Autonomous Scheduling of Agile Spacecraft Constellations with Delay Tolerant Networking for Monitoring Transient Precipitation and Urban Floods

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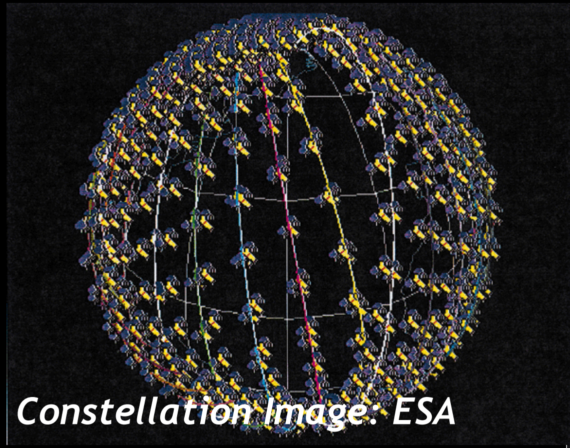
Autonomous Scheduling for Reactive Imaging

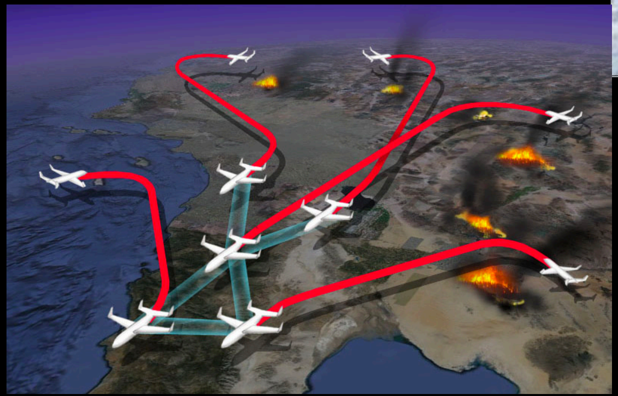
- GEO satellites have 24x7 coverage but coarse resolution (e.g. SOA by NASA for fire remote sensing is 2 km), LEO satellites can do finer (e.g. SOA 150m proposed by FireSat) but need 1000s of sats for 24x7…. Agile LEO ?
- Lots of research on constellation design, scheduling ops for single spacecraft, downlinks for constellations, UAV path planning, and industry advances in spacecraft attitude control… however, very little on combining all of them for responsive remote sensing.
- For a constellation with agile pointing, if one sat measures an event, can it {process its data, predict its evolution, comm. to the next sat} such that it points its payload accordingly? How do we quantify the changing value?



Constellation Image: ESA

CHRIS on single sat Proba: ESA

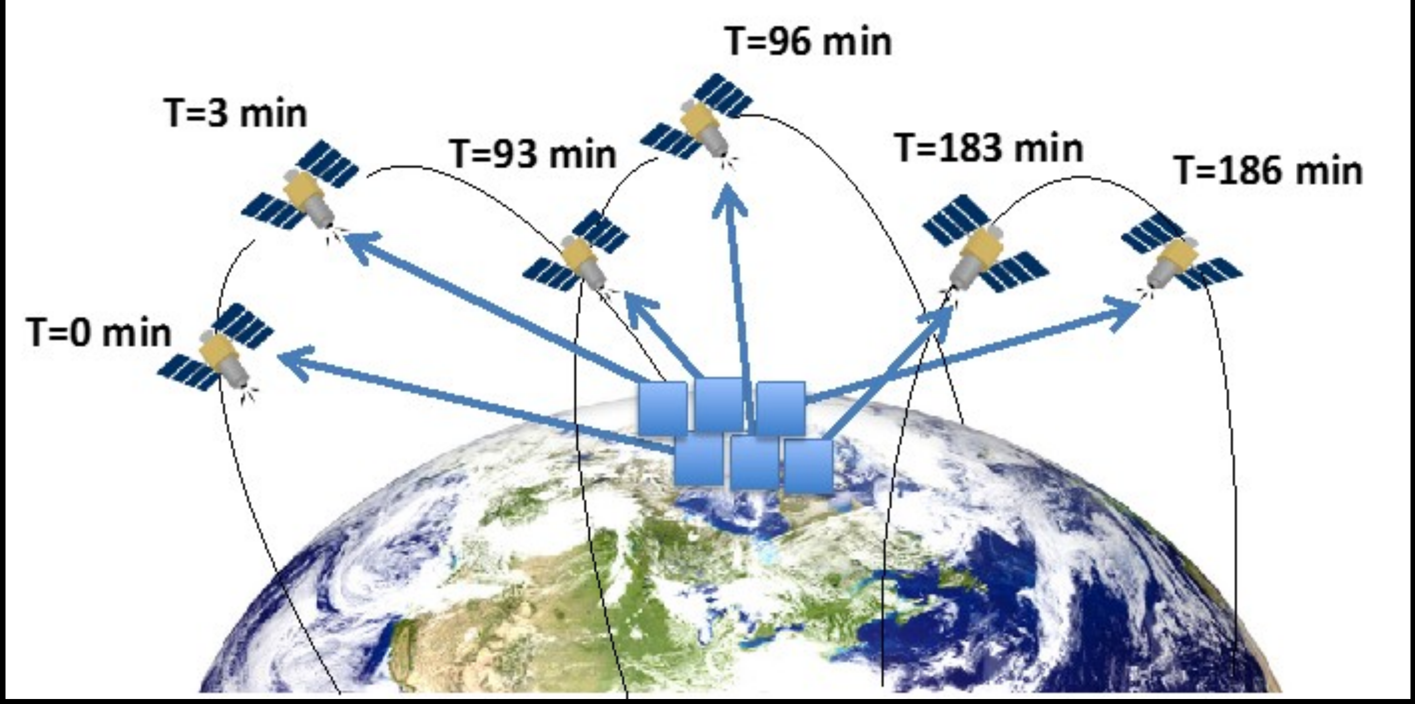
Uwash RAIN Lab



Premise of the Ground Scheduler

Given a global set of images, a fixed constellation of satellites with agile ADCS, satellite specs and coverage constraints, what is the fastest route to cover those images?

