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Orekit at the U.S. Naval Research Laboratory

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Outline

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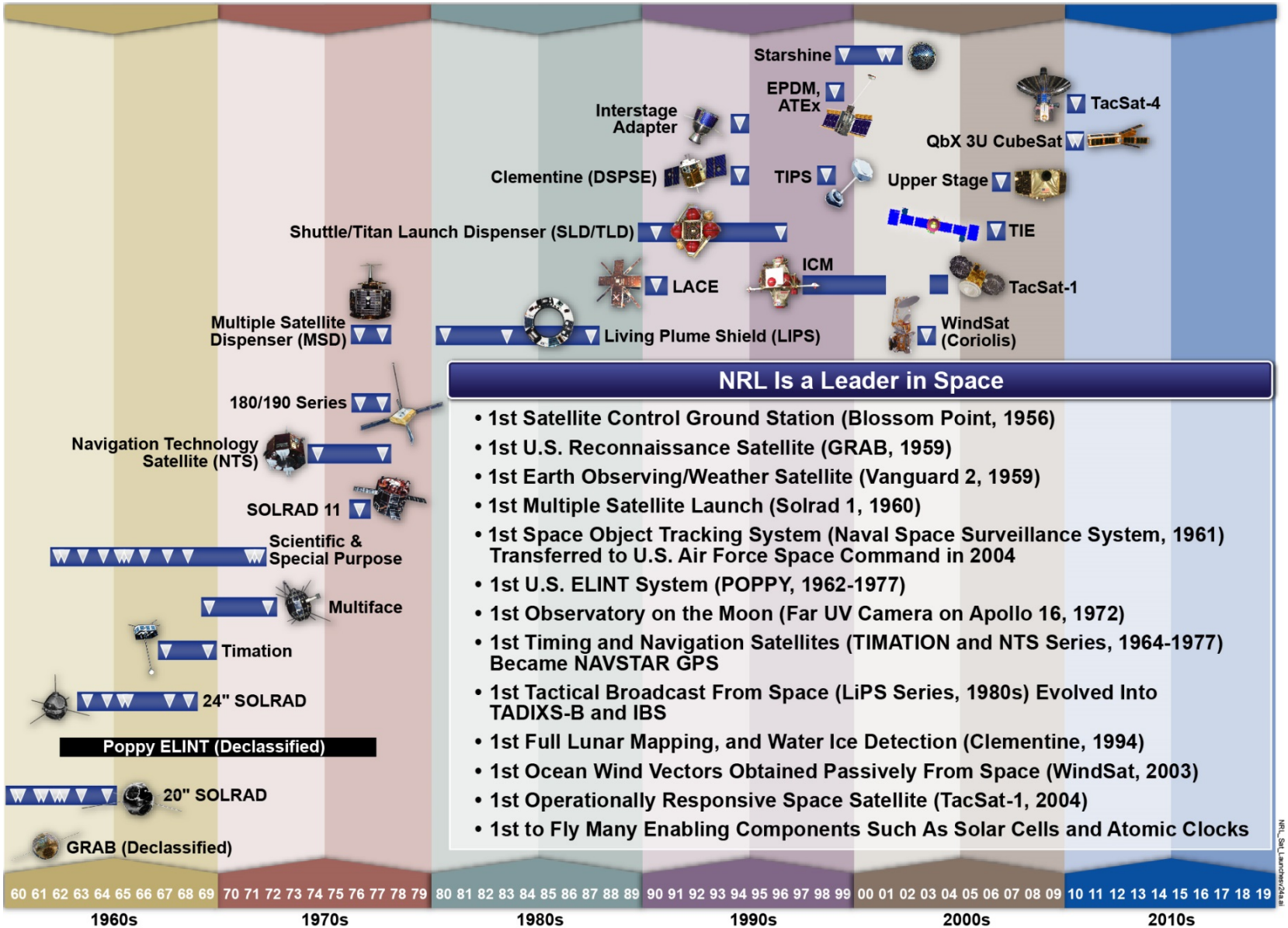
Introduction

Introduction — NRL

“The Government should maintain a great research laboratory to develop guns, new explosives, and all the technique of military and naval progression without any vast expense.”
— Thomas Edison, 1915

Introduction — Naval Center for Space Technology



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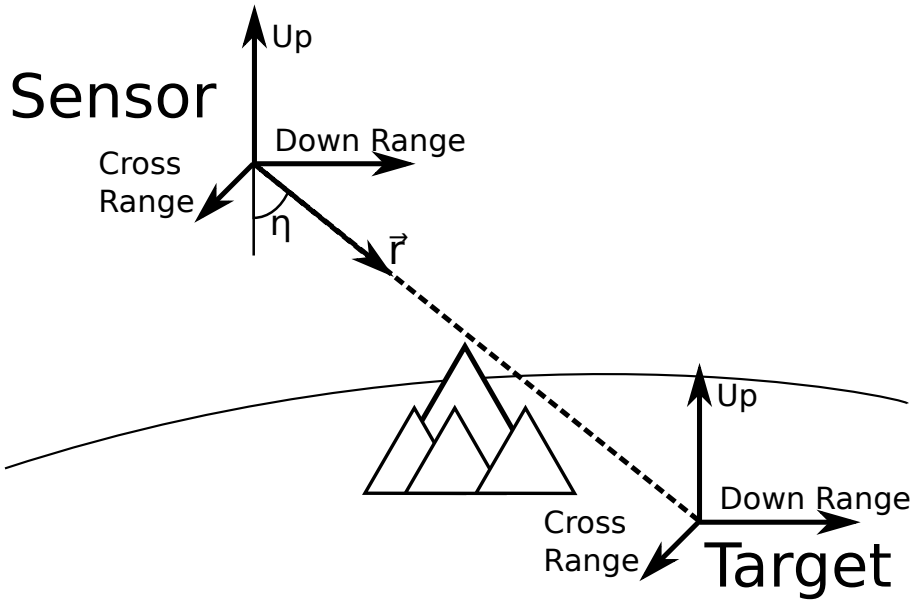
Geolocation with Orekit

