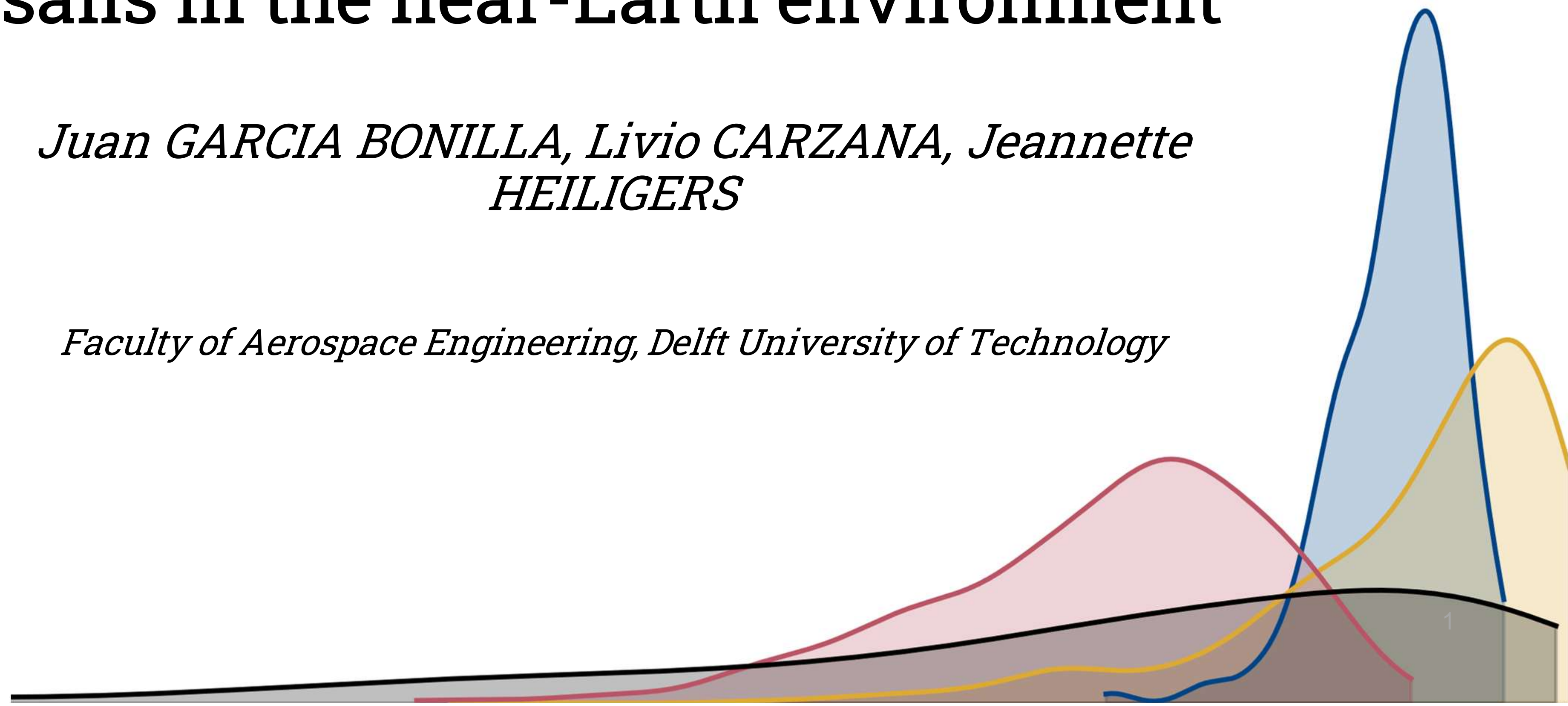
Uncertainty quantification for solar sails in the near-Earth environment

