XGEO PNT Automated Scheduling (XPAS)

Ground System Architectures Workshop (GSAW)

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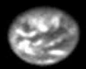
The future of space activity will see a proliferation of missions in XGEO space: the region of space extending from the GEO orbital altitude to the Lagrange points. A cost-effective PNT architecture is needed to enable such missions.



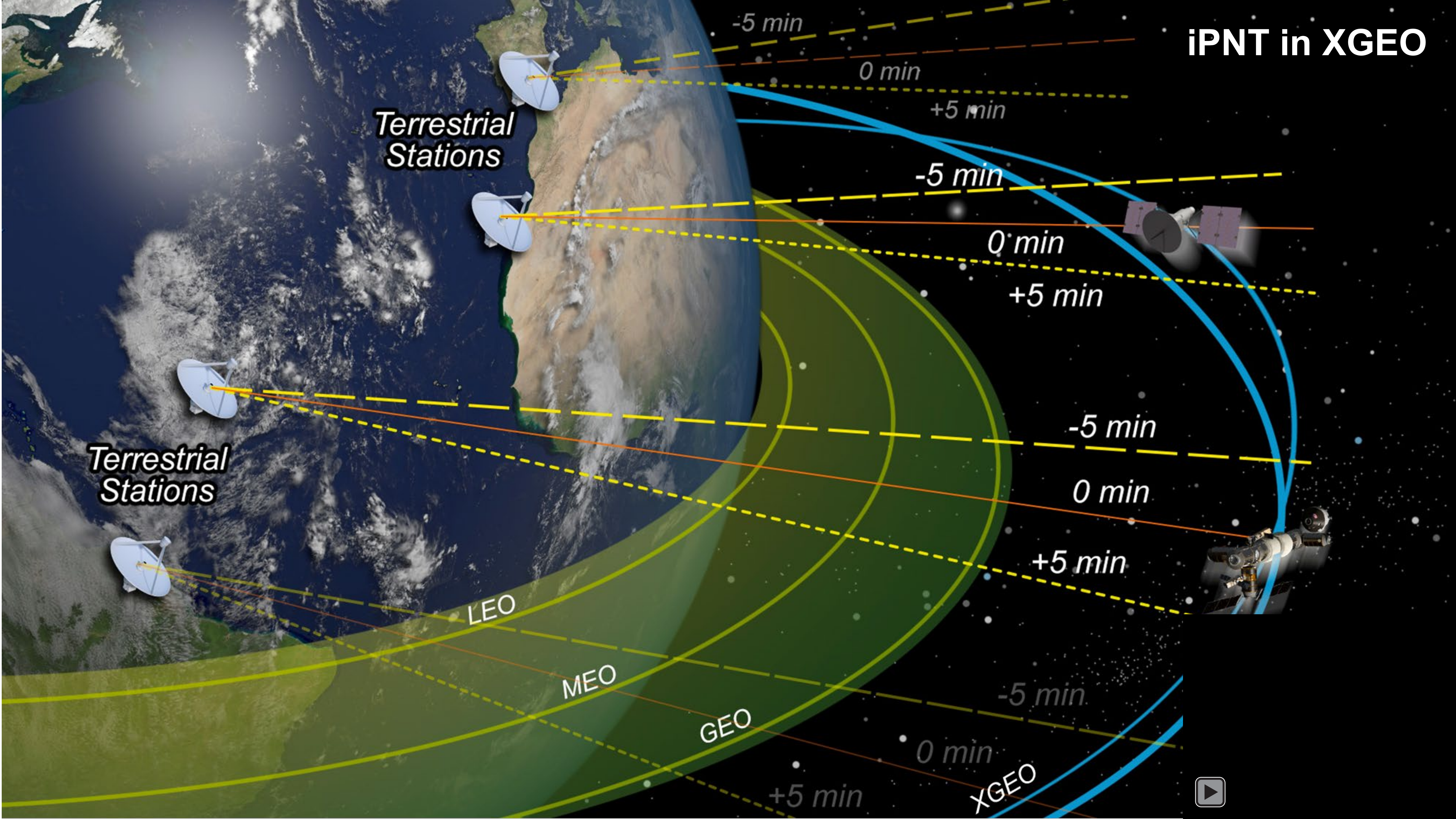
One proposed concept is iPNT, in which ground stations send PNT data to client spacecraft either as scheduled or on demand. The initial concept is to employ ~20 existing ground stations, each equipped with spot beam transmitters, which can be repositioned quickly, to close the RF link with distant spacecraft.