Geolocation — Orekit's first use at NRL

Sensitivity analysis of geolocation systems

- Started in 2011
- Goal to evaluate non-linear effects of terrain
- Sensitivity analysis for non-linear error budget
- Similar to Rugged[1]
- Results published in 2015[2]



[1] https://orekit.org/rugged/

[2] Evan Ward. "Global sensitivity analysis of terrain effects in geolocation systems". In: *IEEE Transactions on Aerospace and Electronic Systems* 51.3 (2015), pp. 2039–2046

Geolocation — Why Orekit?

Astrodynamics library search

- Requirements
  - Precise and accurate
  - Easy to work with
  - Extensible
  - Thread safe
  - Actively maintained
- Examined
  - Internal heritage code
  - AGI's STK
  - Some NASA open source code
  - Orekit

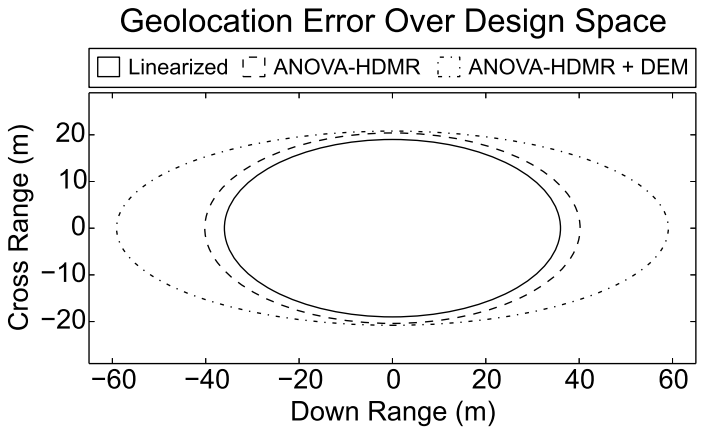
Orekit met all requirements

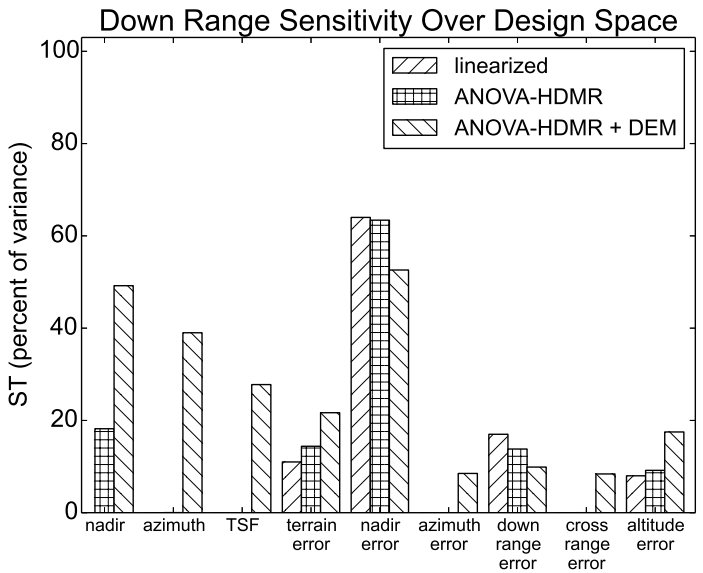
- Thread safety was new to Orekit
- Contributed patches to improve concurrent performance

Geolocation — Results

Simulation

- Airplane with angles-only geolocation sensor
- Computes intersection with a Digital Elevation Model (DEM)
- Sensitivity analysis using Analysis of Variance — High Dimensional Model Representation (ANOVA-HDMR)
  - A Monte-Carlo method





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Orekit & an NRL Satellite

Application of Orekit to an On-Orbit Mission

An on orbit satellite

- A Test And Check Out (TACO) satellite
- Used for end to end testing of NRL's Blossom Point Tracking Facility
- Attitude sensors degraded in 2013
- Needed new algorithm for attitude estimation and maneuver planning

Requirements

- Low cost
- Low level of effort
- Minimal verification requirements
- Accept ill-conditioned data
- Moderate accuracy requirements

Attitude Determination and Control

Orekit and Apache Commons Math based solution

- Orekit provided
  - Frames
  - Time
  - TLES
  - Attitude propagation
  - Planetary ephemerides
- Apache Commons Math provided
  - Vector geometry
  - Levenberg-Marquardt Optimizer

Concept to spacecraft maneuver in a few weeks

- Successfully corrected attitude on first try
- Approaching 4 years of use
- Still in use today

Orekit enabled meeting the requirements

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Orbit Determination Research with Orekit

Orbit Determination Research

State Estimation Application (SEA)