- Need a linear-time algorithm to schedule the re-orientation and capture by any constellation and of any targets
- Using Landsat as a case study (710 km, SSO, 15 deg FOV). Has a 14 day revisit; Daily revisit needs ~15 satellites or 4 satellites with triple FOV.
- Assumed a 20 kg satellite platform to try the option of agile pointing
- Re-orientation was based on a bang-bang + PD controller; Scheduler was based on Dynamic Programming
- The images, constellation/satellite number, specs and constraints (e.g. clouds, ground station outage) are assumed modular for generality

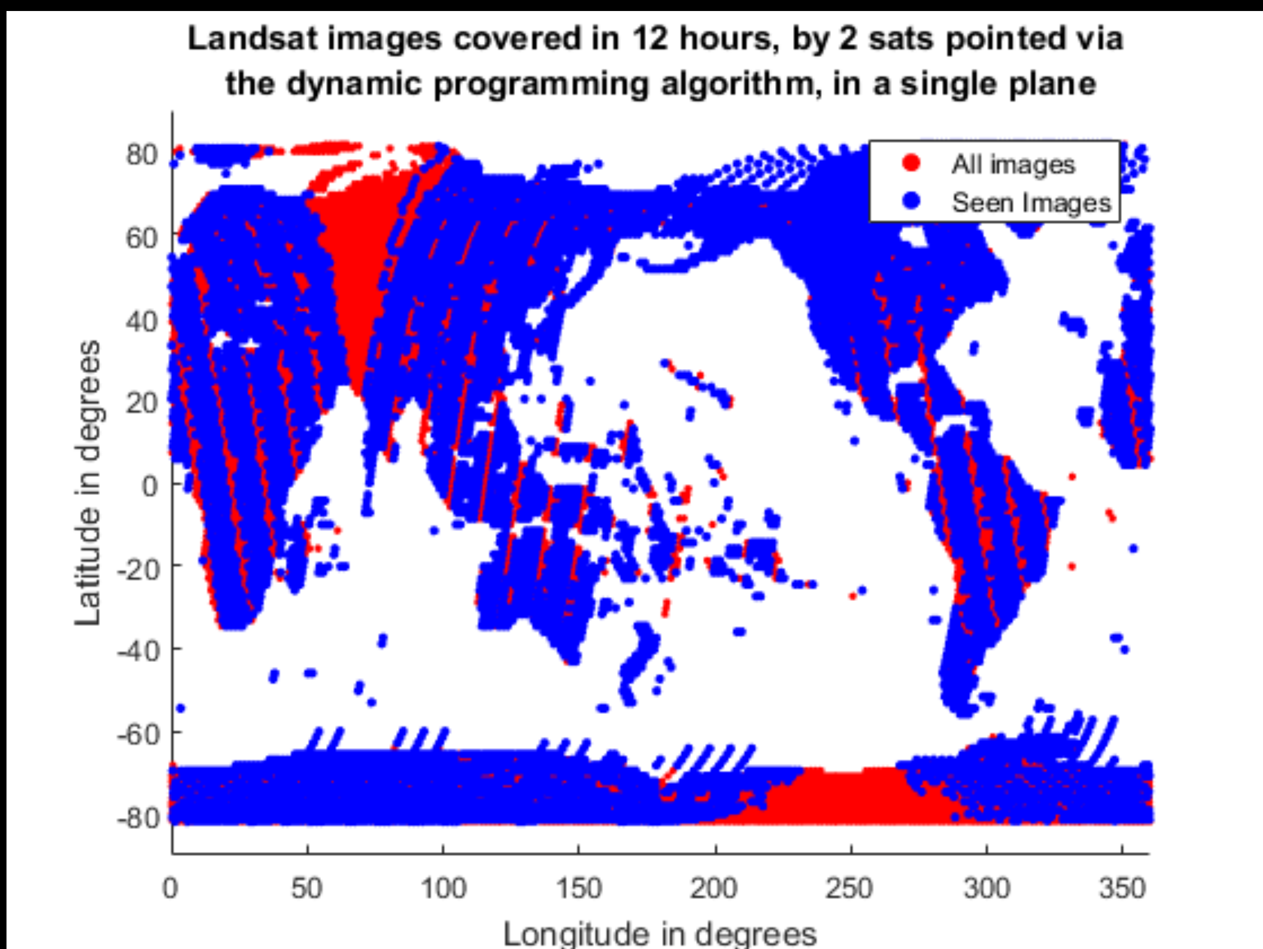


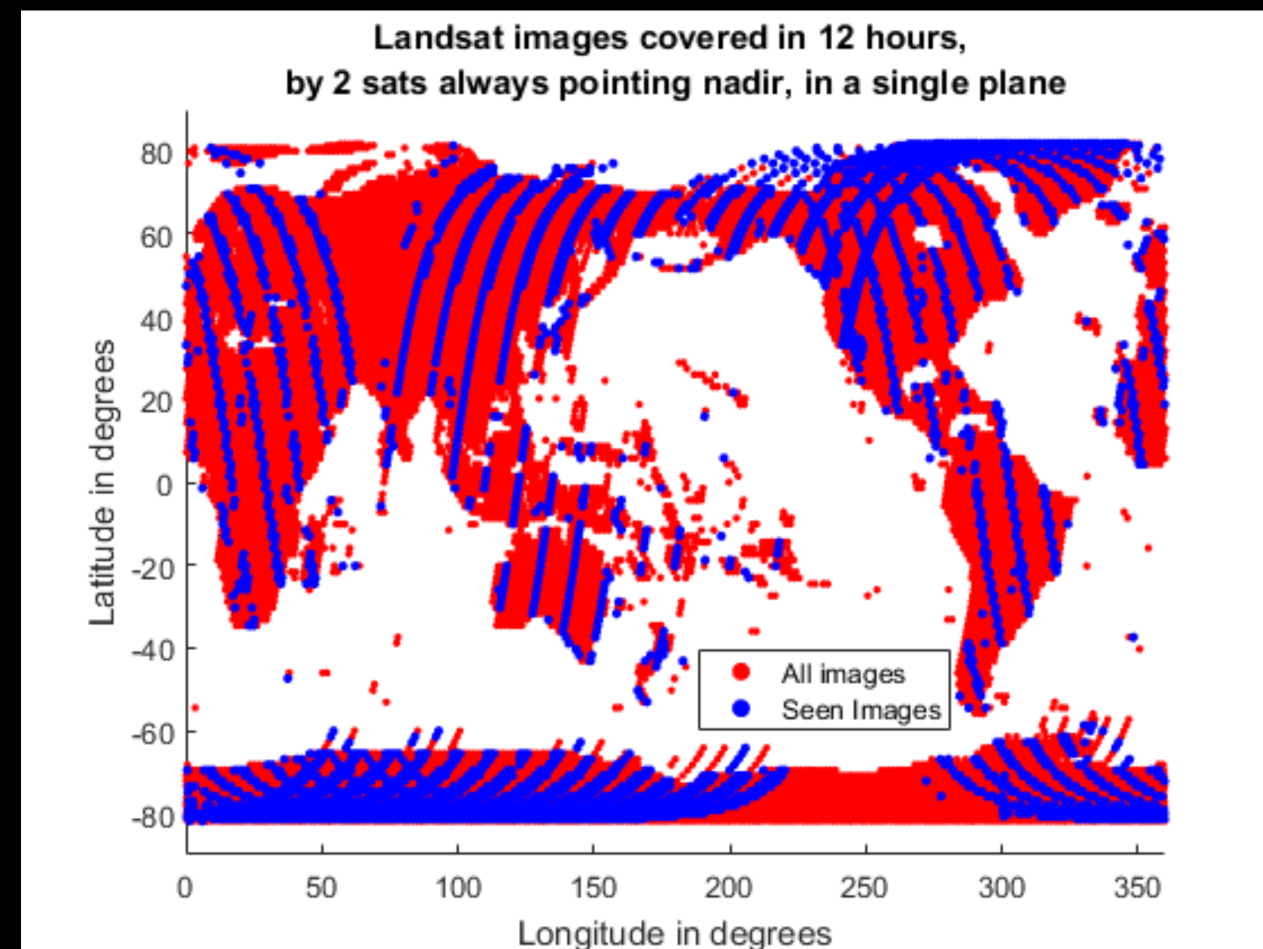
