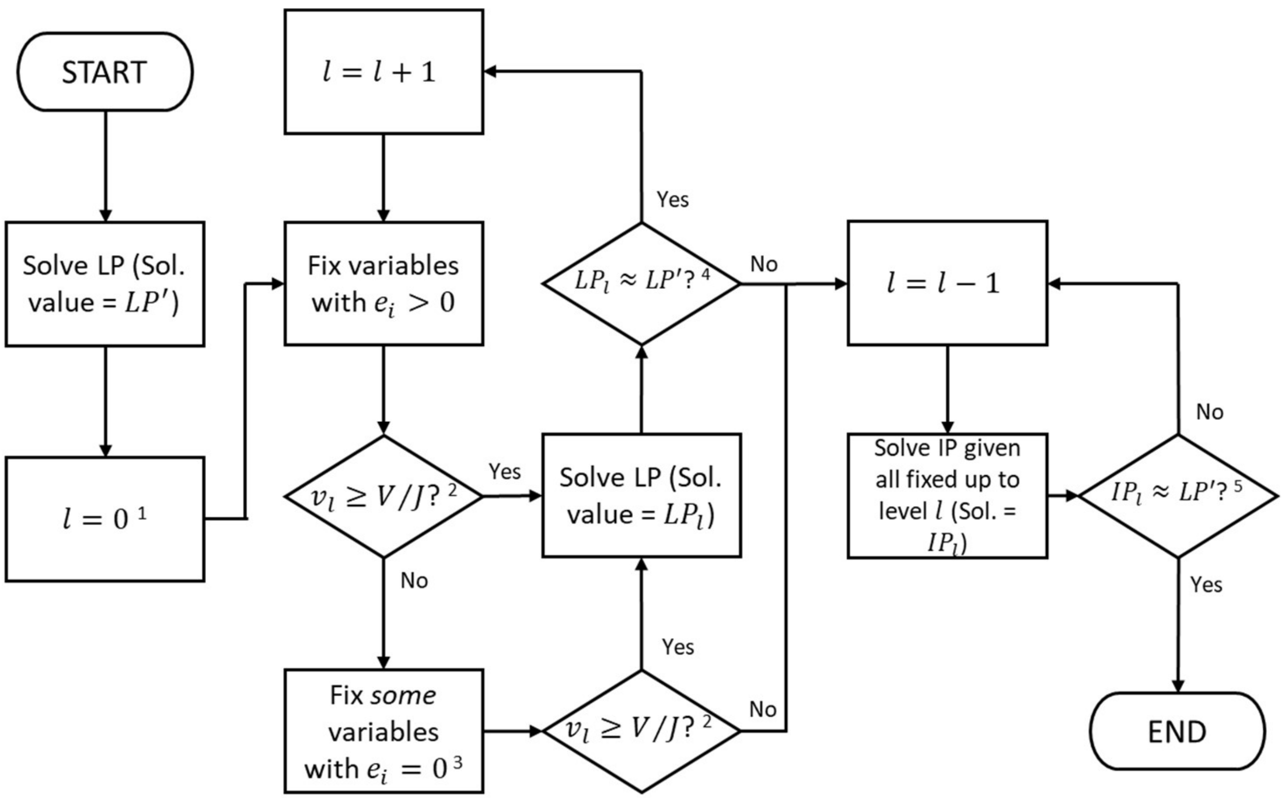
AFOPT - Lagrangian Iterative Solution Methodology



1. Let l be the algorithm round counter with $l \leq L$.
2. Let v_l be the number of fixed variables in round l and let V be the total number of requests.
3. Start with those whose LP solution is largest and proceed until $v_l = V/J$. Stop at any user-defined value (LP value of 0.50 in these tests). Test any other criteria before fixed if desired.
4. Test is $LP_l - LP' \leq \min(mispen_r)$.
5. Test is $IP_l - LP' \leq \min(mispen_r)$.