- Orbit Determination (OD) application using Orekit
- Written in 2014
- Inspired by Luc Maisonobe's addition of tide models
- Used to evaluate new OD concepts
- Can be quickly modified
  - Java
  - Extensive OSS libraries
  - Automatic differentiation

Used in 3 publications

- Validation against NRL's Orbit Covariance Estimation & Analysis (OCEAN) application
- Radius of convergence
- Directional measurement representation

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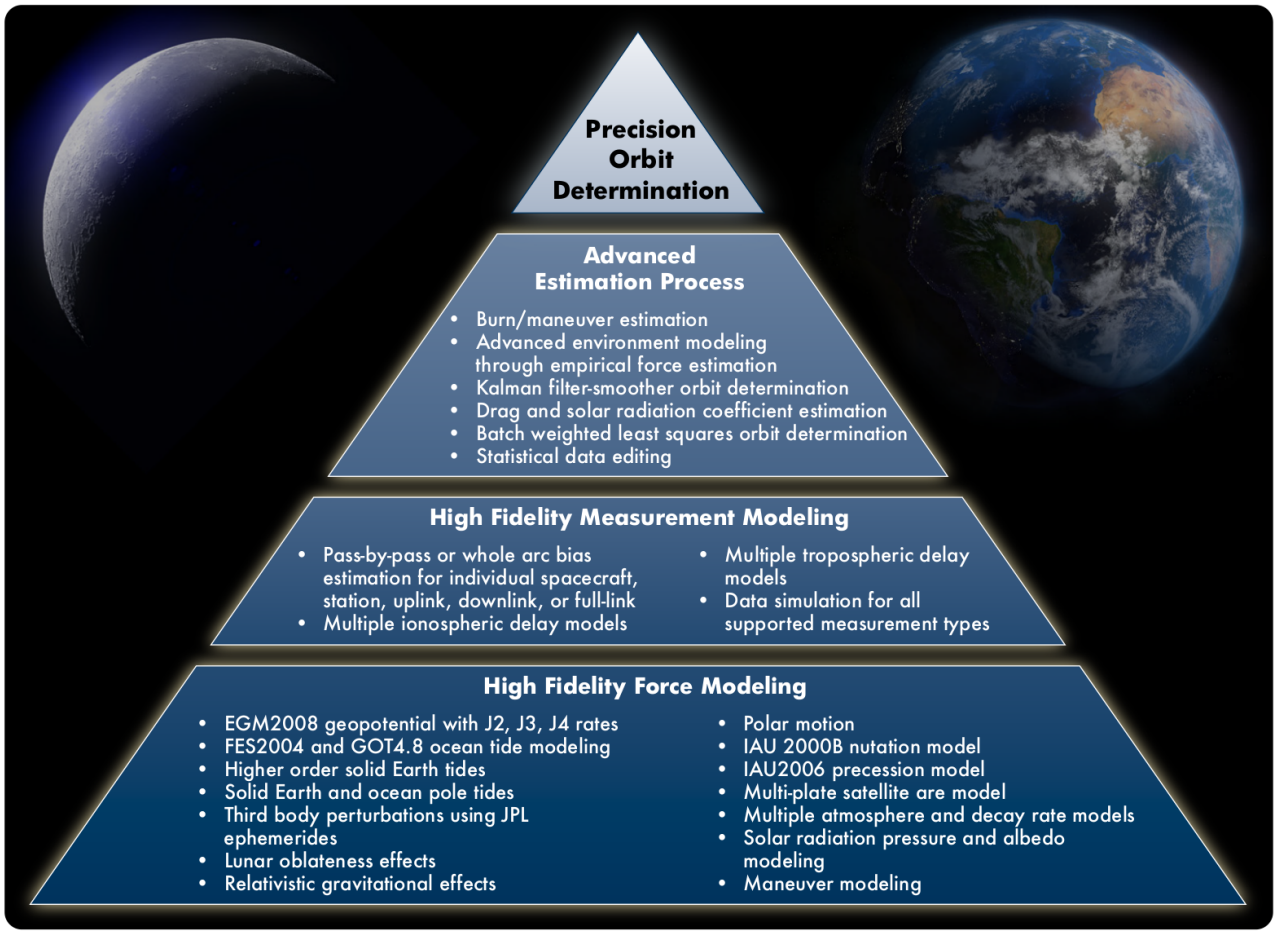
Comparison with Heritage



NRL OCEAN

- High precision OD
- Fortran-based
- Extensive heritage
- Basis of comparison for SEA

Comparing SEA and OCEAN

Evaluate predictive ability[3]

- Satellite Laser Ranging (SLR) test case
- Using STELLA satellite
  - SLR target in Low Earth Orbit (LEO)
- Use similar configuration for OCEAN and SEA
  - Drag models were biggest difference
  - No drag model supported by both

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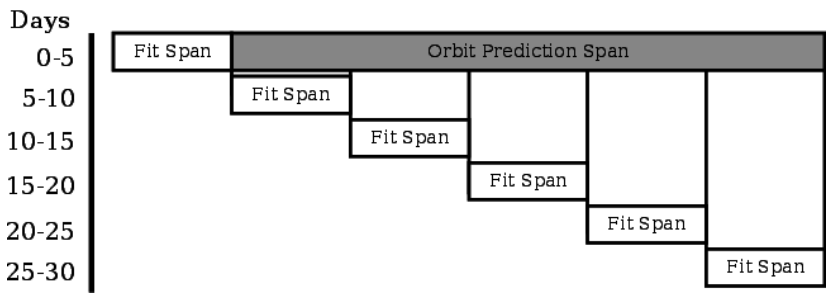
[3] Evan M. Ward, John G. Warner, and Luc Maisonobe. “Do Open Source Tools Rival Heritage Systems?: A comparison of tide models in OCEAN and Orekit”. In: *AIAA/AAS Astrodynamics Specialist Conference*. 2014