The architecture must scale to support hundreds of simultaneous XGEO spacecraft having different orbits, missions, security requirements, priorities, accuracy requirements, and timeliness, among other factors. The management of this process requires a fully automatic infrastructure without the costs and inefficiencies of manual intervention and decision-making. What is needed is a “hands-off” solution that can self-sustain for years, possibly decades.

Automated scheduling for an iPNT network would unlock opportunities in XGEO space that are not yet achievable. This problem has not yet been solved, so m investment is needed for an affordable, ubiquitous XGEO PNT solution*. We int show that automated scheduling is achievable using a technical approach developed by The Aerospace Corporation.*

Image C

iPNT in XGEO



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XGEO

XGEO PNT Problem & Solution Statements

Problem Statement: Need PNT in XGEO

- Users in XGEO orbits (i.e., operating beyond GEO) need position-navigation-timing (PNT) solutions that are accurate and timely
- Existing PNT systems are not optimized for XGEO
  - *Approaches like iPNT can solve this problem, but, in turn, they can create potential traffic overloads*
- Various users will present with various needs
  - *E.g.,. A military user may need a high-priority solution to perform a maneuver while a commercial user just needs an answer within the next 30 minutes*
- Sometimes, user needs will conflict
  - *In some cases, satisfying one user request will leave one or more other requests unsatisfied*
  - *More users = more conflict*

Solution Statement: iPNT for XGEO

- We propose an inverted PNT (iPNT) approach to optimize a PNT solution for XGEO
- For this, we propose to use existing ground stations to provide the PNT solutions based on scheduling user requests
  - *The iPNT system must accept the ground and space elements as they are*
  - *The iPNT system must not add costly requirements*
- To address potential traffic overload challenges, we propose an AI-enabled automated scheduler to minimize the degree to which satisfying one requests causes other requests to go unsatisfied

This presentation focuses on the automated scheduling portion of the iPNT solution

XGEO iPNT Scheduling Problem & Solution Statements

Problem Statement: Need Scheduling

- Manually-based systems require human operators
- As XGEO users proliferate, more operators will be needed to keep up with demand for PNT solutions
- Time to provide scheduling increases with proliferation of users as complexity rises and conflicts become more frequent
- Scale will rise to the point that hiring more operators becomes untenable
- Retrofitting a manual solution with automation after the fact is much more difficult than building in the needed AI/autonomy from inception
  - *E.g., it is often more challenging to get buy-in from humans using the system to trust it*

Solution Statement: AI-ML Automated Scheduling

- We propose an automated scheduling solution because it can accommodate increasing numbers of users without increasing human workload or response time
  - *No need to hire more and more operators*
- iPNT scheduling is amenable to AI-enabled automated scheduling
  - *The inputs, outputs, and concept of operations can be defined for a growing number of users and for changing conditions*
  - *Of the automated scheduling solutions we're aware of so far, AI-ML seems the most promising because it can adapt to these changes*
  - *Specification of performance and how to monitor and control as well as when, why, and how to retrain or replace the AI-ML would produce an AI-enabled solution that builds in trust*

How do we expect our iPNT system to work?

And what is the XPAS automated scheduler's role?