S. Nag, A.S. Li, J.H. Merrick, "Scheduling Algorithms for Rapid Imaging using Agile Cubesat Constellations", COSPAR Advances in Space Research - Astrodynamics 61, Issue 3 (2018), 891-913

Results with a 2-Sat Constellation

Over 12 hours of planning horizon using 2 satellites, 180 deg apart in the same plane :

- Using our **proposed DP algorithm**
- Using a **fixed Landsat sensor**, as is

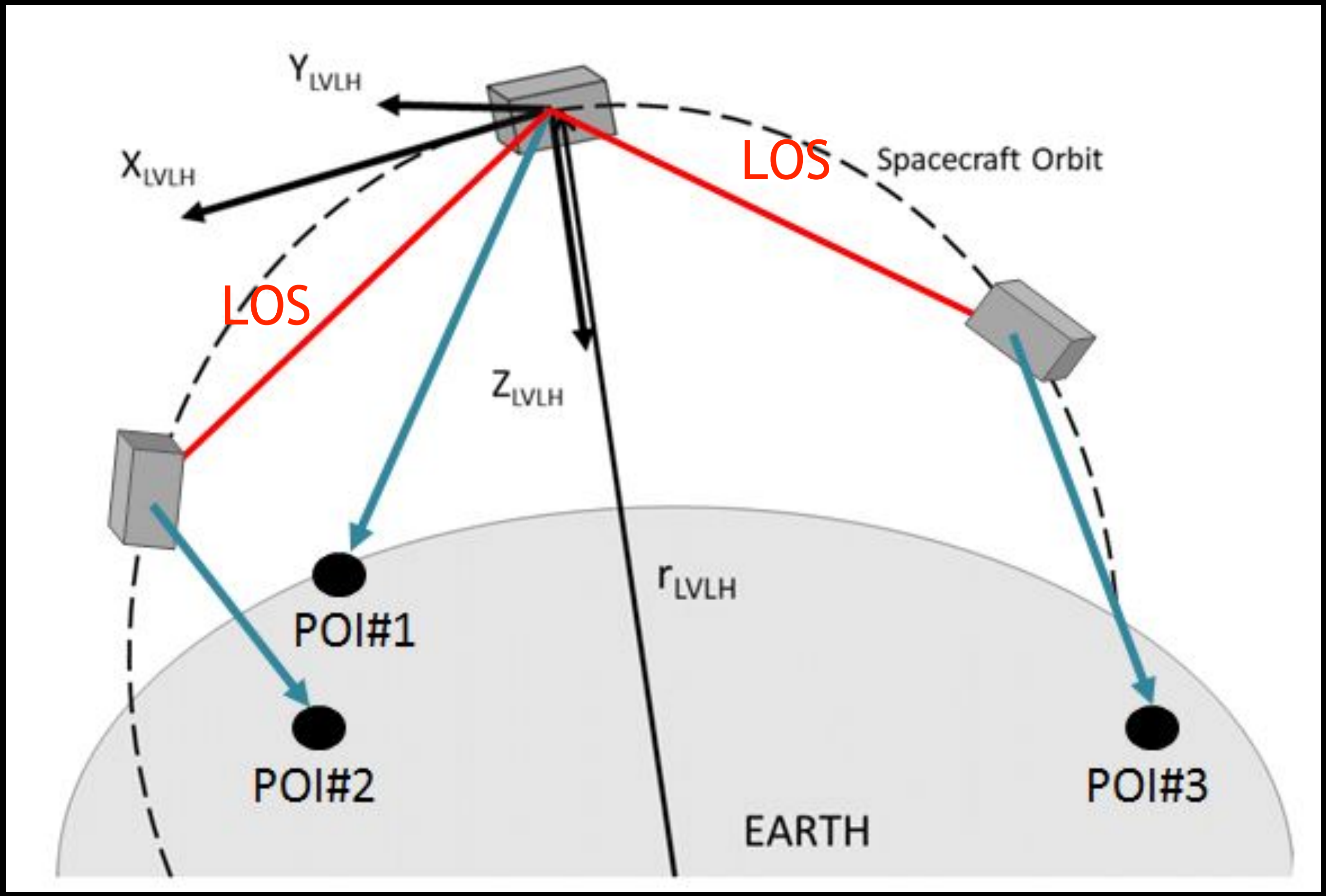




Of 14164 possible images, 10848 were seen.
Algorithm covered 76.6% from possible images and 65% from total.
2.5x the number using the fixed pointing approach.
1.5x possible with a 4-sat, single plane constellation.