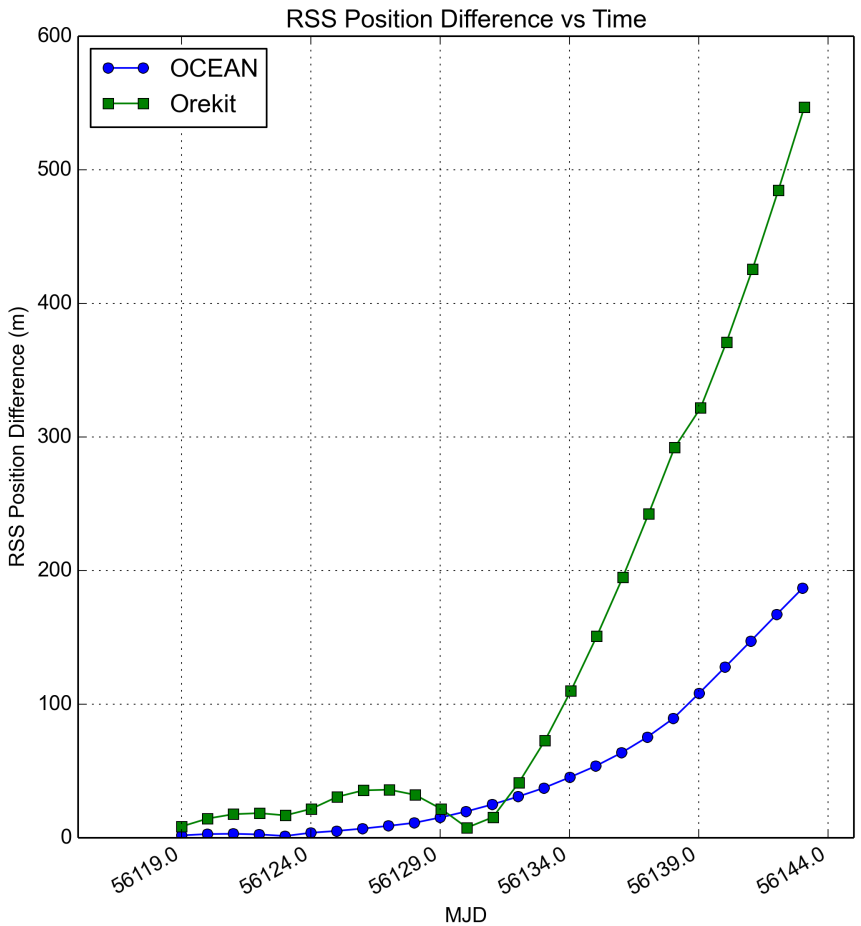
[4] STELLA Satellite. Image Credit: CNES

Comparison and Results

Process

- Fit to five days of data
- Predict for 25 days
- Compare predict to successive five day fits





SEA has sufficient accuracy for use in further research

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Radius of Convergence

Radius of Convergence

Examine sensitivity to errors in initial conditions[5]

- Using SLR satellite LAGEOS-1
  - SLR provides high precision measurements
- Initial condition moved progressively further from truth
- Used SEA and Hipparchus optimizers

At what point is the OD algorithm unable to find a solution?

Evaluate several algorithms

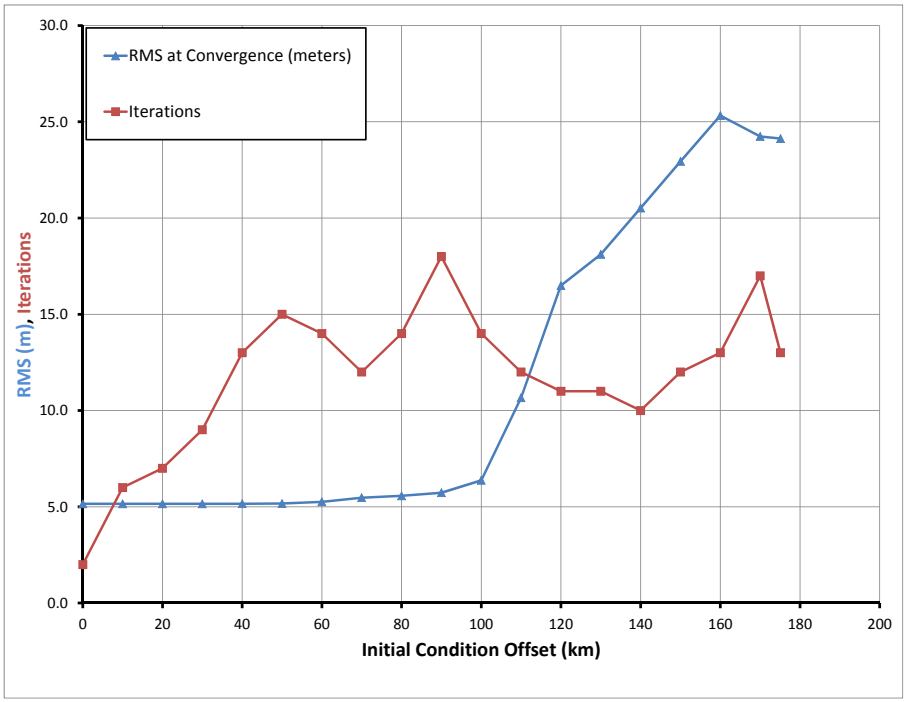
Iteration Method	Matrix Decomposition	Explicit Normal Equations
Levenberg-Marquardt	QR	No
Gauss-Newton	Cholesky	Yes
Gauss-Newton	LU	Yes
Gauss-Newton	QR	No
Gauss-Newton	SVD	No