Before launch, each customer agrees to an Interface Control Document (ICD) with the system that specifies technical configuration, mission needs, and CONOPS

Upon launch, the new mission sends a "launch confirmation" to the system to allow an initial PNT fix

The system sends a PNT upload to the customer's spacecraft, and its control center confirms receipt, closing the loop between the system and the spacecraft

On a fixed schedule thereafter or upon request, the system uploads a PNT solution by aiming antennas at the calculated spacecraft position, and the spacecraft control center confirms receipt

The process continues for the life of the spacecraft mission, with requirements changing as the mission proceeds either in accordance with the ICD or changes to the ICD based on the evolving situation

XGEO PNT Automated Scheduling (XPAS) is responsible for efficiently managing this process without human intervention

Focus on Automated Scheduling for Solution Scalability & Longevity

This work on automated scheduling to support XGEO PNT is just beginning

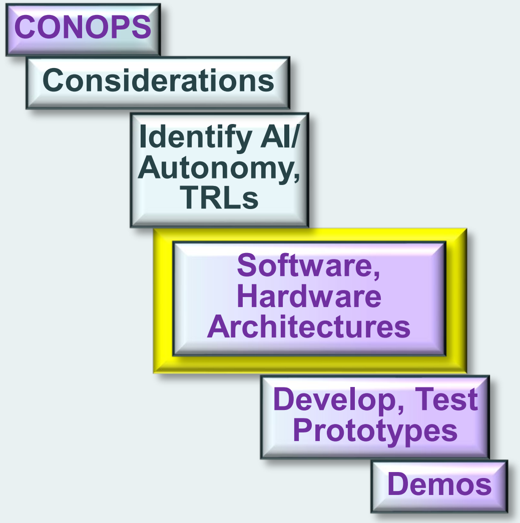
- The XGEO PNT problem has many parts
  - *These include orbital mechanics, user requirements (e.g., solution accuracies, response times for timeliness, update frequencies), safeguarding/firewalling sensitive user information, timely allocation of ground resources, etc.*
  - *Latencies and limited availability of ground resources require an infrastructure for managing solutions, especially when user needs conflict*
- As PNT needs in XGEO proliferate, manual scheduling will be overcome by needs and challenges
  - *Manual scheduling comes with high operation cost due to negotiation and human-in-loop, time required to schedule, system scalability*
  - *Automation can run 24/7, reduce time to produce scheduling solutions while requiring fewer human operators, and scale up without increasing costs; thus,* ***automated scheduling is key to this PNT infrastructure***
- Multi-variable optimization techniques will be required to coordinate across potentially competing variables and user needs
- We intend to identify an appropriate automated scheduling approach, cost function(s), quality of service metric(s), and a concept of operations for the levels of service we propose
  - *We will initially demonstrate single representative use cases and scale up to supporting proliferated constellations*
  - *Fundamental modeling and simulation is part of this effort, starting with selecting candidate algorithms and testing them for one user at a time and scaling up*

We intend to map out the software, process, test cases, and next steps needed for a complete XGEO PNT scheduling solution—not to solve the problem but to show that we can solve it

Working toward an AI-enabled Automated Scheduling Solution

Aerospace has a process for developing trustworthy AI-enabled solutions

Aerospace AI Solution Architecting Process



Software and hardware architectures require iterative co-design to build in tests, monitoring, and control for trust

Perform the model trade analyses

Model architecture requires optimization:

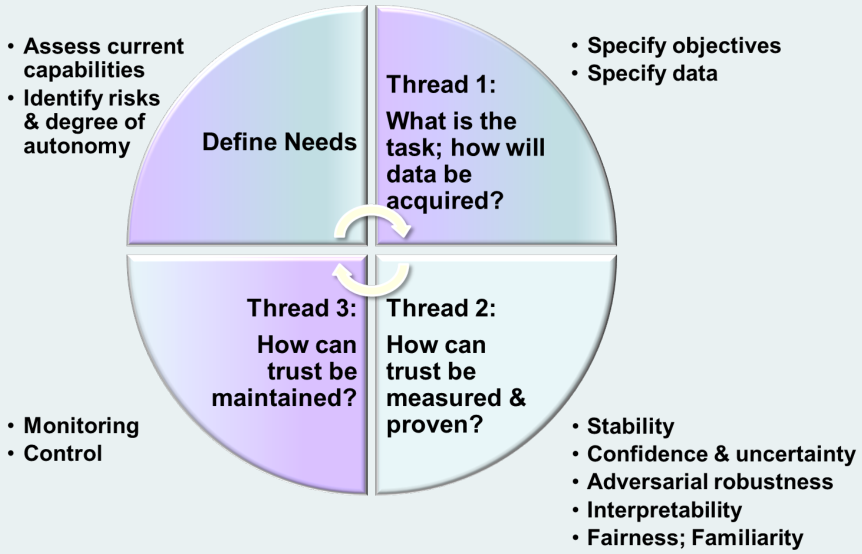
- **Model size, Data sources**
- **Languages, Libraries**
- **Accuracy**
  - More complex model
  - Harder to train
  - More data, compute resources
- **Simplicity**
  - Smaller model
  - Fewer parameters
  - Less data, compute resources
  - Might reduce overfitting
- **Transfer learning vs learning from scratch**