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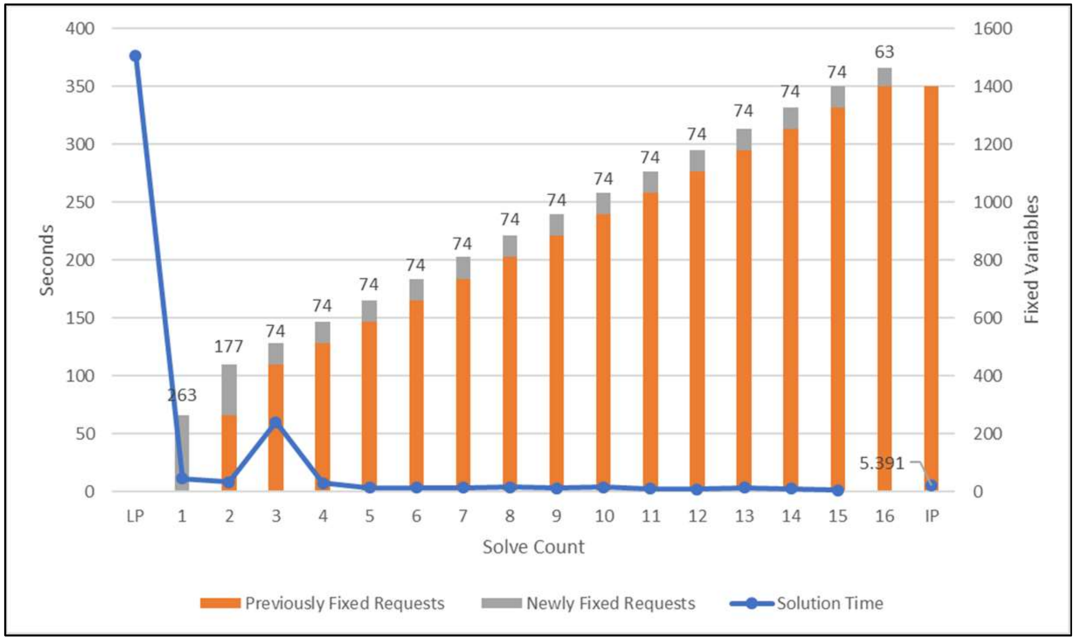
AFOPT - Lagrangian Iterative Solution Methodology

- **Processing Flow Example (CPLEX + GAMS)**

IP Solve (13.66 min.)
- LP: 8.24 min.
- B&B: 5.42 min.

Lagrangian Iterative Solve (8.37 min)
- LP: 6.28 min.
- Iterations + IP: 2.09 min.



Iterative solve completed 61% faster (than regular IP solve) and fixed ~1400 requests before starting final IP solve

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AFOPT - Lagrangian iterative solution methodology

- **Site and/or Antenna choice**
  - May need to solve problems where we are limited by the total number of sites/antennas
  - Process (for sites):
    - Solve LP w/o any limits
    - If enough sites closed, STOP
    - Guess based on LP solution which to site to close without duplicating prior guess
      - Site whose value is closest to zero which hasn't been tested yet
    - Solve LP with new site closure
      a) If solution value hasn't changed drastically, got to (2)
      b) If solution value has changed drastically …
         - Try another if possible and go to (3)
         - Otherwise select best possible option thus far and go to (2)
  - Repeat process if antenna limits are not satisfied