[5] John G. Warner et al. "Comparing Radius of Convergence in Solving the Nonlinear Least Squares Problem for Precision Orbit Determination of Geodetic Satellites". In: *AIAA/AAS Astrodynamics Specialist Conference*. 2016, p. 5339

Radius of Convergence Results

Levenberg-Marquardt

Method	Radius of Convergence Distance (km)
Levenberg-Marquardt	175.1
Gauss-Newton Cholesky	9.353
Gauss-Newton LU	9.353
Gauss-Newton QR	9.353
Gauss-Newton SVD	9.353



Levenberg-Marquardt uses trust region for larger radius of convergence

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Directional Measurement Representation

Motivation

Angles only orbit determination[6]

- Ground station measures direction to satellite
- Does the coordinate system matter?
- Using Weighted Least Squared
  - Assumes residuals are Normally distributed
- OD textbooks recommend spherical coordinates
- OCEAN weights azimuth by cosine of elevation

[6] Evan M. Ward and Greg Carbott. "On Directional Measurement Representation in Orbit Determination". In: *AIAA/AAS Astrodynamics Specialist Conference*. 2016. DOI: 10.2514/6.2016-5369

Three Angular Representations — Cost Functions

Spherical Coordinates

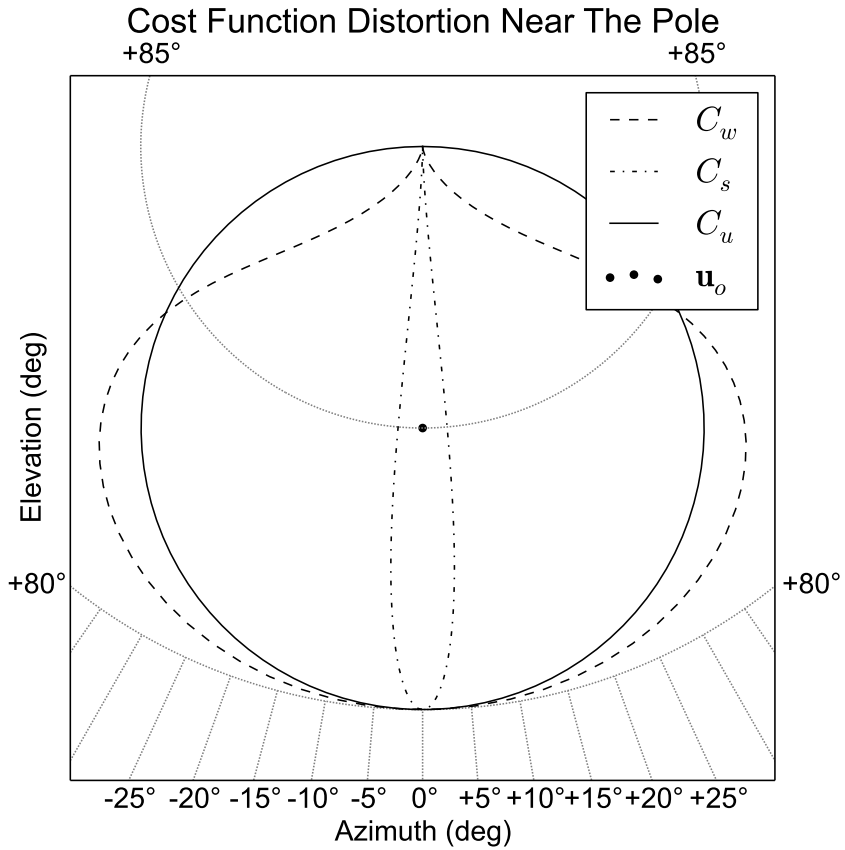
$$C_s = (\alpha_c - \alpha_o)^2 + (\varepsilon_c - \varepsilon_o)^2$$

Weighted Spherical Coordinates

$$C_w = ((\alpha_c - \alpha_o)\cos\varepsilon_o)^2 + (\varepsilon_c - \varepsilon_o)^2$$

Unit Vector

$$\sin\theta = |\mathbf{u}_c \times \mathbf{u}_o|$$
$$C_u = \theta^2$$



Representation determines shape of probability distribution

Comparison

Analytic

- C_w, C_u equivalent for small $\Delta\alpha$, $\Delta\varepsilon$
  - Distortion increases with $\Delta\alpha$, $\Delta\varepsilon$
- C_w, C_s equivalent for small ε_o
  - Distortion increases with ε_o
- All three equivalent with all above assumptions