Select or design the model

Use AI Solution Architecture inputs, e.g., trades, to select/design a feasible, appropriately sized model:

- CONOPS
- Considerations
- AI/Autonomy needs
- Model size
- Data needs and availability
  - Data sources, quality, etc. (5Vs)
  - Design of and 5V requirements for simulated data
- Ceiling analysis
- Hardware constraints

Use the Trusted AI Framework to build trust in the model in from inception



Trusted AI is a nascent field requiring explicit definitions into meaningful, generalizable, measurable, and testable attributes. High consequence environments often entail high risk in mission criticality, algorithm complexity to meet mission criticality and complexity, and level of autonomy to meet issues like communications latency. data volume, etc.; technical, cost, and schedule risks must be quantified so they can be mitigated

Complexity of the CONOPS, considerations, & constraints drive the AI design. The following slides give a taste of this analysis to help show that the automated scheduling problem is tractable and amenable to AI-ML.

Considerations

Needs & Scenarios

Needs

- What is needed is a feasible scheduling solution set that avoids saturating XGEO ground stations and resolves request conflicts
- Automate the operation as much as possible (currently, scheduling is done manually)
  - *Automated operation would make our iPNT solution more scalable and affordable*

Scenarios

We will identify candidate automated scheduling algorithms, implement one (possibly more, if a “bake-off” is merited), and see how the algorithm(s) perform in the following scenarios

- *Ensure correct implementation and understand which conditions lead to the algorithm(s) bottle-necking*

1. Single user
   - Verify reliably finding an optimal solution to minimize use of resources to meet the user’s request
2. Two users
   - Demonstrate consistent ability to solve the over-constrained problem when scheduling to support User A meets a request from User B that conflicts the existing scheduling
3. Multiple users
   - Demonstrate that the scheduling solution scales up appropriately or identify when/why it breaks down

Considerations

Constraints & Objectives

Growth

- The system should be “elastic” to grow seamlessly to support hundreds of XGEO spacecraft

Minimize equipment needs

- The system should employ the minimum quantity of ground stations and the time needed from each

Minimize costs

- The system should avoid any “standing Army” (i.e., scaling up should not require increasing numbers of operators)

Mission capable

- The system must meet every “customer’s” needs for timeliness and precision

System efficiency

- The system must allocate resources in real time to avoid resource allocation conflicts

A Few Assumptions

Different users will have different needs; more users will have more needs

We assume a three-tiered service to accommodate a variety of users with a variety of needs

Gold tier

- Users requiring the most urgent solutions, the highest update frequencies, etc.
- Example: military users about to perform maneuvers; commercial customers who need spacecraft PNT to assess whether their launch succeeded