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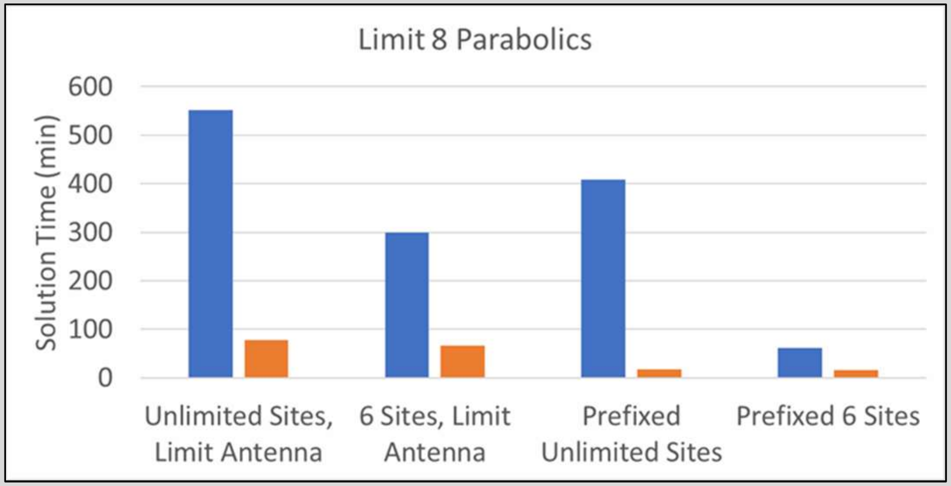
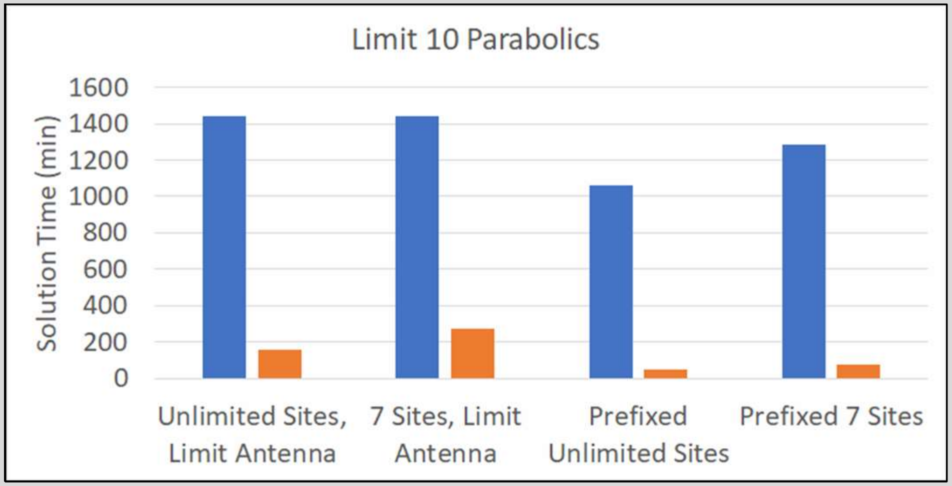
AFOPT - Lagrangian iterative solution methodology

Experiment Set 1*



Experiment Set 2*



Iterative solve 7.3x faster on average. 3 out of 24 experiments finished 20x faster with iterative solve. Iterative solve has better average on harder problems.

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* Experiments run using fictional contacts and ground assumptions

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Agenda

- **Air Force Optimization Tool (AFOPT)**
- **Excursion**
  - Background
  - Results
- **Conclusions**
  - Summary
  - Future Work

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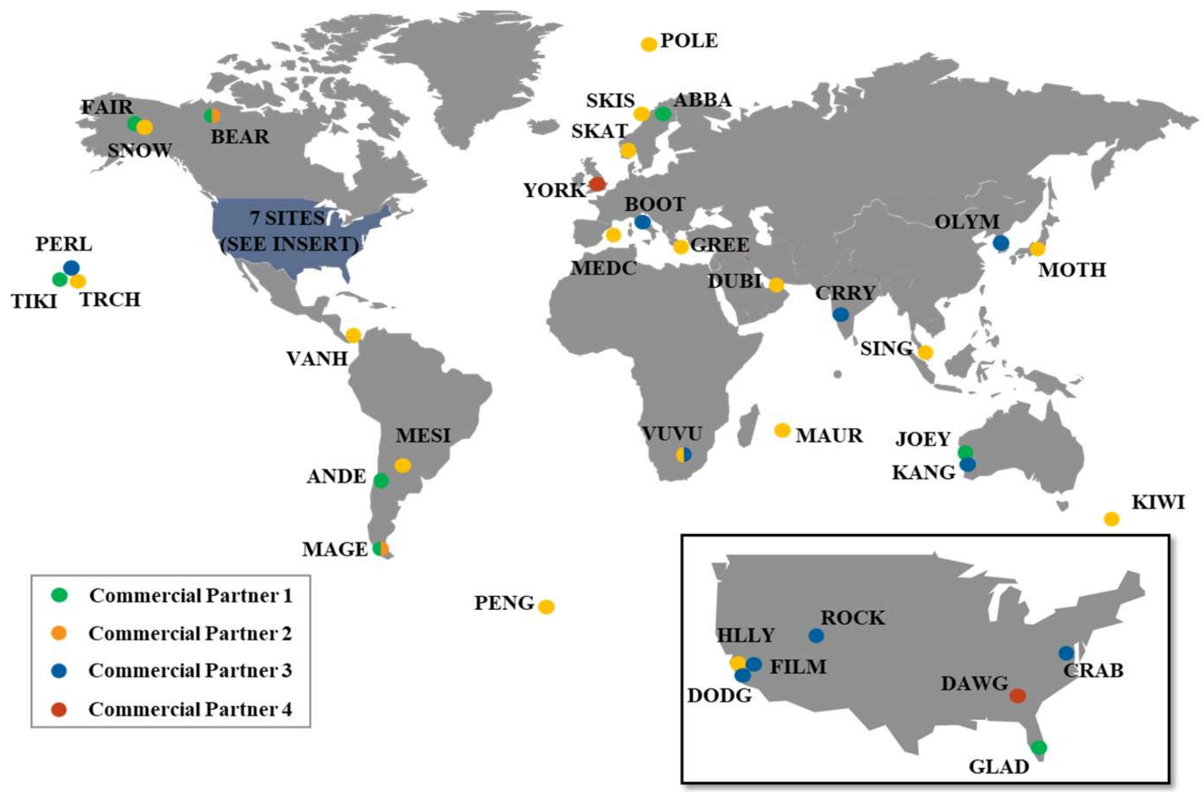
Excursion - Background