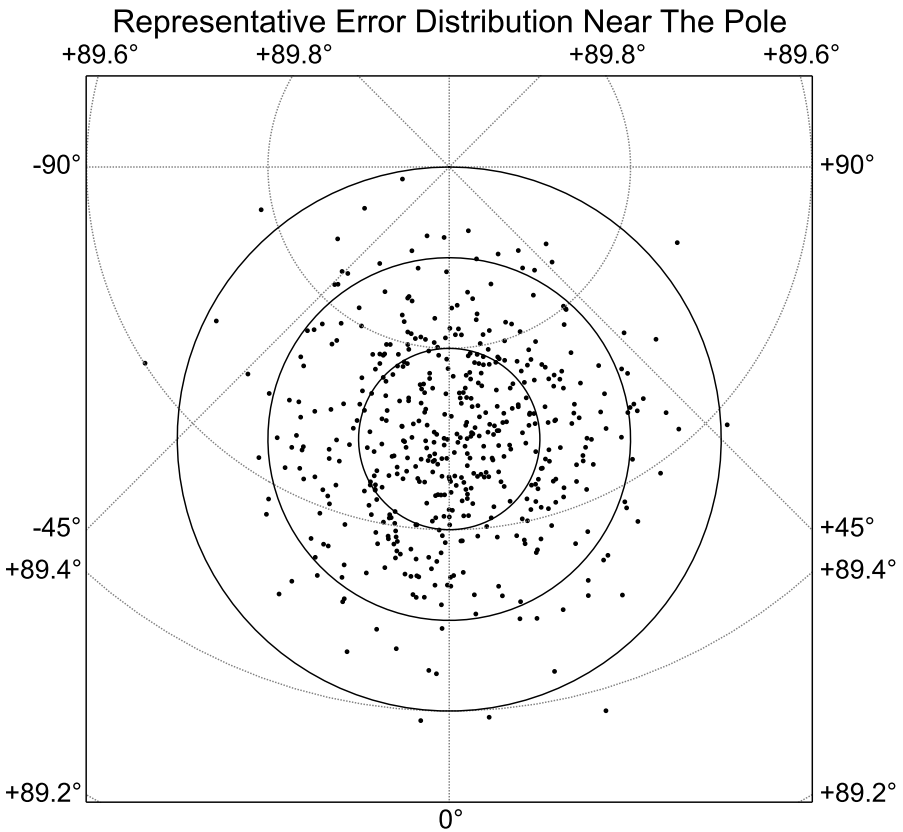
Hypotheses

- Unit vector quicker to converge
  - Measured using number of iterations
- Unit vector attains more accurate solution
  - Measured using RSS ephemeris difference

Observation Simulation

Noise

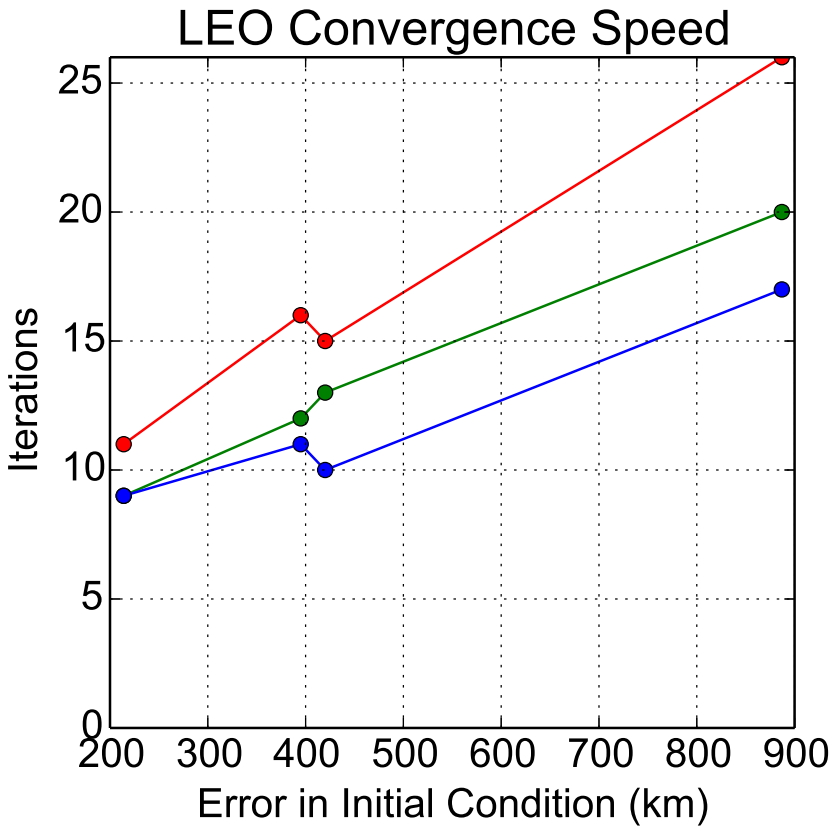
- Symmetric about true direction
- Independent of true direction
- Normal with $\sigma = 0.1°$