Can the Scheduler also run Onboard?

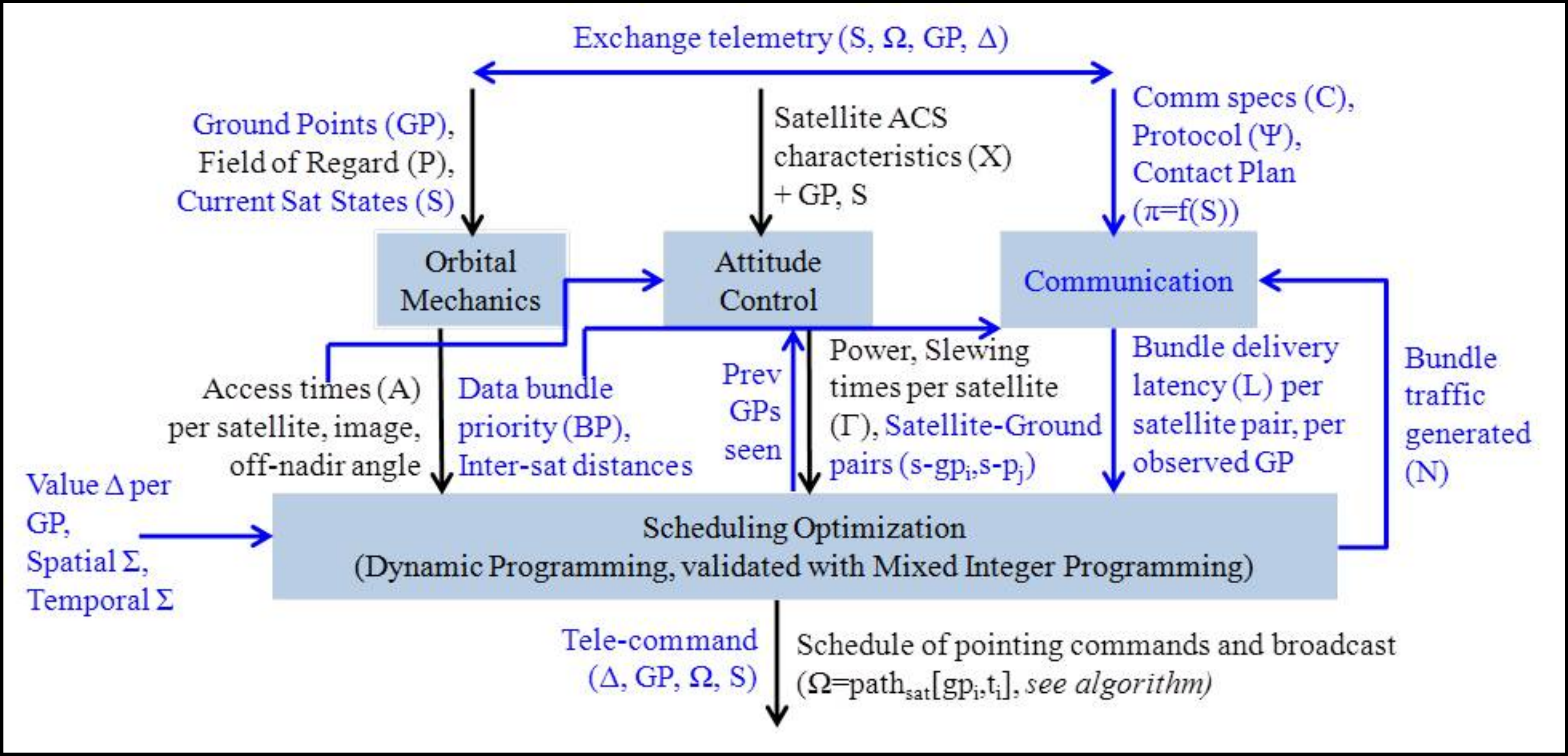
- DP Also expected to run on the satellites ~ can make observation decisions in a distributed fashion and react to the changing ground conditions quickly
- Will need inter-sat communication, and onboard processing
- Ground-based centralized w/ data downlinked & schedules uplinked vs. Onboard decentralized w/ data communicated & implicit consensus of schedules
- Factors: Onboard capacity, GS network, need for schedule consensus inv. prop to time transiency of phenomena.



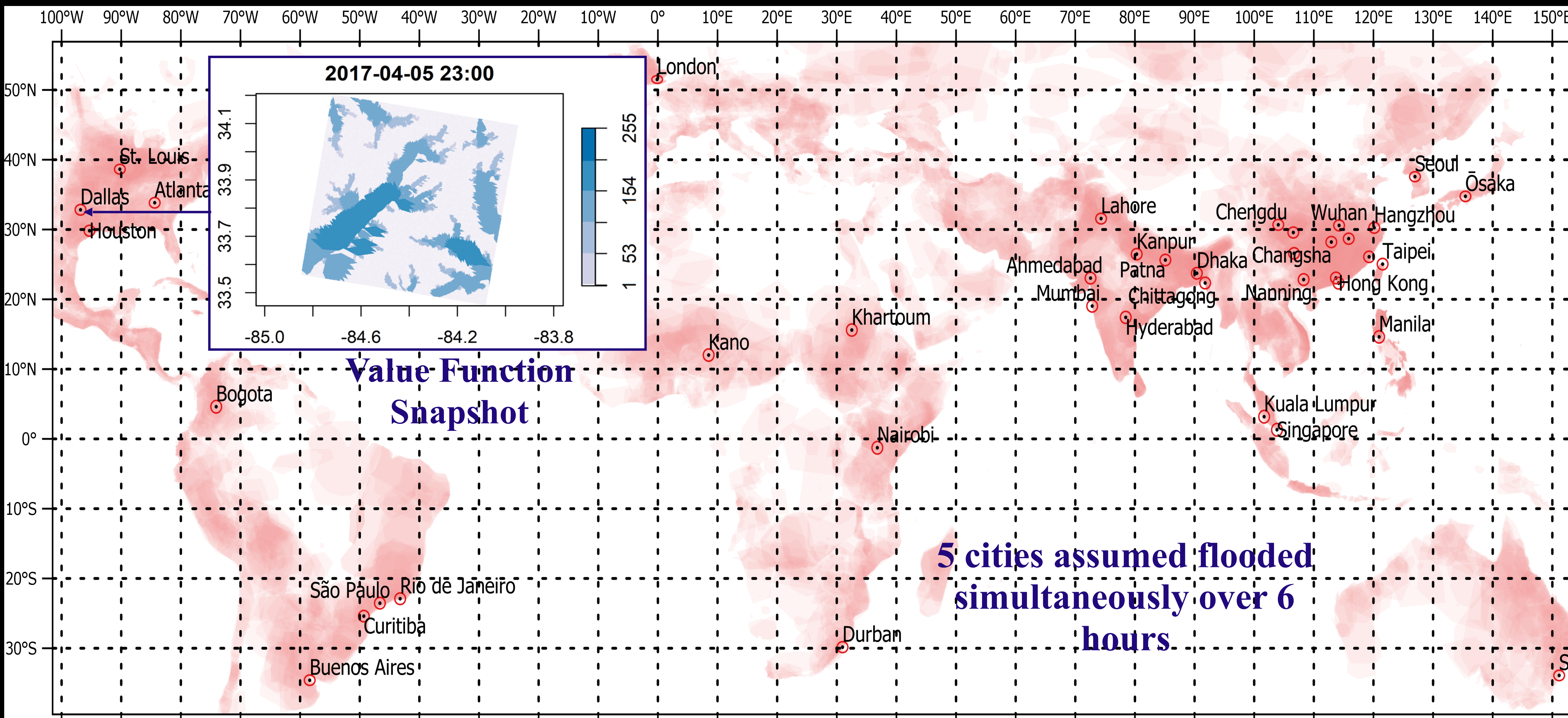
S. Nag, A. S. Li, V. Ravindra, M. Sanchez Net, K.M. Cheung, R. Lammers, B. Bledsoe, "Autonomous Scheduling of Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Imaging", International Conference on Automated Planning and Scheduling SPARK Workshop, Berkeley CA, July 2019

