Agent Model of On-Orbit Servicing Based on Orbital Transfers

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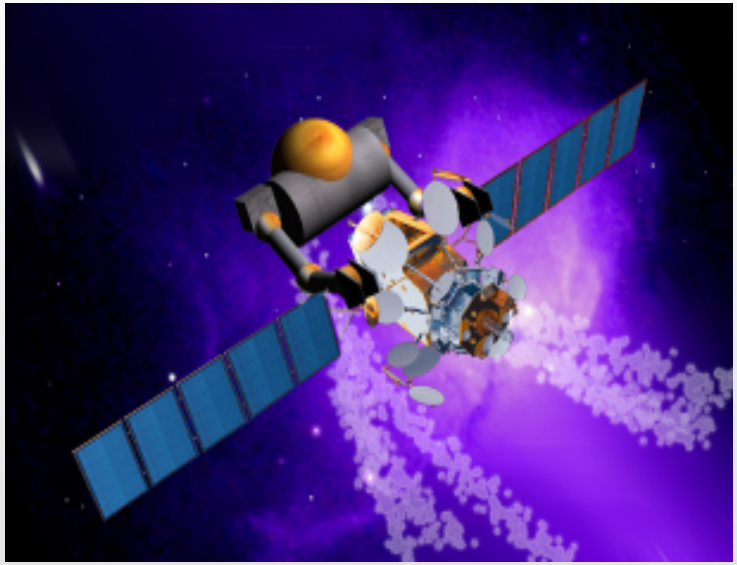
Agenda

- On-Orbit Servicing (OOS) Overview
- Model Scope
- Agent Model Development
  - Agents
  - Behaviors
  - Assumptions
- Agent Model Results
  - Sample Run
  - Monte Carlo Analysis
- Key Findings
- Future Work



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Overview: On-Orbit Servicing

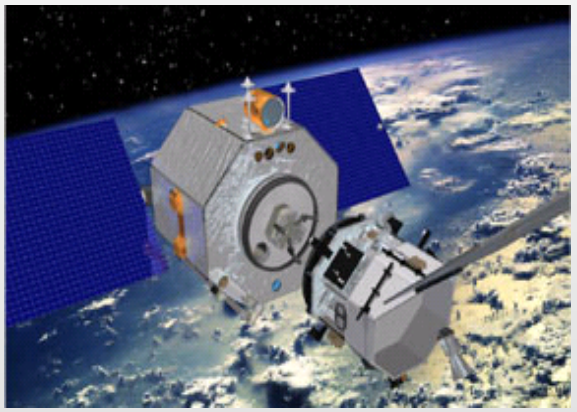
The process of improving a space-based capability through a combination of in-orbit activities which may include inspection; rendezvous and docking; and value-added modifications to a satellite's position, orientation, and operational status

Missions of OOS

- Inspection
- Relocation
- Rescue
- Refueling
- Upgrade
- Repair

complexity

Example: DARPA Orbital Express



On-orbit validation of autonomous docking, refueling, component swapping

Astro servicer, NextSat client

Servicing provides options to space missions, mitigates vulnerabilities to monolithic spacecraft, and enables a more robust space enterprise

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Research Opportunity

- Majority of robotic OOS studies are point designs on servicing provider architecture
- Some studies, mostly done at MIT, address customer valuation of servicing
  - Lamassoure (2001)
  - Saleh (2002)
  - Joppin (2004)
  - Sullivan (2005)
  - Long (2005)
- Few studies address satellite architecture of the customer
  - *e.g.,* DARPA's NextSat of Orbital Express
  - However, work that does exist on serviceable spacecraft focused on implementing design changes in future satellites

Research opportunity: investigate physical amenability of satellites currently in orbit to OOS

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Model Scope

- Investigate physical amenability of orbital slots to servicing
  - Primary outputs: mean ΔV expenditure, availability
  - Proximity operations treated as “black box”
- Context: five-year GEO servicing campaign
- Servicer CONOPS: multivariable optimization problem
  - ΔV expenditure
  - Transfer time