- **Commercial Augmentation Study**
  – Quantify impact of offloading some satellite supports onto possible commercial partners
- **Ground inventory**
  – Top 10 out of 36 commercial options for offloaded supports



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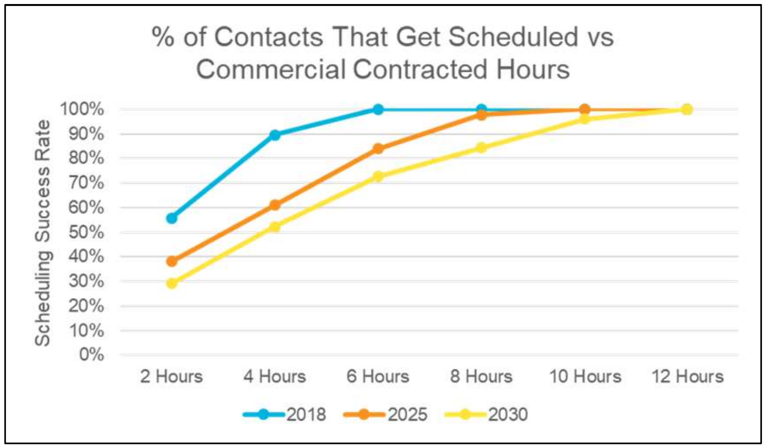
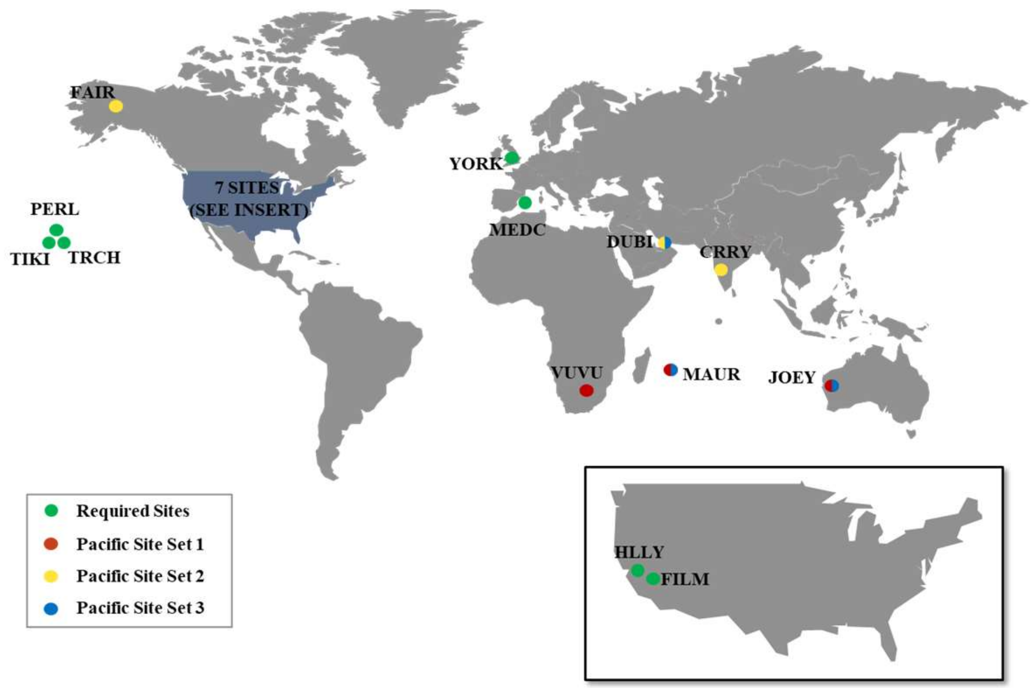
Excursion - Results