Onboard/Ground Scheduler

Information Flow between Scheduler Modules:
(white text/flows for ground alone, blue text/flows for onboard reqs)



Use Case: Episodic Precipitation and Transient Floods



Data: Dartmouth Flood Observatory (Brakenridge 2012)

Scheduling, Value Modeling, Replanning

Execution of Schedule:

```
Inputs – sat, path_sat[gp_i,t_i]
Output – observations_sat[gp_i,t_i]
For tNow in mission_simulation do
    If tNow in planTimes_for_planHorizon then//Compute
        For c in Constellation-{sat} do
            modelParams(t_i≤tSrc_c), path_c[gp_i,t_i≤tSrc_c] ←
                DTN_inbox(c,tSrc_c,sat,tNow)
        Procedure Scheduling Algorithm in Table 1
            return path_sat[gp_i,t_i∈planHorizon]
        path_sat[gp_i,t_i≥tPlanNow] ← path_sat[gp_i,t_i≥tPlanNow] +
                                      path_sat[gp_i,t_i∈planHorizon]
    Procedure execute path_sat[gp_i,t_i=tNow] //Execute
        return observations_sat[gp_i,tNow]
    modelParams(t_i≤tNow) ← observations_sat[gp_i, t_i≤tNow]
    For c in Constellation-{sat} do //Communicate
        DTN_outbox(sat,tNow, c,tNow+TTL_c) ←
                    modelParams(t_i≤ tNow, path_sat[gp_i,t_i≤tNow]
```

Scheduling Algorithm:

```
Inputs – sat, planHorizon, initFlood([gp_x,t_y])
Output – path_sat[gp_i,t_i]
For tPlanNow in planHorizon do
    For gpNow in GroundPntsInFOR(sat, tPlanNow) do
        GroundPntsInBND=[tPlanNow-max(slewTime):
                     tPlanNow-min(slewTime),1:numGP]
        For s in satsWoverlappingFOR(sat,gpNow) do
            For [gpBef,tPlanBef] in GroundPntsInBND do
                potentPaths_s[gpNow,tPlanNow]=
                    path_s[gpBef_s,tPlanBef_s]+[gpNow,tPlanNow]
                Procedure Value Update Algorithm in Table 4
                    return val[s][gp_x,t_y≥tPlanNow]
            v_combi =
                    val[permute(s in satsWoverlappingFOR)]
            For vn in reverse_sort(v_combi)
                slewTime=computeManueverTimes(s_combi,
                    [gpBef_s_combi,tPlanBef_s_combi],
                    [gpNow,tPlanNow])
                If slewTime≤[tPlanNow-tPlanBef_s_combi]  then
                    path_s[gpNow,tPlanNow]←
                    path_s[gpBef_s,tPlanBef_s]+[gpNow,tPlanNow]
                    break // forLoop for vn
```

Value model performance:

$$updateValError = \sum_{x=1}^{numGP} \sum_{y=1}^{tSteps\_in\_OSSE} |trueFlood([gp_x, t_y]) - floodMag_{est}([gp_x, t_y])| \quad \text{Equation 7}$$

S. Nag, A. S. Li, V. Ravindra, M. Sanchez Net, R. Lammers, "Agile and Intelligent Spacecraft Constellations with Disruption Tolerant Networking for Monitoring Urban Floods", submitted to International Joint Conference on Artificial Intelligence, Yokohama Japan, July 2020

Scheduling, Value Modeling, Replanning

Updated Value Computation:

```
Inputs – sat, tPlanNow, floodMag_init([gp_x,t_y]),
        potentPath_sat[gp_i,t_i], path_c[gp_i,t_i≤tSrc_c], modelParams
(t_i≤tSrc_c),observations_c([gp_obs,t_obs≤tSrc_c])∀c∈Constellation
Output – val[sat][gp_x,t_y≥tPlanNow], precip_obs([gp_obs,t_obs])
For c in Constellation do
    truePrecip([gp_i,t_i]) ← observations_c([gp_obs,t_obs≤tSrc_c]),
                             modelParams(t_i≤tSrc_c)  //latest data
    If c == sat then
        precip_obs([gp_obs,t_obs]) ←
                   truePrecip([gp_i,t_i] ϵ potentPath_sat[gp_i,t_i])
    Else: precip_obs([gp_obs,t_obs]) ←
                   truePrecip([gp_i,t_i] ϵ path_c[gp_i,t_i])
Procedure Apply Equation 4
    return floodMag_est([gp_x,t_y])  // Updated estimate
For t ϵ [tPlanNow,planHorizon(end)] do
    Procedure Apply Equation 2 or Equation 3
        return value_est([gp_x,t_y])  // Updated estimate
    Procedure Apply Equation 5; constraint Equation 6
        return value[sat][gp_x,t_y≥tPlanNow]
```