Focus on serviceability of target satellites, not provider architecture

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Agent Model Overview

An agent model simulates a population of independent agents to observe aggregate emergent behavior

- Target satellites
  - Initiate servicing missions by issuing servicing "tickets" in a binomial process
  - States
    - Full health
    - Operational with request for scheduled servicing
    - Not operational with request for emergency servicing
- Servicing vehicles
  - Cooperate to complete servicing missions (minimize ΔV expenditure)
  - States
    - Parked in GEO
    - In transit to target satellite via circular coplanar phasing
    - Servicing target satellite
    - Out of fuel

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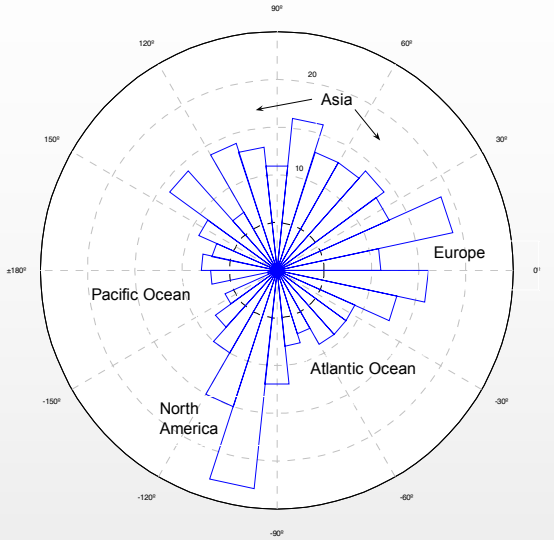
Target Satellites

- Initialized based upon UCS Database
- 335 GEO satellites (on March 11, 2006)
- Assumptions:
  - Zero degree inclination
  - Identical failure modes
- Failure probabilities:



Service	Average Annual Opportunities	Average Annual Opportunities in GEO	Predictable?
Refuel	20.0	8.9	yes
ORU Replacement	4.4	2.0	yes
General Repair	3.8	1.7	no
Relocation in GEO	13.0	13.0	yes and no
Deployment Assistance	0.3	0.1	no

Annual servicing opportunities based on empirical data (derived from comprehensive database of satellite failures)
Brook Sullivan, Ph.D. – University of Maryland Doctoral dissertation (2005)

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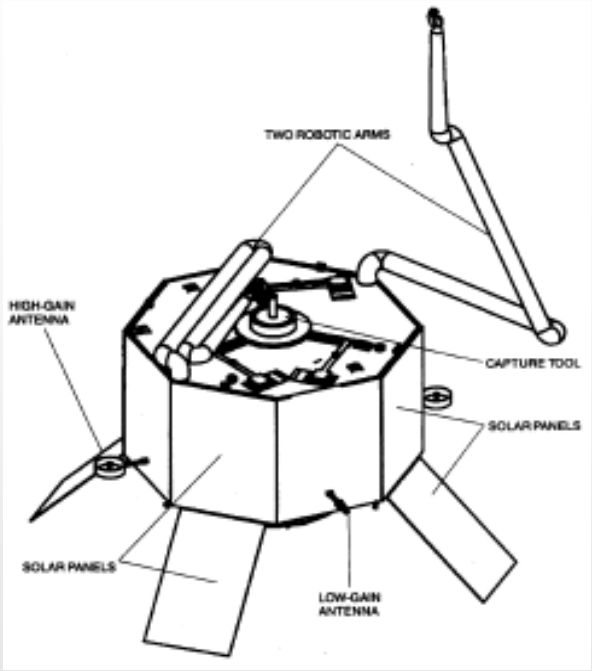
Servicing Vehicles

- Four space tugs parked in GEO
- Bipropellant: 300 Isp
- Dry mass: 1200 kg
- Concept-of-Operations
  - Initially evenly spaced
  - Remains parked near orbital slot serviced
- Two-cases
  - Treat normal and urgent tickets the same (5 phasing revolutions)
  - Vary response time as a function of urgency (5 or 1 revolutions)