- **Offloaded Supports**





- **Offloading contacts today requires ~6 hrs. per commercial site**

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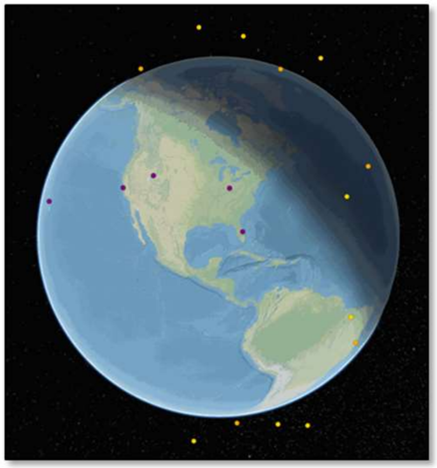
Conclusions

- **AFOPT provides an optimal (at a minimum close w/ bound) Tx/Rx analytical capability for AFSCN or similar systems**
- **Iterative Solve Methodology**
  – Solving LP and iteratively fixing variables to reduce size of IP solve
  – On average 7.3x faster than direct IP solve
  – 3 out of 24 experiments finished 20x faster than direct IP solve
  – Iterative solution methodology outperforms IP solve better on average for harder problems
- **Continued and future work**
  – Continuation of analyses for agencies and sponsors
  – Heuristic driven solutions when commercial licensing isn't viable
  – Visualization tool of analysis results
  – GUI-Driven analysis package



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Questions?

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Citations

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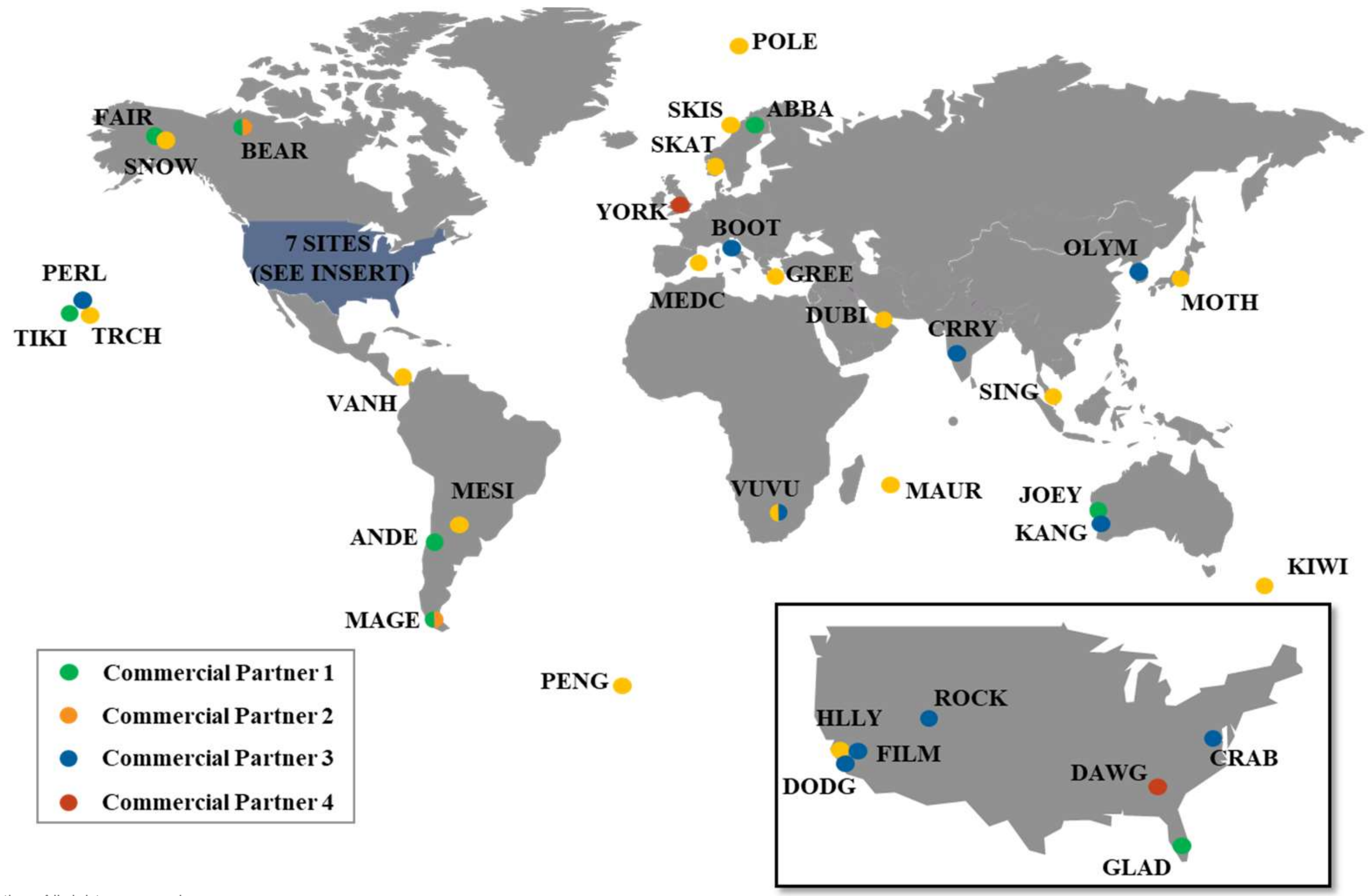
BACKUP – Commercial Partner Sites