Juan GARCIA BONILLA, Livio CARZANA, Jeannette HEILIGERS

Faculty of Aerospace Engineering, Delft University of Technology



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Introduction

Solar sailing is a complex and relatively nascent technology

Mission design is burdened with uncertainty

Optical properties

Structural deformation

Control

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- Uncertainty propagation
- Test case
- Constant Random Value Uncertainties
- Stochastic Process Uncertainties
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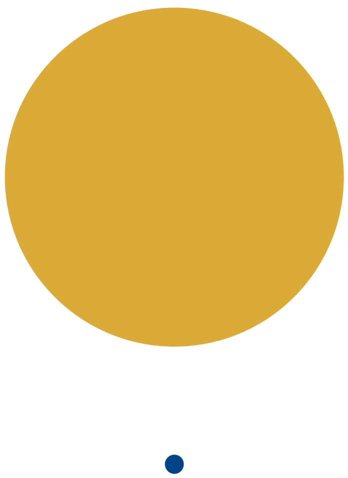
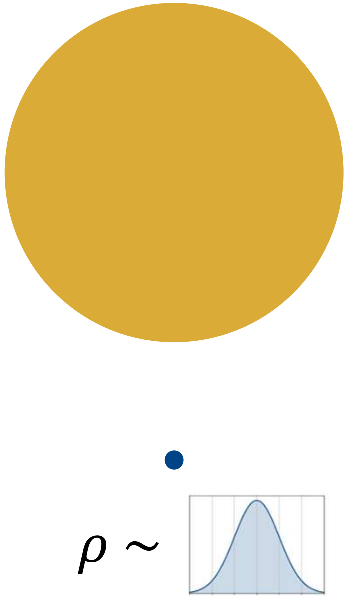
Uncertainty propagation: in astrodynamics



Uncertainty propagation: in astrodynamics

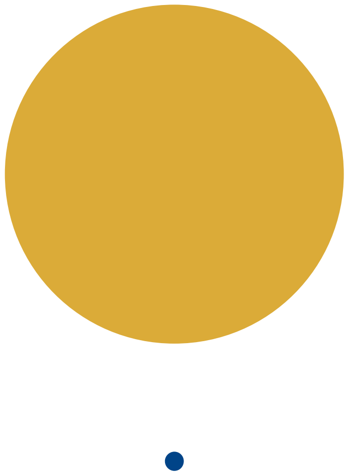
Uncertainty in the system

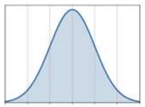
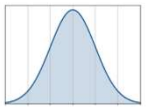


Uncertainty propagation: in astrodynamics

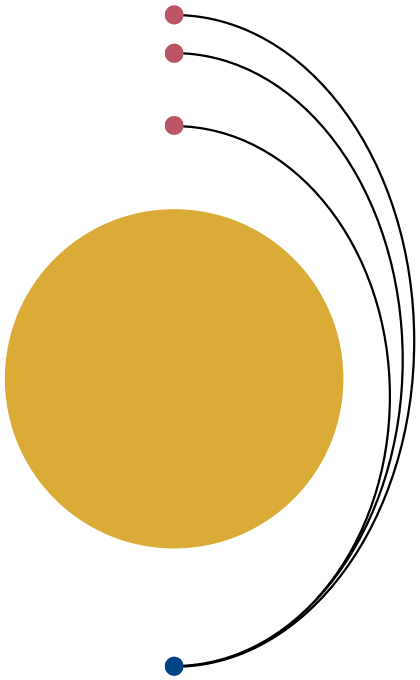
Uncertainty in the system

Affects acceleration on the sail



$\rho \sim$  $\Rightarrow a_{SRP} \sim$ 

Uncertainty propagation: in astrodynamics



$\rho = 0.$[illegible]