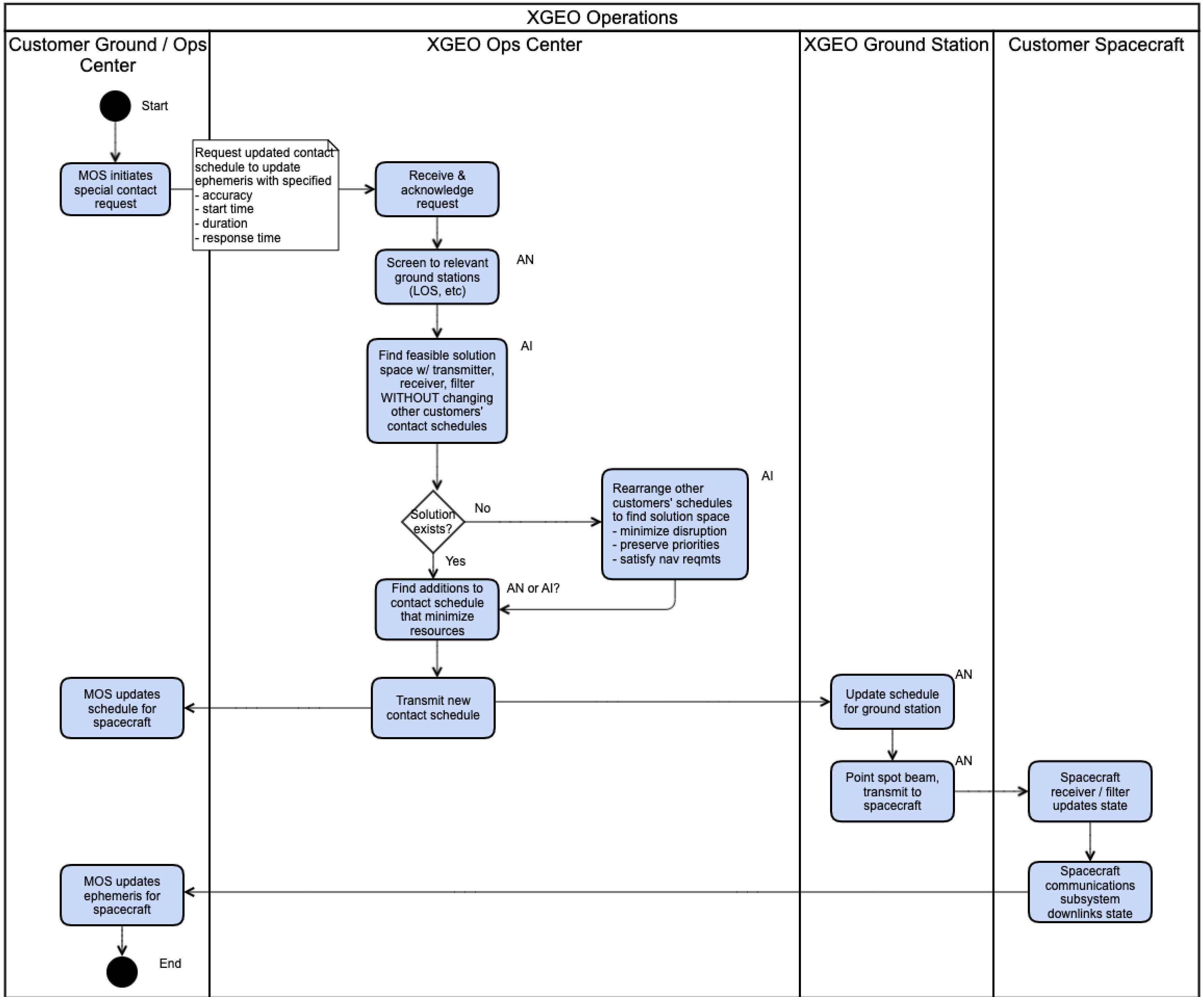
Silver tier

- Users that can tolerate some delay or that require somewhat less frequent updates
- Example: routine but regular military, science, or commercial users

Bronze tier

- Users that can tolerate more scheduling interruptions to accommodate top-priority users or that require even less frequent updates
- Example: routine commercial users

Customers will have to pay more for higher-tier service. Automated scheduling caps those costs because growing numbers of users will not require hiring of greater numbers of operators.