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BACKUP – Variable Details

- **SETS**
  - R: Set of all requests
  - $RS \subseteq R$: Set of soft requests
  - $RH \subseteq R$: Set of hard requests
  - $CC \subseteq R$: Set of continuous communication requests
  - D: Set of downtimes/maintenances
  - J: Set of parabolics
  - T: Set of time periods
  - $TH_{jr} \subseteq T$: Subset of viable starting times for hard request r on antenna j
  - $tis_{rt} \subseteq T$: Subset of times when other requests of r cannot start assuming another request started at time t

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BACKUP – Variable Details

- **SETS**
  - $downtoj_d \in J$: Antenna needed for downtime d
  - $jtodown_j \subseteq D$: Set of downtimes applicable to antenna j
  - $ttot_{rt} \subseteq T$: Set of times which would occupy antenna by request r starting at time t
  - $ttotd_{dt} \subseteq T$: Set of times which would occupy antenna by downtime/maintenance d starting at time t
- **PARAMETERS**
  - $mispen_r$: Penalty for not scheduling request r
  - hrt_r: Ideal starting time for hard request r
  - $offpen_r$: Per period penalty for not starting hard request r at the requested time
  - $tiepen_{jrt}$: Perturbation value for soft request r on antenna j at time t
  - srf_r: Number of contacts requested for soft request r
  - $totaltime_r$: Total time required to complete request r on the antenna
  - $antcap_j$: Number of effective apertures for parabolic/array j
  - $antavail_j$: Total time available for parabolic/array j
  - $parabolicLimit$: Total time permitted across all parabolics

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BACKUP – AFOPT Formulation

- **Variables:**
  - $S_{jrt} \in \{0,1\}$: Scheduling of soft request r on antenna j at time t
  - $H_{jrt} \in \{0,1\}$: Scheduling of hard request r on antenna j at time t
  - $SNOT_r \geq 0$: Number of missed soft requests r
  - $HNOT_r \geq 0$: Missed hard request r
  - $DWN_{dt} \in \{0,1\}$: Scheduling of downtime d at time t
- **Minimize:**

$$\underbrace{\sum_{r \in RH} mispen_r \cdot HNOT_r}_{\text{Penalty for missing hard requests}} + \underbrace{\sum_{r \in RS} mispen_r \cdot SNOT_r}_{\text{Penalty for missing soft requests}} + \underbrace{\sum_{\substack{j \in J \\ r \in RH \\ t \in TH_{jr}}} |t - hrt_r| \cdot offpen_r \cdot H_{jrt}}_{\text{Penalty for missing ideal hard request start time}} - \underbrace{\sum_{\substack{j \in J \\ r \in RS \\ t \in T}} tiepen_{jrt} \cdot S_{jrt}}_{\text{Soft request perturbation}}$$