ESA's Geosynchronous Servicing Vehicle (GSV)

$$\Delta V_{total} = g(I_{sp}) \ln \frac{M_p + M_f}{M_f} = 9.81(300) \ln\left(\frac{5076+1200}{1200}\right) \approx 4869 \text{ m/s}$$

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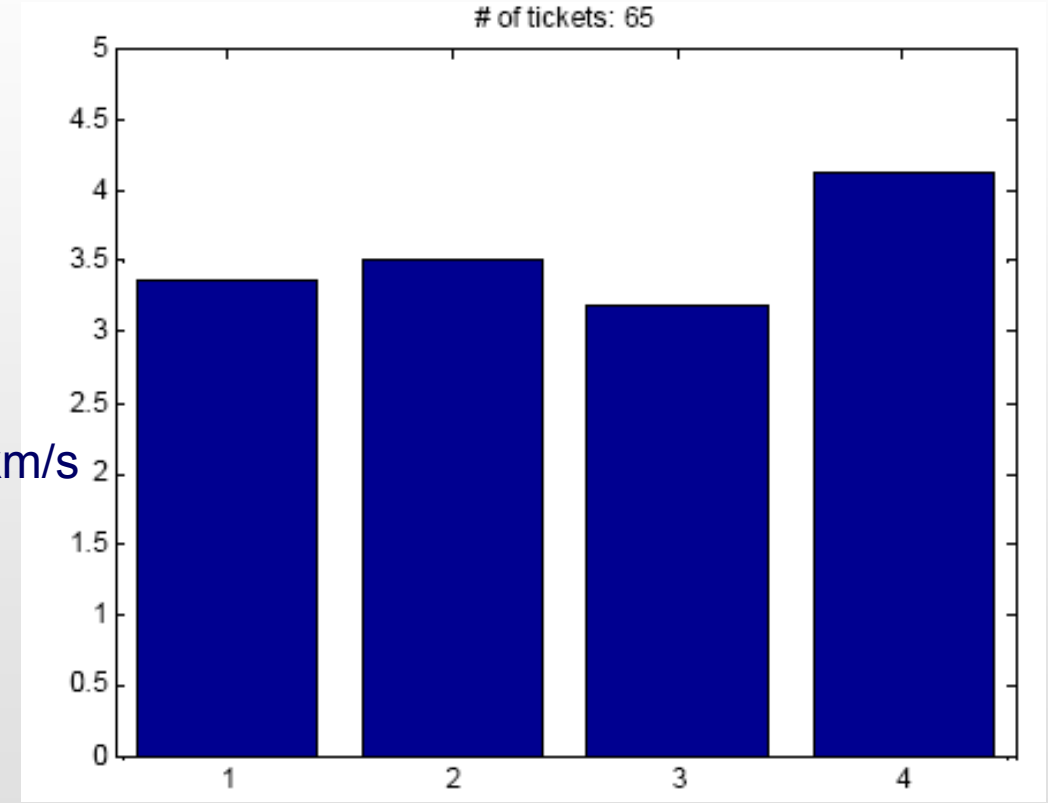
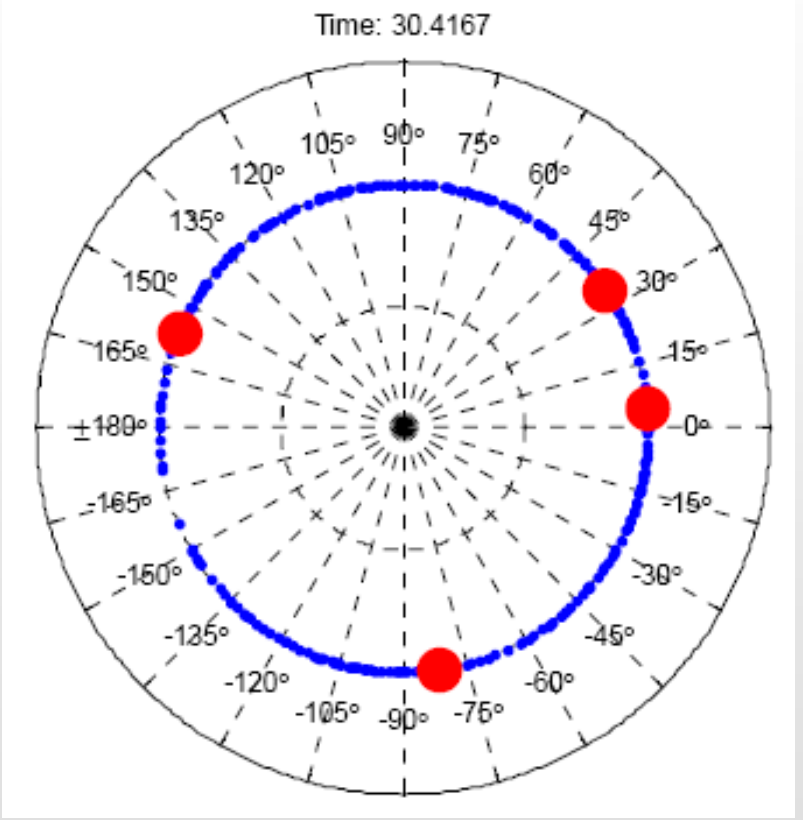
Tool Dashboard