XGEO PNT Automated Scheduler (XPAS) Activity Diagram

- We assume gold, silver, and bronze tiers of PNT service users in XGEO
- As this activity diagram shows, XPAS must schedule PNT solutions by tier priority and satisfy new requests without disrupting servicing of existing requests

Legend

- *Automation (AN): machine takes action where there is no uncertainty*
- *Autonomy (AY): machine makes decisions and takes action to manage uncertainty*
- *Machine Learning (ML): in a learning system, performance improves with experience*
- *Artificial Intelligence (AI): machine does what a human normally would do*
- *Expert System (ES): AI using rules-based reasoning that captures human expert decision processes*

Activity Diagram Details

This use case covers AI/autonomy for the proposed XGEO PNT system

- In general, this is a resource allocation planning and scheduling problem
  - *Very similar to the Deep Space Network (DSN) scheduling problem*
- In this use case, PNT signals are sent ONLY from ground stations to user spacecraft beyond geosynchronous orbit
  - *At a later date, we may examine adding space-based signals.*
- ~20 ground stations form the basis of the XGEO iPNT system
  - *Each ground station has a narrow spot beam that can be quickly re-pointed to different user spacecraft*
  - *This gives ~20 dB advantage over an omni antenna to overcome the $1/R^2$ space loss*
  - *XGEO ground stations will have zero impact on the existing GPS ground stations and satellites*
- The automated scheduling notions presented here help the XGEO iPNT system provide updates to customer spacecraft (aka "users")
  - *The scope of AI/autonomy here is to plan and schedule resource allocation to service user PNT*
  - *This includes minimizing operations staff, optimizing link parameters and filter parameters, accommodating dynamic priority levels for customer service, and navigation requirements that vary over mission phases*
  - *For example, position and velocity accuracy requirements may increase before and after a maneuver*
- Planning and scheduling algorithms must also integrate with simulations that drive system design to create new ground stations and transmitters
  - *Thus, the AI/autonomy should integrate with Model Based System Engineering or digital engineering models*

Activity Diagram Details

Pre-conditions & assumptions for the XGEO iPNT system (i.e., the "system") and customers/users

- At start of use case, the system has an existing solution set for schedule and link parameters for all customer spacecraft ("users")
- The system "knows" user receiver and filter capabilities
- The system can simulate performance of user receiver and Kalman filter
- System can point spot beams
- System has a high-fidelity model of its own capacity envelope
  - *Number of users it can service*
  - *User-required accuracies and ranges*
  - *Includes a digital engineering analysis framework*
- System maintains a sophisticated priority scheme for customers that include timing and mission phase
  - *Some customers may have higher priority in certain mission phases and lower priority in other phases*
- Customers know the system capabilities
  - *Documented in **generic** User's Guide and **customer-specific** Interface Control Document (ICD)*
- ICD defines user communication protocol and more
  - *Maximum range etc. are documented in the ICD.*
  - *System can change contact schedule (with same or worse timing and accuracy for low priority customers) per terms in the ICD with automatic notification to affected users but without negotiation with them*
  - *Customers consent to terms defined in ICD*
- Users maintain Kalman filters onboard
- Customer ephemeris is accurate enough to enable system to point spot beams
- Customer ground/operations send ephemeris updates to system periodically
  - *System always has latest ephemeris for spacecraft*
- Customer maintains own operations team and navigation capabilities

Activity Diagram Details

Outcomes/post-conditions, exceptions/caveats, and AI, ML, and autonomy requirements

Outcomes and post-conditions

- Customer spacecraft receives enough contacts to enable the customer to generate updated ephemeris with required accuracy

Exceptions and caveats

- Interference and threats
- A feasible solution space cannot be found even after rearranging other customers' contact schedules

AI, ML, and autonomy requirements

- The primary need is for automated planning and scheduling to find a feasible solution set that avoids saturating the ground stations with PNT requests.
  - *There are two versions of an AI-enabled solution: one where the algorithm is constrained to not violate other customers' contact schedules and another where the algorithm can change others' contact schedules*
- AI may also play a role in optimizing contact schedules to minimize resource utilization
  - *In this case, resource utilization can mean contact duration, but the objective function may contain additional terms*
  - *For example, the objective function may include operational cost (staff, power transmission, etc.)*
- Other parts of the iPNT system may also require automation