Uncertainty in the system

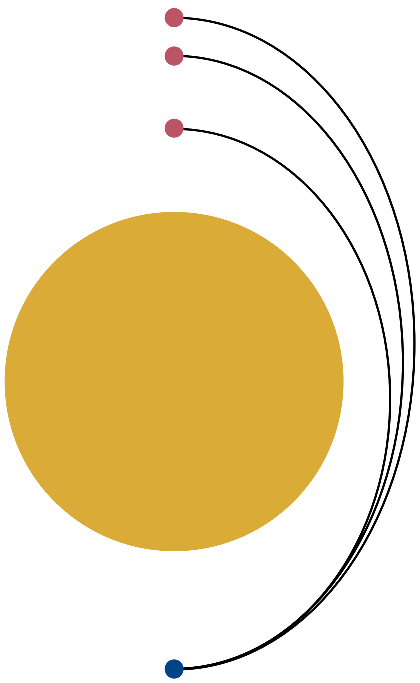
↓

Affects acceleration on the sail

↓

Affects the trajectory

Uncertainty propagation: in astrodynamics



Uncertainty in the system

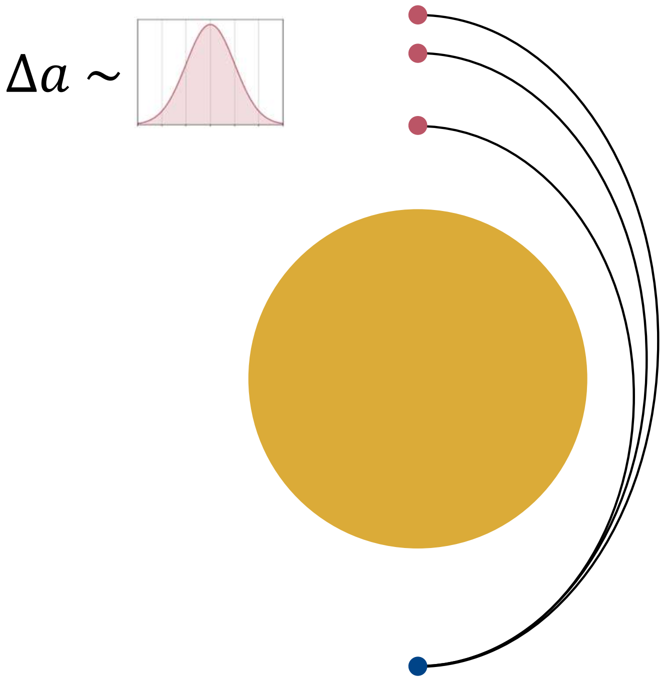
↓

Affects acceleration on the sail

↓