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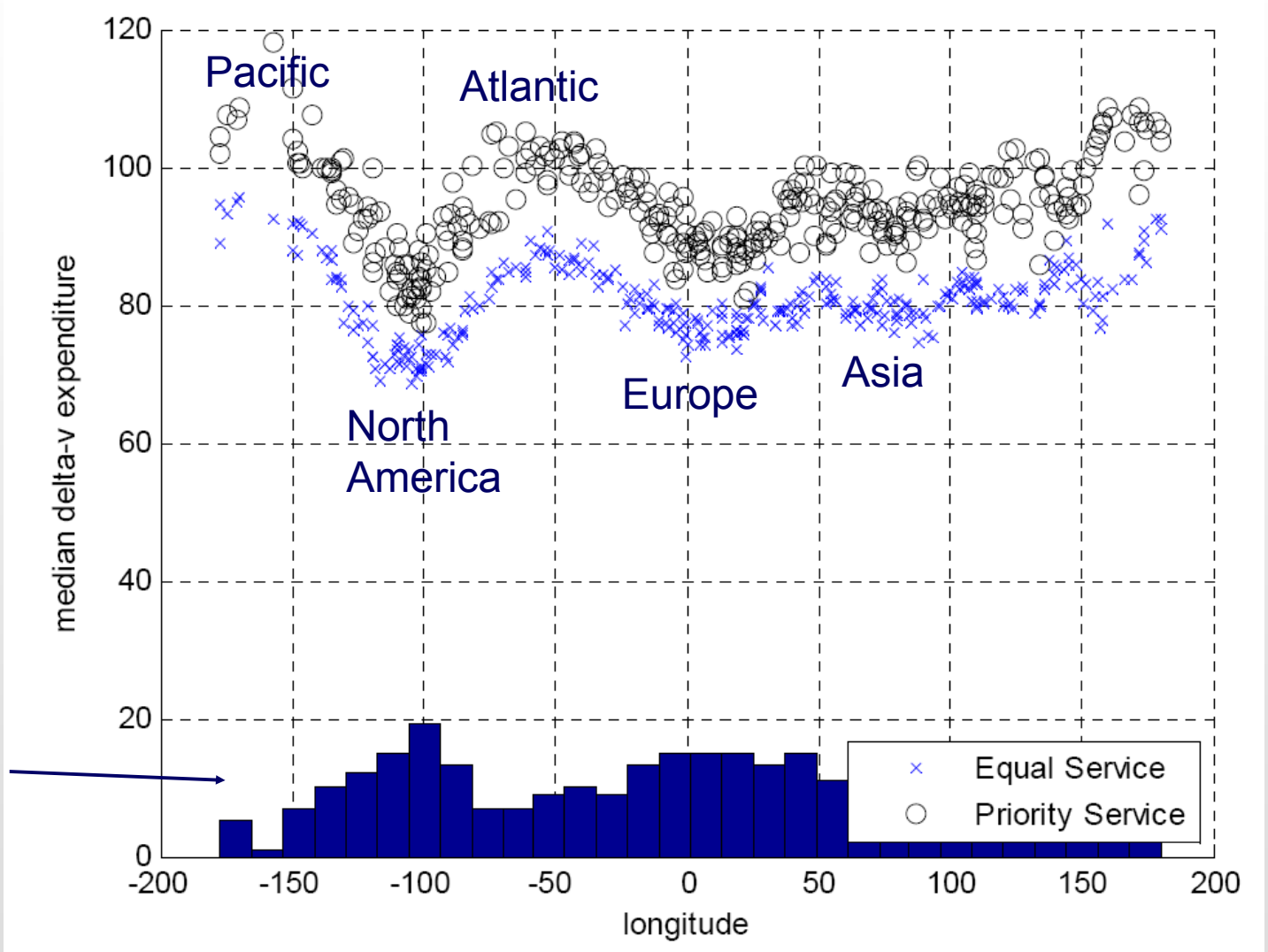
Monte Carlo Results: Median ΔV Expenditure for Orbital Slots