Scheduling Algorithm:

```
Inputs – sat, planHorizon, initFlood([gp_x,t_y])
Output – path_sat[gp_i,t_i]
For tPlanNow in planHorizon do
  For gpNow in GroundPntsInFOR(sat, tPlanNow) do
    GroundPntsInBND=[tPlanNow-max(slewTime):
                     tPlanNow-min(slewTime),1:numGP]
    For s in satsWoverlappingFOR(sat,gpNow) do
      For [gpBef,tPlanBef] in GroundPntsInBND do
        potentPaths_s[gpNow,tPlanNow]=
          paths_s[gpBef_s,tPlanBef_s]+[gpNow,tPlanNow]
          Procedure Value Update Algorithm in Table 4
          return val[s][gp_x,t_y≥tPlanNow]
      v_combi =
            val[permute(s in satsWoverlappingFOR)]
      For vn in reverse_sort(v_combi)
        slewTime=computeManueverTimes(s_combi,
              [gpBef_s_combi,tPlanBef_s_combi],
              [gpNow,tPlanNow])
        If slewTime≤[tPlanNow-tPlanBef_s_combi]  then
          paths_s[gpNow,tPlanNow]←
          paths_s[gpBef_s,tPlanBef_s]+[gpNow,tPlanNow]
          break // forLoop for vn
```

Targeting previous GPs:

$$\mathrm{floodMag}_{est}([gp_x \in \delta_{gp_{obs}}, t_y > t_{obs}]) = \mathrm{floodMag}_{init}([gp_x \in \delta_{gp_{obs}}, t_y > t_{obs}]) + 1.85 * \left[\frac{\sum_{t=planHorizon(start)}^{t=t_{obs}} \mathrm{precip}_{obs}([gp_{obs}, t])}{\sum_{t=planHorizon(start)}^{t=t_{obs}} \mathrm{precip}_{est}([gp_{obs}, t])} - 1\right] * \mathrm{floodMag}_{init}([gp_x, t_y > t_{obs}])$$

$$\text{for } \frac{\sum_{t=planHorizon(start)}^{t=t_{obs}} \mathrm{precip}_{obs}([gp_{obs}, t])}{\sum_{t=planHorizon(start)}^{t=t_{obs}} \mathrm{precip}_{est}([gp_{obs}, t])} \geq 0.5$$

$$\mathrm{floodMag}_{est}([gp_x \in \delta_{gp_{obs}}, t_y > t_{obs}]) = 0.05 * \mathrm{floodMag}_{init}([gp_x \in \delta_{gp_{obs}}, t_y > t_{obs}]), \text{otherwise}$$

Equation 4

Exploring new GPs:

$$\mathrm{value}_{new}([gp_x, t_y > t_{obs}]) = \frac{\mathrm{value}_{estimate}([gp_x \in \delta_{gp_{obs}}, y > t_{obs}])}{\sum_{t=planHorizon(start)}^{t=t_y} \mathrm{path}_{sat}([gp_x, t])}$$