Affects the trajectory

Uncertainty propagation: in astrodynamics



Uncertainty in the system

↓

Affects acceleration on the sail

↓

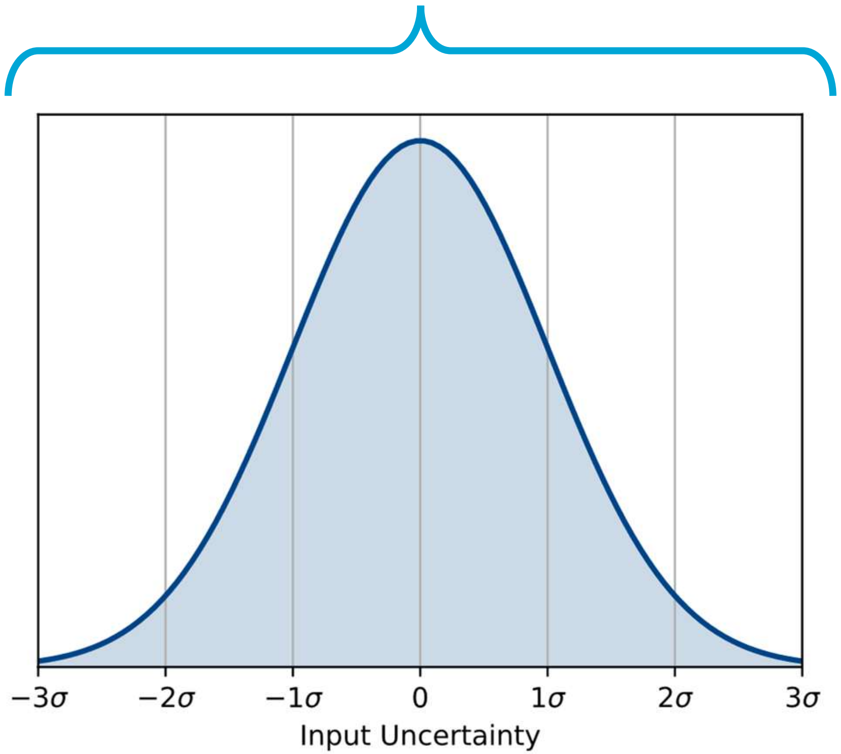
Affects the trajectory

↓

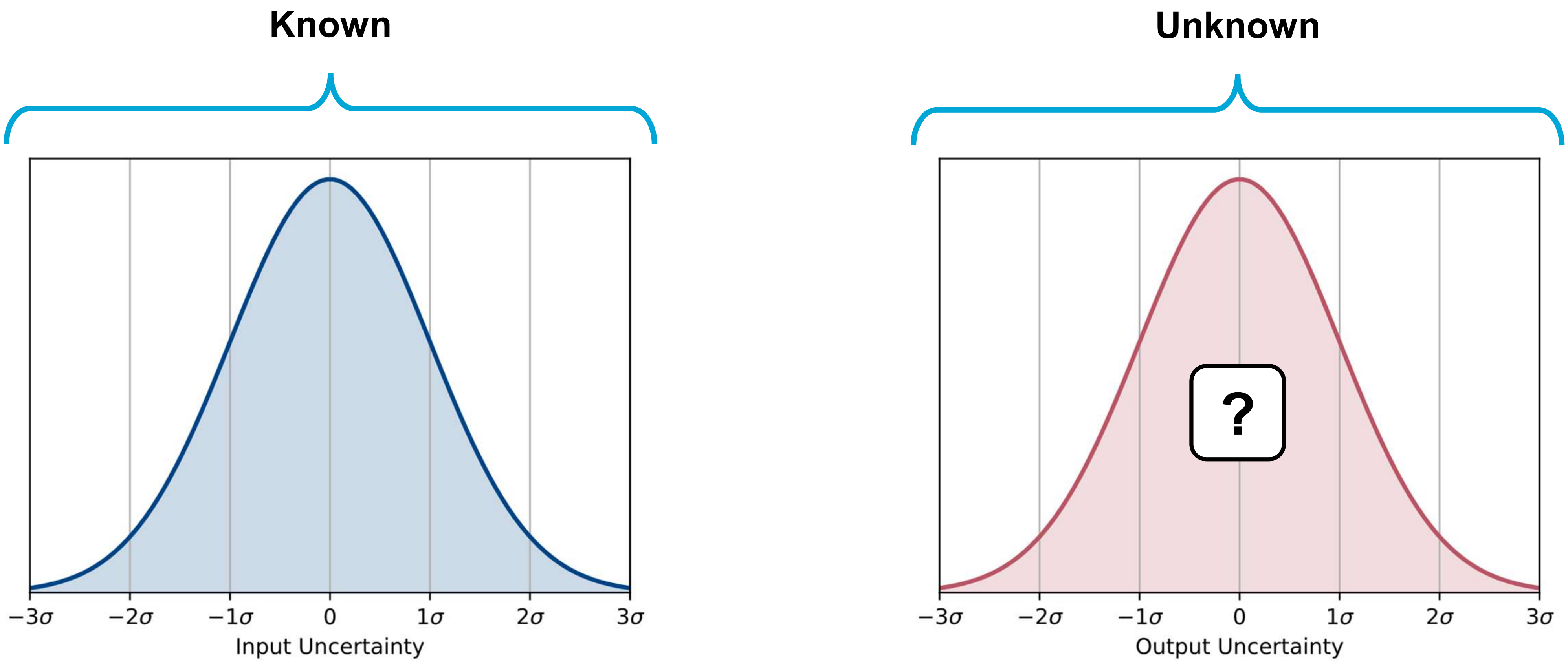
Creates mission performance uncertainty