GEO satellite density (12° bins)

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Key Findings

- ***Demonstrated feasibility of using space tugs in GEO***
  - In terms of market, potential for 25 annual servicing opportunities
  - In terms of ΔV, physical amenability of servicing GEO is high
- ***Found high-level of servicing vehicle availability***
  - Very reliable spacecraft → probability of 2+ servicing vehicles in simultaneous operation less than 1%
  - Opportunity for emergent uses → infrastructure

OOS business models need to balance…

…the attraction of GEO due to the high concentration of high-value spacecraft and friendly orbital dynamics

…with the high-reliability of GEO satellites launched over the past two decades

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Future Work

- Parameter study on reliability of spacecraft
  - At what level of reliability does servicing architecture become over-taxed?
  - Explore the trade between highly reliable space systems and lower cost systems that utilize an OOS system to achieve similar reliability
- Improve model fidelity
  - Differentiate between types of servicing missions
  - Refine astrodynamics model
- Design provider CONOPS
- Model economics / pricing
  - What is decision logic for target satellites initiating servicing tickets?
  - and for servicing vehicles accepting servicing requests?

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Why Service Satellites?

- Reduce risk of mission failure
  - Rescue satellites stranded by upper stage failures (*e.g.,* Milstar 3)
  - Repair faulty spacecraft systems (*e.g.,* Hubble Optical Assembly)
  - Mitigate beginning-of-life failures (*e.g.,* solar array deployment)
  - Orbital debris removal (~100,000 objects currently, growing 175 metric tons/year)
- Reduce mission cost
  - Design for a shorter life with the option to service or abandon
  - Reduce need for on-orbit and launch-ready spares
  - Place high-value payload on EELVs and consumables on low-cost launch vehicles
- Increase mission performance
  - Option for lifetime extension
  - Option to upgrade to maximize revenue and prevent technological obsolescence
  - Improved fault detection and health monitoring
- Improve mission flexibility
  - Option to modify to meet different requirements
  - Capture emergent terrestrial market with constellation reconfiguration
  - Tactical maneuvering for military surveillance
  - Enable extremely low altitude orbits

Servicing provides options to space missions, mitigates vulnerabilities to monolithic spacecraft, and enables a more robust space enterprise

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Circular Coplanar Rendezvous