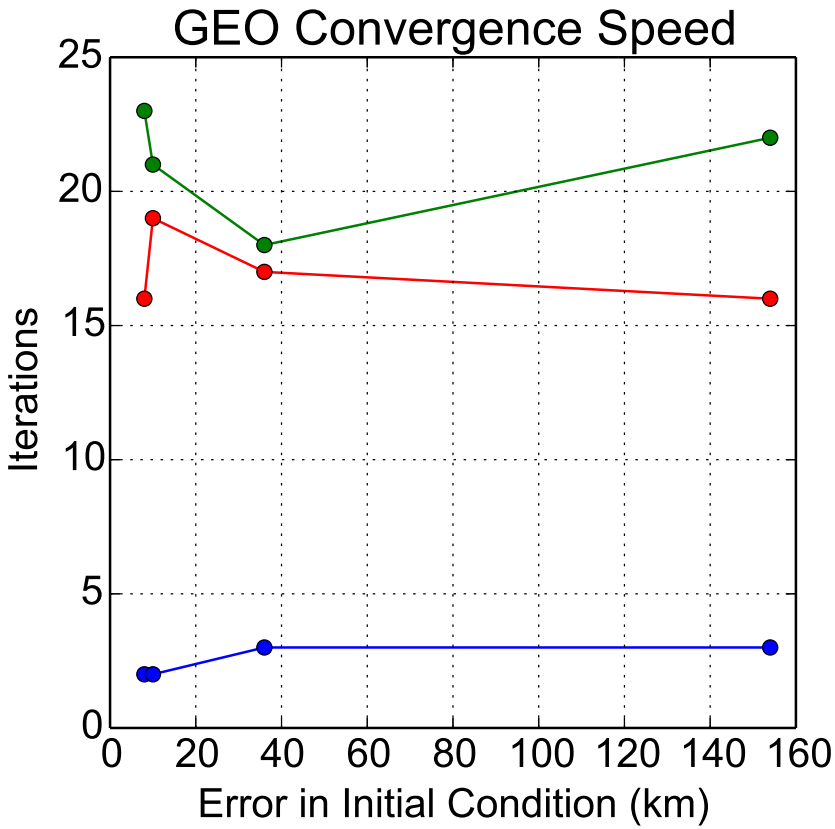


Satellites

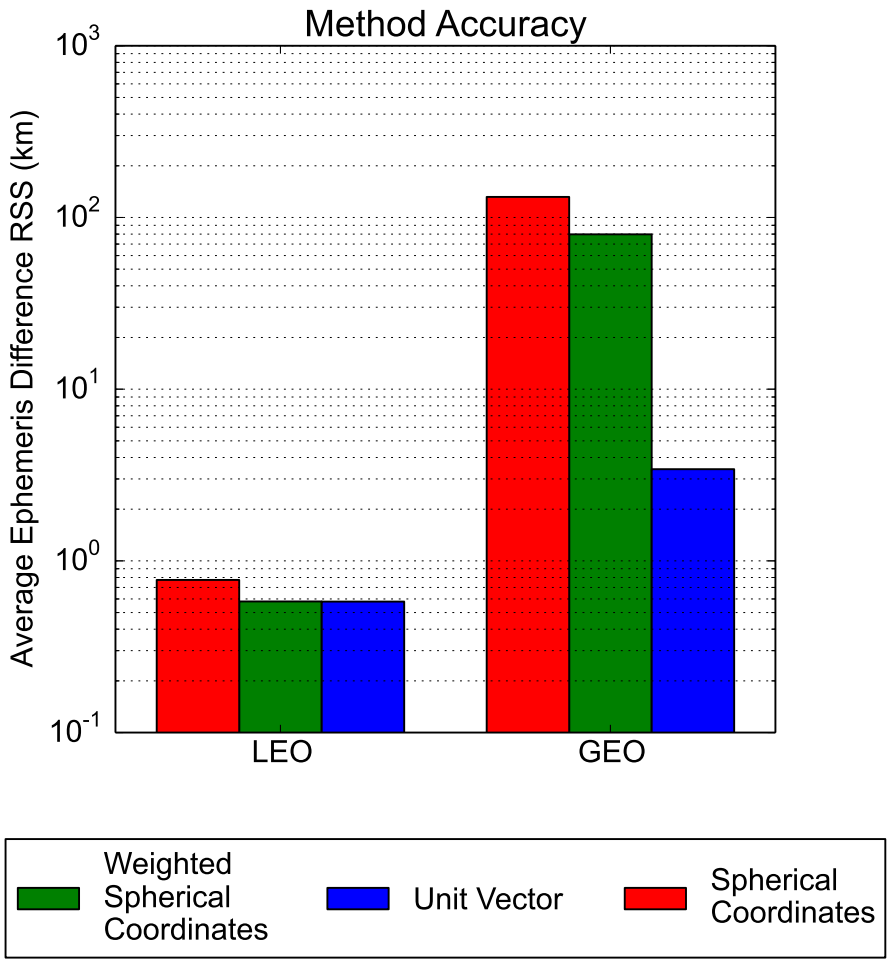
- 500km circular LEO
- GEO
  - Ground station near sub-satellite point
- Several initial conditions
  - Control size of residuals