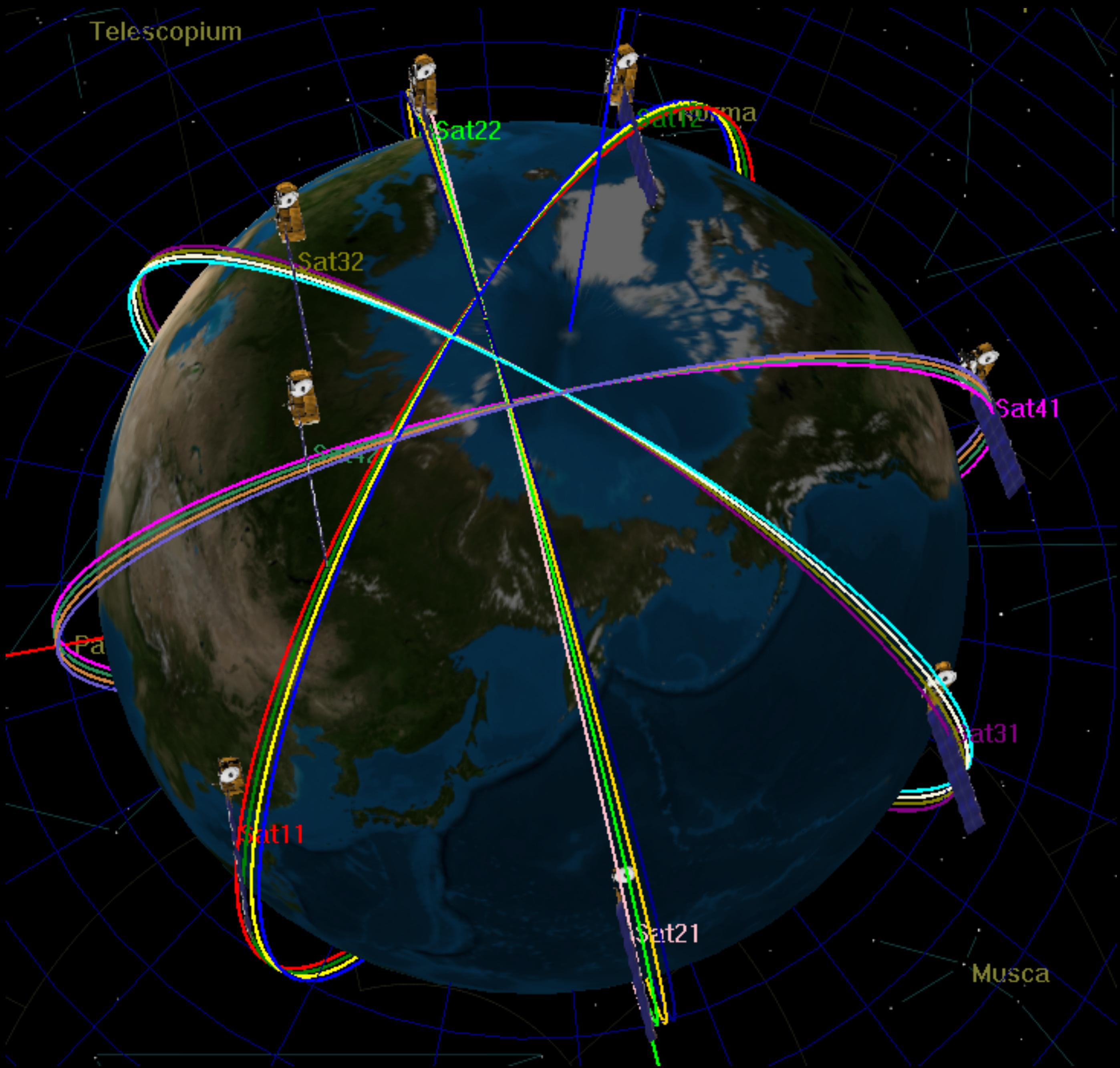
Equation 5

$$\sum_{t=t_y}^{t=t_y+15m} \mathrm{value}_{new}([gp_x, t]) = 0$$

Equation 6

Simulated 12-sat Constellation

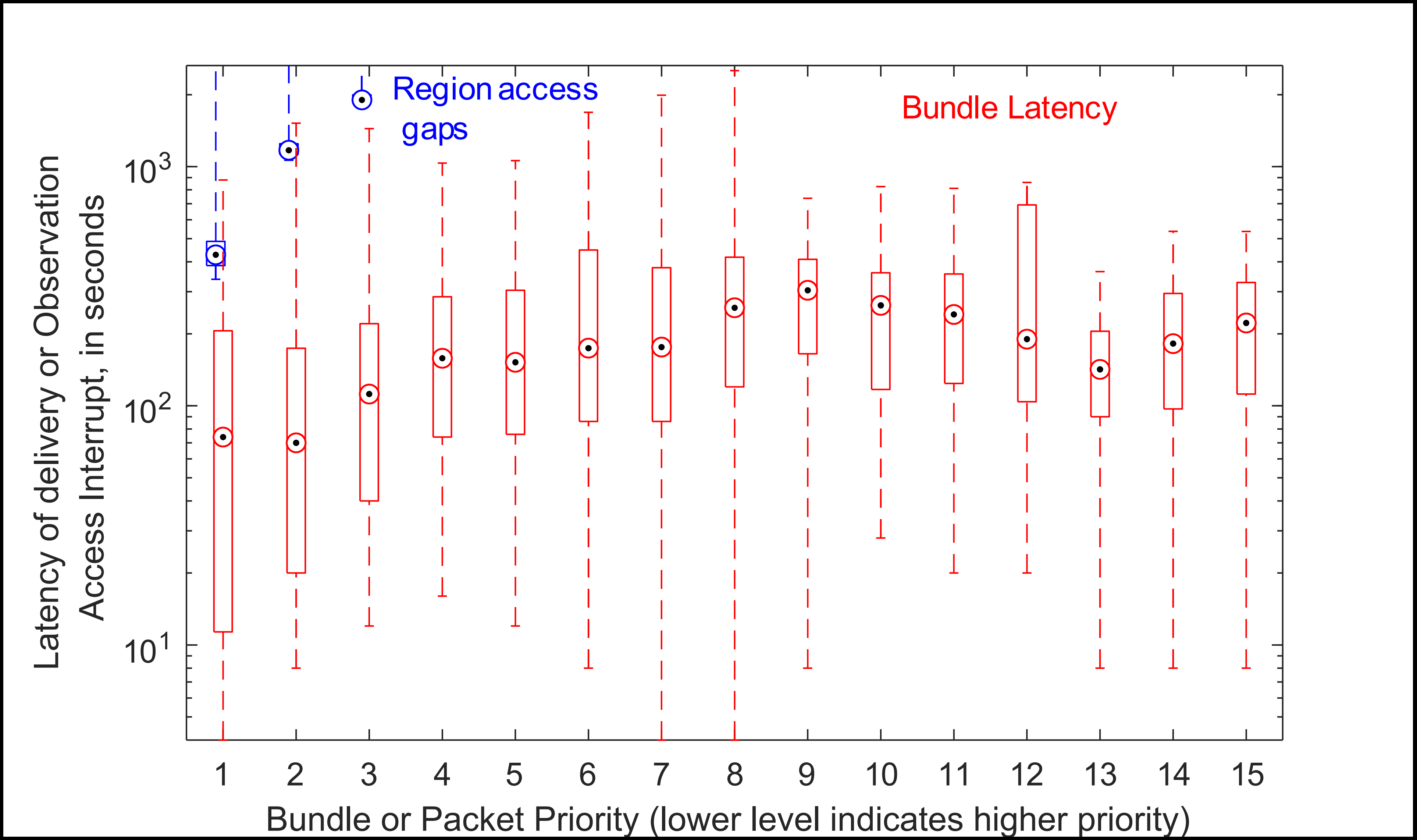
- 24 (20 kg cubic) satellites in a 3-plane Walker constellation observing floods in 5 global regions of interest (ROI)
- 710 km, sun sync orbits (Landsat, A-Train)
- Median 5.2 mins & max 6.2 mins of access time (within FOR) to ROIs
- 3 planes: Median gap ~ 56 mins & max gap ~4.5 hrs
- 8 sats per plane: At chosen altitude, this ensures consistent in-plane LOS, cross-plane LOS is restricted to polar regions only
- 5W RF power => 1kbps data rate. 2 kbits of payload data assumed per GP observed, but easily changeable



GMAT example of 4 orbital planes

Communication Latency vs. Imaging Gaps

Latency of data bundle delivery over all satellite pairs compared to the gaps between satellite Field of Regard access to any region:



DTN Performance:

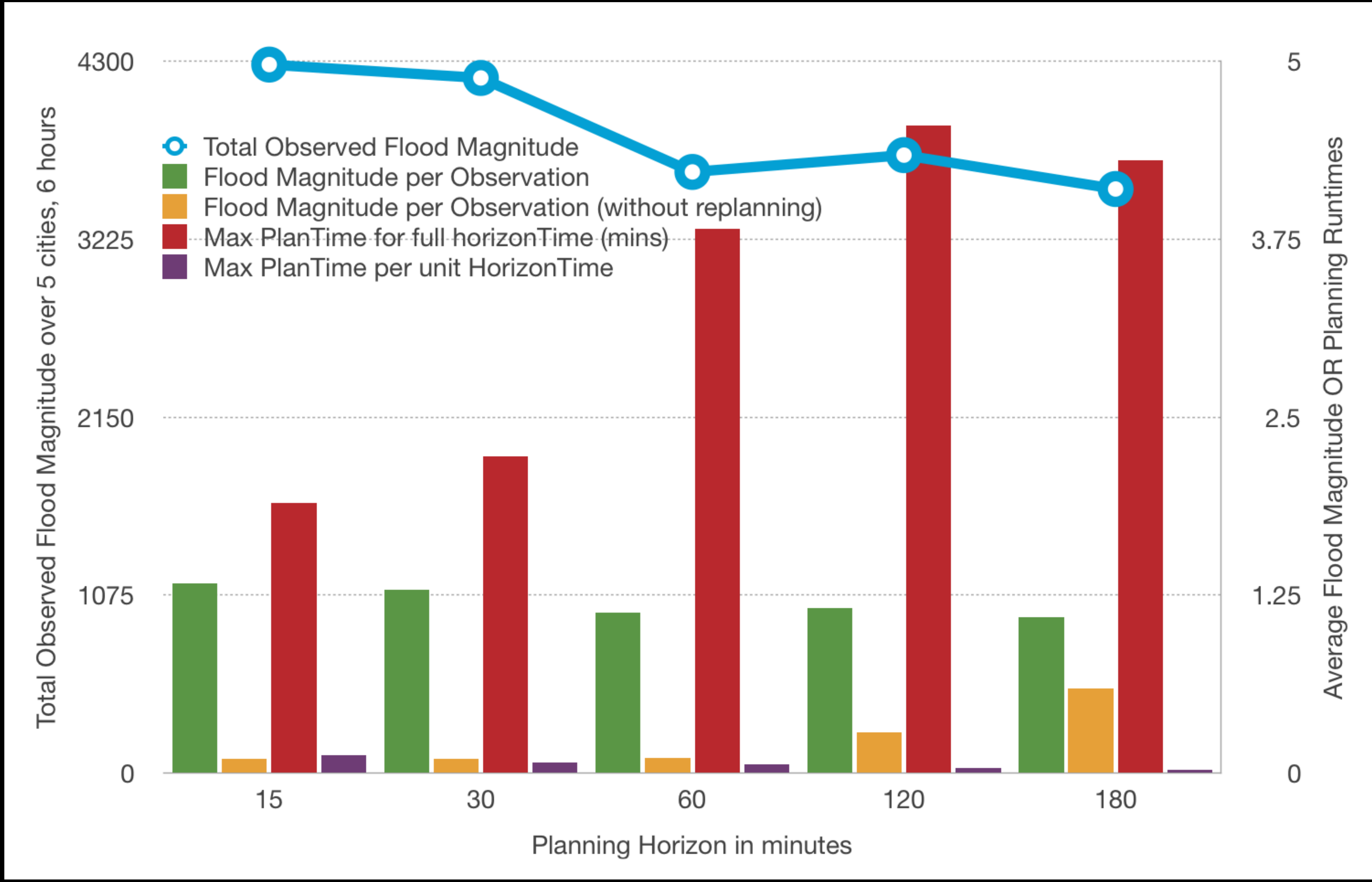
- 8341 bundles generated and sent over a 6 hour simulation
- No bundles dropped in multi-hop
- Dependence on traffic, packet size, power, topology analyzed

If longest latency < shortest gap, for pairs with the same priority => each satellite can be considered fully updated with information from all others, i.e. perfect consensus is possible, in spite of distributed decisions made on a disjoint graph.

Discussion of Results

Scheduler (plan=replan):

1. Longer horizons mean less replanning, thus fall in total (blue curve) and per observation (green bar) value
2. Longer horizons mean better optimization per horizon, thus more value (yellow bar)
3. Runtime per sat ~ 1-2% of the planning horizon (red bar)
4. Runtime per unit horizon gets worse with longer horizons (purple bar)



- DECENTRALIZED: Scheduler runs on onboard & uses collected information from other sats as they come through the DTN. Thus predicts GP value at an average of LESS different from actual value, due to bundles about some GPs arriving later than the satellite has observed them
- CENTRALIZED: Scheduler runs on the ground and uses collected information from other sats as they downlink. Ground stations are placed at both poles to emulate the best possible scenario of collection-based re-computation twice an orbit. But this predicts GP value at an average of MORE different from actual value, because value functions are based on data collected <=1 orbit earlier, i.e.up/downlink latency between any sat pair
- Eitherway, a constellation with no agility sees ~8% GPs of either de/centralized scheduling

Discussion of Results

	Planning Horizon (mins)	Total Observed Flood Magnitude	Flood Magnitude per Observation	Flood Magnitude per Observation (w/o replanning)	Max PlanTime for horizonTime (mins)	Max PlanTime per unit HorizonTime
Decen-tralized Plan Onboard before entering Region	**5 (3m replan)**	2661.7 (-1.6%)	0.825 (-0.7%)	0.1 (worst)	**1.794**	0.359 (+51.5%)
	10 (5m replan)	**2703.7 (+2.5%)**	**0.831 (+1.5%)**	0.1 (worst)	2.374	0.237 (+50%)
	15 (10m replan)	2638 (+2.24%)	0.819 (-0.4%)	0.1 (worst)	2.374	0.158 (+327%)
Central-ized Plan on Ground	**2 GS contact per orbit**	2580.3 (+2.1%)	0.799 (+1.5%)	0.156 (+56%)	3.705	0.037 (+48%)
	1 GS contact per orbit	2528.5 (worst)	0.787 (worst)	**0.591** (+278.8%)	5.029	**0.025** (best)

Summary and Future Work

- Current performance improves with more replanning but is limited by short planning horizons. Exploring an MIP approach instead of DP?
- Improvements needed to the value update function for the chosen application. Will extend to other soil moisture applications
- Scheduler will be extended to include more knobs - multiple, heterogeneous instruments, power duty cycle, data limits and latency requirements, etc. ; include DTN and comm-related decision making in the scheduler loop

Questions?

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