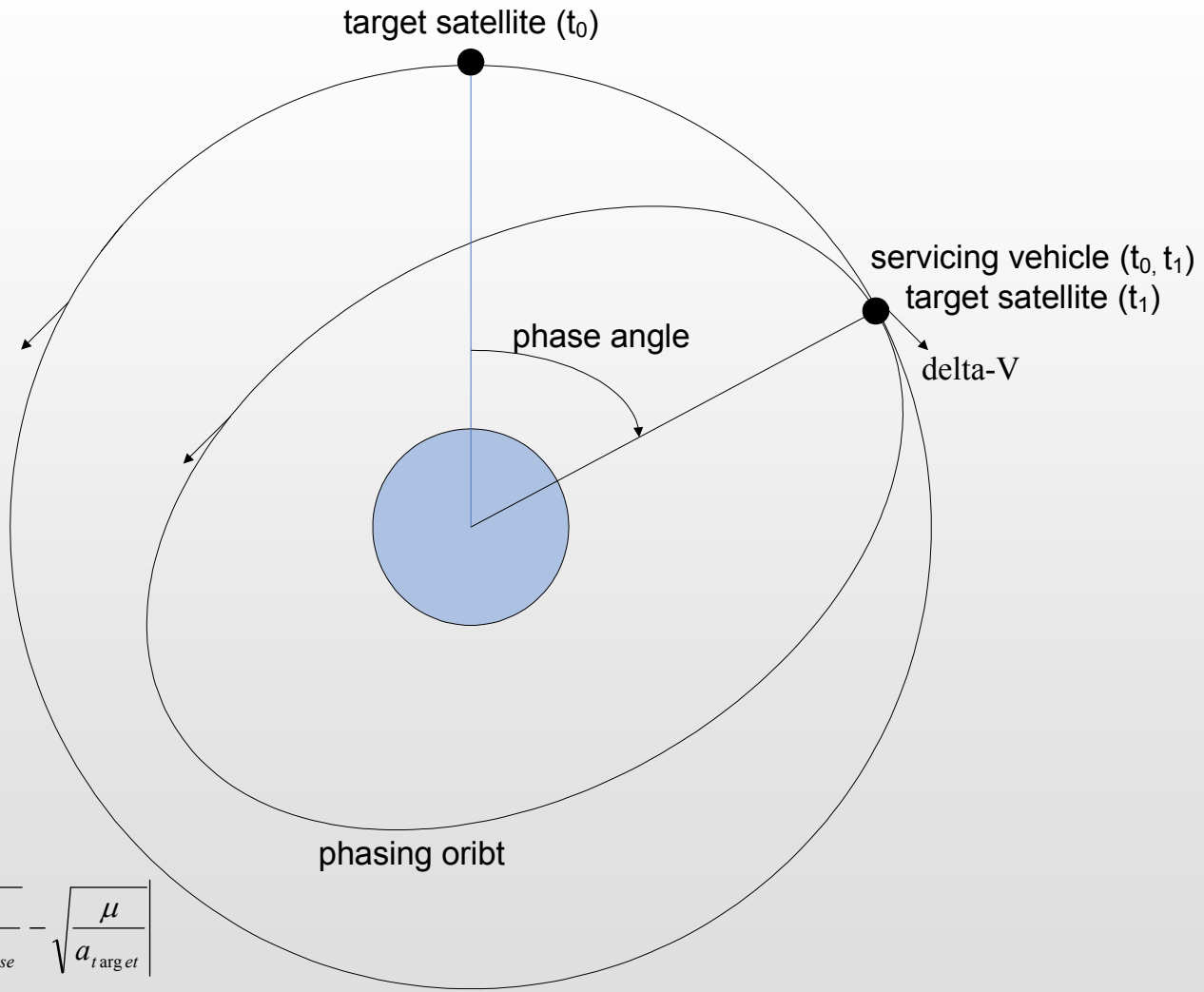
Key equations

$$\omega_{target} = \sqrt{\frac{\mu}{a_{target}^3}}$$

$$T_{phase} = \frac{k_{target}(2\pi) + \vartheta}{\omega_{target}}$$

$$a_{phase} = \left(\mu \left(\frac{T_{phase}}{2\pi k_{servicer}} \right)^2 \right)^{1/3}$$

$$\Delta V_{phase} = 2\left| v_{phase} - v_{servicer} \right| = 2\left| \sqrt{\frac{2\mu}{a_{target}} - \frac{\mu}{a_{phase}}} - \sqrt{\frac{\mu}{a_{target}}} \right|$$