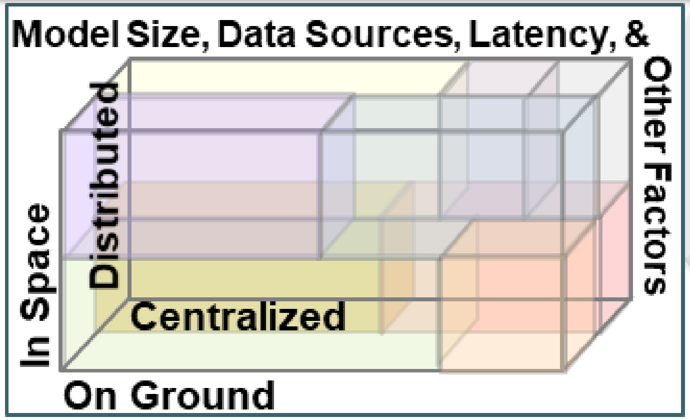
AI-ML/autonomy trade space: what does a solution landscape look like?

Factors like those illustrated below drive whether, which, and where for using AI/autonomy

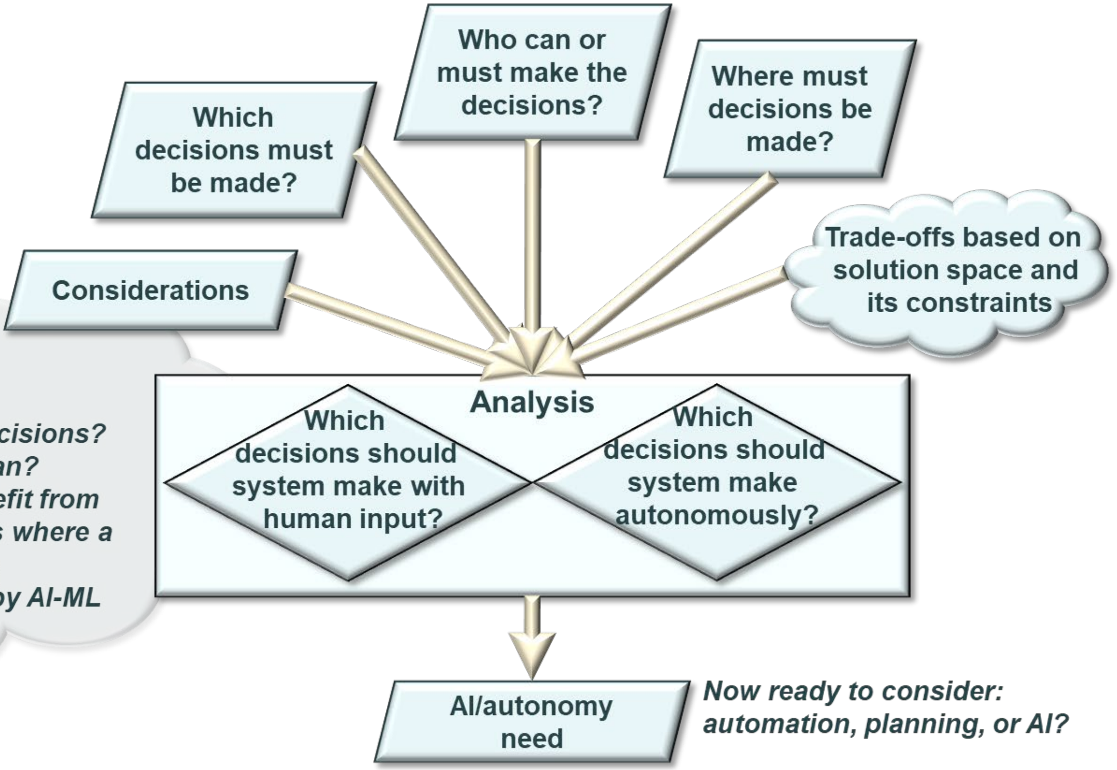
- Are real time instructions or responses required?
- How hostile or benign is the operating environment?
- Are there more nodes than human operators can control?
- Is there data/model/environment uncertainty? If so, where and how much?
- 5Vs of Data: Volume, Velocity, Variety, Veracity Value?
  - Is the data imagery? Telemetry? Other signals?
  - What size data? How frequent? Streams or batches?
  - What fidelity is required or expected?
- Does distance latency preclude real time comms?
- How well can the system, control, and environment be modeled?
- How much can be accomplished using non-AI/autonomy?
- How do human operators make decisions with similar systems today?
- What are the current policies, and how do they intersect with this mission?
- Is the operational team a constraint, or is it subject to design?
- Cost/schedule/risk? Supplier skill sets? Test capabilities?
- If AI/autonomy is required, where, which, and how much?