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BACKUP – AFOPT Formulation

- **Subject to…**

$$\sum_{\substack{j \in J \\ t \in T}} H_{jrt} + HNOT_r = 1 \quad \forall\, r \in RH$$

Enforcing $HNOT_r$ if enough hard requests are not satisfied

$$\sum_{\substack{j \in J \\ t \in T}} S_{jrt} + SNOT_r = srf_r \quad \forall\, r \in RS$$

Enforcing $SNOT_r$ if enough frequency srf_r for soft request r is not met

$$\sum_{\substack{j \in J \\ t' \in tis_{rt}}} S_{jrt'} \leq 1 \quad \forall\, r \in RS, t \in T$$

Ensuring satellite is not contacted more than requested during any continuous set of time periods

$$\sum_{\substack{r \in RS \\ t \in T}} totaltime_r \cdot S_{jrt} + \sum_{\substack{r \in RH \\ t \in T}} totaltime_r \cdot H_{jrt} \leq antcap_j \cdot antavail_j \quad \forall\, j \in J$$

Enforcing time limits on antenna availability

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BACKUP – AFOPT Formulation

- **Subject to…**

$$\sum_{\substack{j\in PB\\ r\in RS\\ t\in T}} totaltime_r \cdot S_{jrt} + \sum_{\substack{j\in PB\\ r\in RH\\ t\in T}} totaltime_r \cdot H_{jrt} \leq parabolicLimit$$

Enforcing time limits on antenna availability across all parabolics

$$\sum_{t\in T} DWN_{dt} + \sum_{\substack{r\in CC\\ j\in downtoj_d}} S_{jr1} \geq 1 \quad \forall\, d \in D$$

Ensuring downtime is scheduled unless continuous comms requests are present

$$\sum_{\substack{r\in RH\\ t'\in ttot_{rt}}} H_{jrt'} + \sum_{\substack{r\in RS\\ t'\in ttot_{rt}}} S_{jrt'} + \sum_{\substack{t'\in ttotd_{dt}\\ d\in jtodown_j}} DWN_{dt'} \cdot antcap_j \leq antcap_j \quad \forall\, j \in J, t \in T$$

Ensure antenna capacity limits

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BACKUP – Antenna/Site Selection Formulation

- **Additional Sets:**
  - $SITES$: List of all sites (may contain one or more parabolics)
  - $jtos_s \subseteq J$: Antennas which are at site s
- **Additional Parameters:**
  - $pblimit$: Limit on parabolics
  - $sitelimit$: Limit on sites
- **Variables:**
  - $ACTIVESITE_S \in \{0,1\}$: Indicator if site s is active
  - $ACTIVEANT_j \in \{0,1\}$: Indicator if antenna j is active

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BACKUP – Antenna/Site Selection Formulation

- **Modified Constraints:**

$$\sum_{t \in T} DWN_{dt} + \sum_{\substack{r \in CC \\ j \in downtoj_d}} S_{jr1} \geq \sum_{j \in downtoj_d} ACTIVEANT_j \quad \forall\, d \in D$$

$$\sum_{\substack{r \in RH \\ t' \in ttot_{rt}}} H_{jrt'} + \sum_{\substack{r \in RS \\ t' \in ttot_{rt}}} S_{jrt'} + \sum_{\substack{t' \in ttotd_{dt} \\ d \in jtodown_j}} DWN_{dt'} \cdot antcap_j \leq antcap_j \cdot ACTIVEANT_j \quad \forall\, j \in J, t \in T$$

- **New Constraints:**

$$\sum_{j \in PB} ACTIVEANT_j \leq pblimit$$

$$\sum_{S \in S} ACTIVESITE_s \leq sitelimit$$

$$ACTIVEANT_j \leq ACTIVESITE_s \quad \forall\, s \in S, j \in jtos_s$$

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