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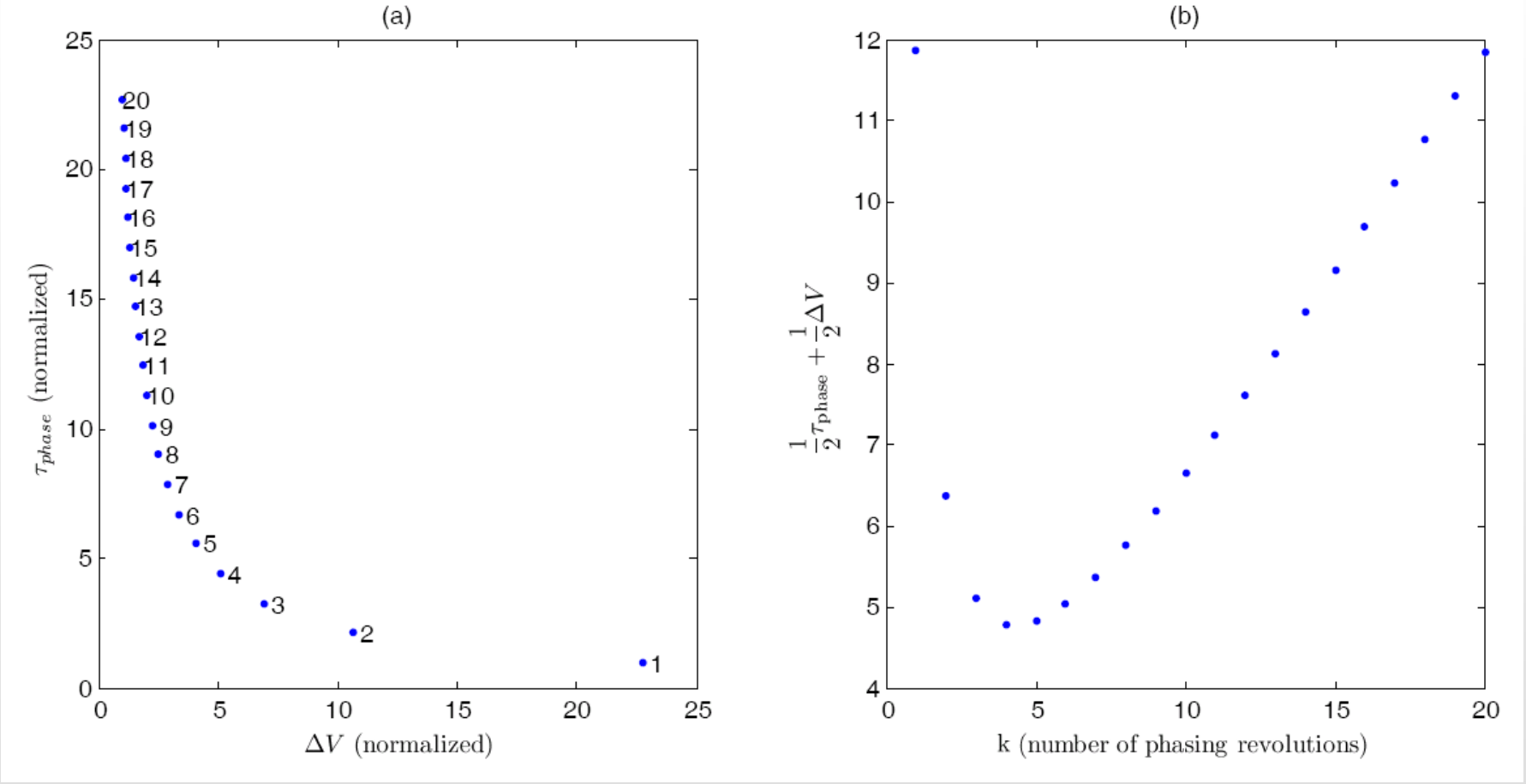
Multi-Objective Optimization



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