What we know:

- Autonomy is required to make our XPAS scheduling solution sustainable as the population of users scales up
  - *We expect to have to interleave among priorities*
- Real-time PNT may not be needed or feasible
- Processing will be centralized on the ground



- *Define decisions*
- *Identify trade-offs*
  - *Autonomous-only decisions?*
  - *Augment for/by human?*
- *Some missions might benefit from a spectrum with gray areas where a human makes the ultimate decisions but augmented by AI-ML*



Candidate algorithms: which are best for automated scheduling?

We are researching which algorithms to implement (e.g., for a bake-off)

AI-ML

- ML
  - Supervised
    - Support Vector Machines
    - Bayesian networks
  - Unsupervised
    - Clustering (e.g., k-means, hierarchical, fuzzy c-means
    - Principal Component Analysis
    - Genetic algorithms
  - Reinforcement
    - Q-learning, W-learning
- AI
  - Neural Networks
    - Configurations include feed-forward, deep, recurrent, etc.
    - Applications include anomaly detection, identification/classification, computer vision, regression for solution optimization, etc.

Non-AI-ML (e.g., statistical, optimal control, etc.)

- Multi-objective optimization (e.g., Pareto, in which improving one factor degrades at least one other)
- Greedy algorithms
- Decision theory
- Mixed-integer linear programming
- Rulebases, including fuzzy

Each technique has benefits and drawbacks

- Approaches that learn and evolve over time are more resilient to changing conditions (e.g., onboard sensor degradation, environmental changes)
  - *However, they pose challenges for trust (e.g., interpretability, maintaining performance over time as conditions change, etc.)*

Two promising approaches we will explore:

- **Genetic algorithms are useful for parallelization and multi-objective optimization—solutions improve over time—and Aerospace is using them for scheduling**
- **JPL developed a deep reinforcement learning neural network for Deep Space Network scheduling**

Next Steps for XPAS

We need your engagement and your help

There is a need for reliable, cost-effective PNT infrastructure to accommodate proliferation in XGEO.

An iPNT solution minimizes cost, schedule, risk. To maximize elasticity, automated scheduling is needed.

We believe the automated scheduling problem is tractable and amenable to AI-ML, hence XPAS.

This work is only beginning, so next steps include, for example, laying out the trade space so that we can select candidate algorithms and perform modeling and simulation to see which to implement.

Part of this includes identifying performance metrics for the XPAS AI-enabled automated scheduler,

Identifying figures of merit for the PNT service, etc. For example, we need measures of effectiveness we can compare against a manual system as a function of system parameters.

For example, we can assume that each upload takes 5, 10, or 30 minutes with 1, 2, or 5 simultaneous uploads and 10, 50, or 100 active customers and compare how XPAS performs vs manual scheduling.

We hope that this presentation opens a dialog so that we can hear from you.

What have you tried? What were your lessons learned? What do you recommend?

THANKS!

Sponsorship

As an FFRDC, Aerospace is a trusted partner for handling sensitive information without entanglements that for-profit contractors could encounter

We can also help commercial and academic interests who might also operate in XGEO

Opening the playing field to commercial users should increase our overall agility for operating in XGEO

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