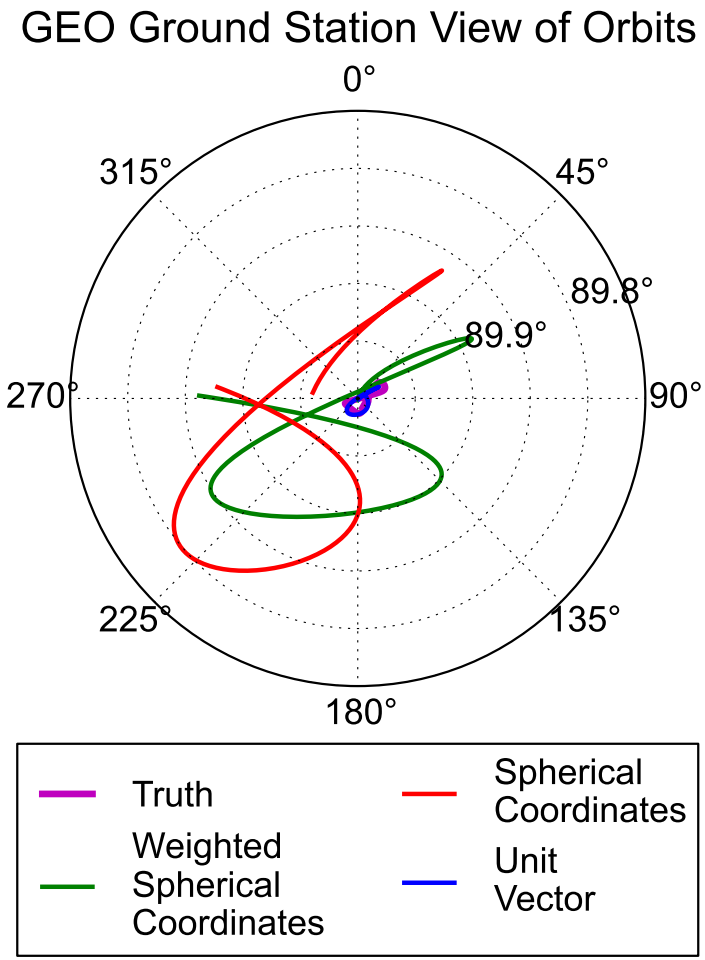
Results — Speed





Results — Accuracy





Unit vector method best for high elevation angles

Why?

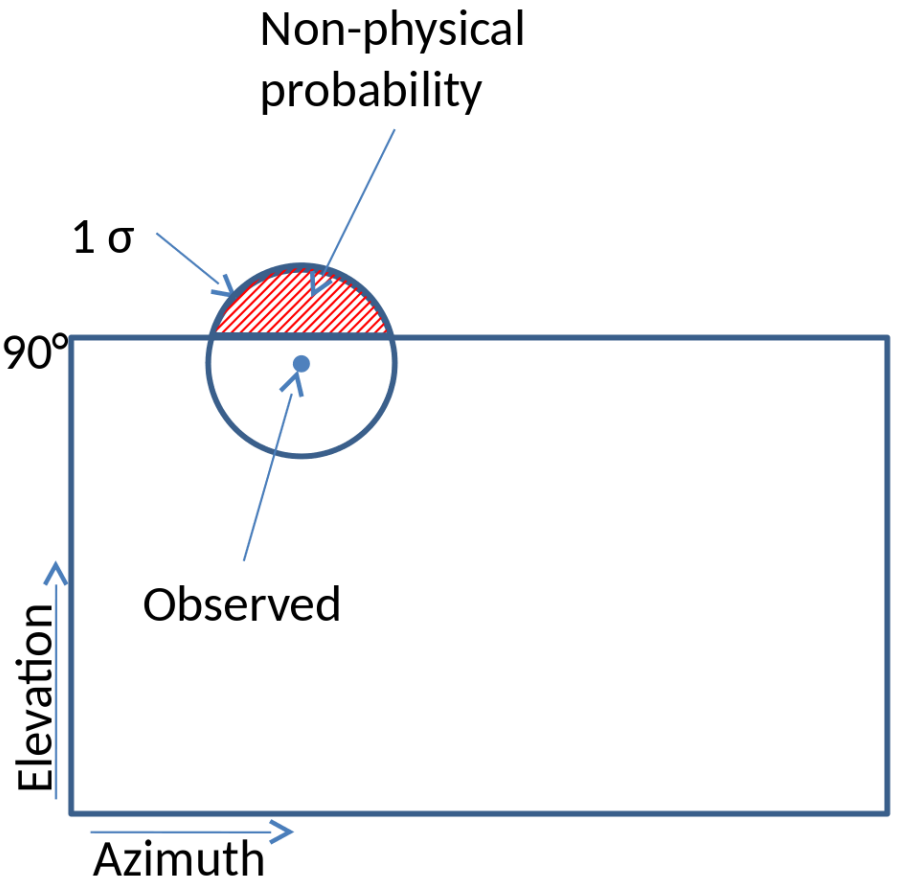
Distortion

- Small θ does not imply small $(\alpha_c - \alpha_o)$
- Shortest path is not a straight line

Clipping

- Positive probability placed on non-physical solutions

Both effects prevent averaging



Unit vector method has neither effect

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Conclusions & Future Work

Final Thoughts on Orekit

Great tool for research

- Highly reconfigurable
- Quick development
- High fidelity

Welcoming Community

- Responds quickly
- Patient with new users

Opportunity to improve documentation

- Documentation is good for experts in astrodynamics and computer science
- Received feedback from several new users
  - Documentation is unclear / confusing
  - Can't find the answer
- Perhaps more high level overviews and tutorials

Orekit Future Work

Interoperability with other analysis tools

- Parser & Writer for STK `.e` and Cesium CZML files
- Add covariance to `EphemerisFile` interface
- Better frame to name mapping
- One Line Element Sets (OLES)

Internal Interoperability

- Instantiatable `FramesFactory`, `TimeScaleFactory`
  - Compare EOP series
- `Frame` from/to `PVCoordinatesProvider`, `AttitudeProvider`
- Analytic `Propagator` from a `PVCoordinatesProvider`
  - Event detection for planets, etc.

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Questions?