Uncertainty propagation

Known



Uncertainty propagation



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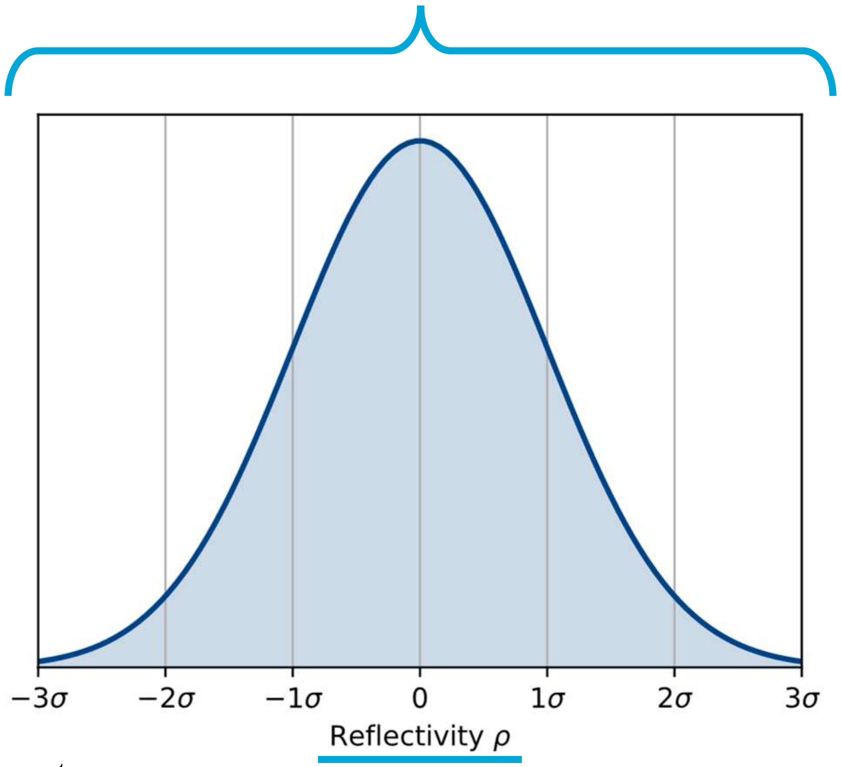
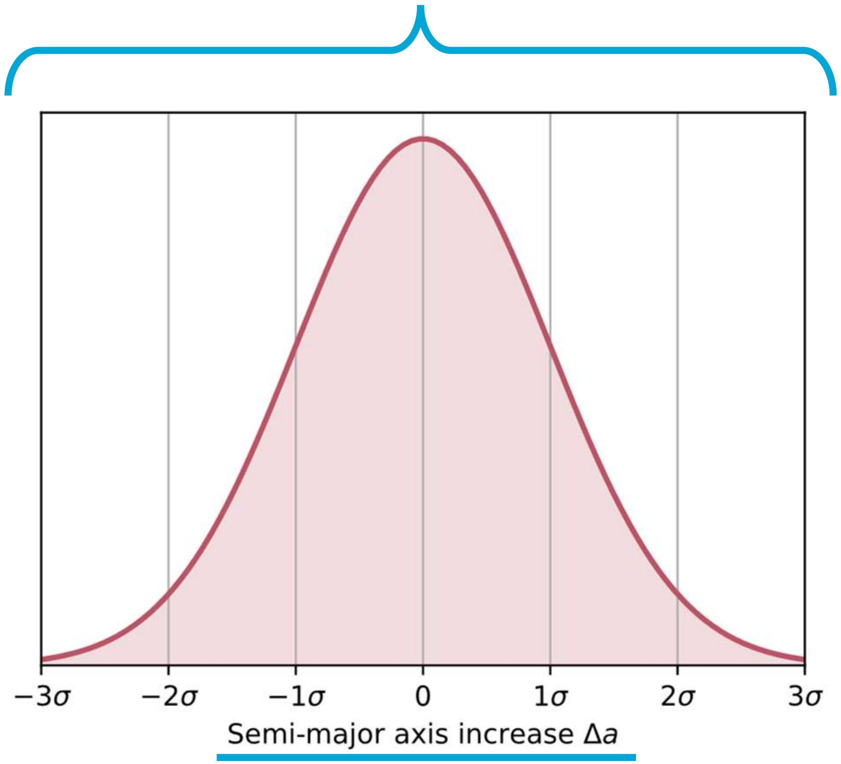
Uncertainty propagation

Known



Unknown



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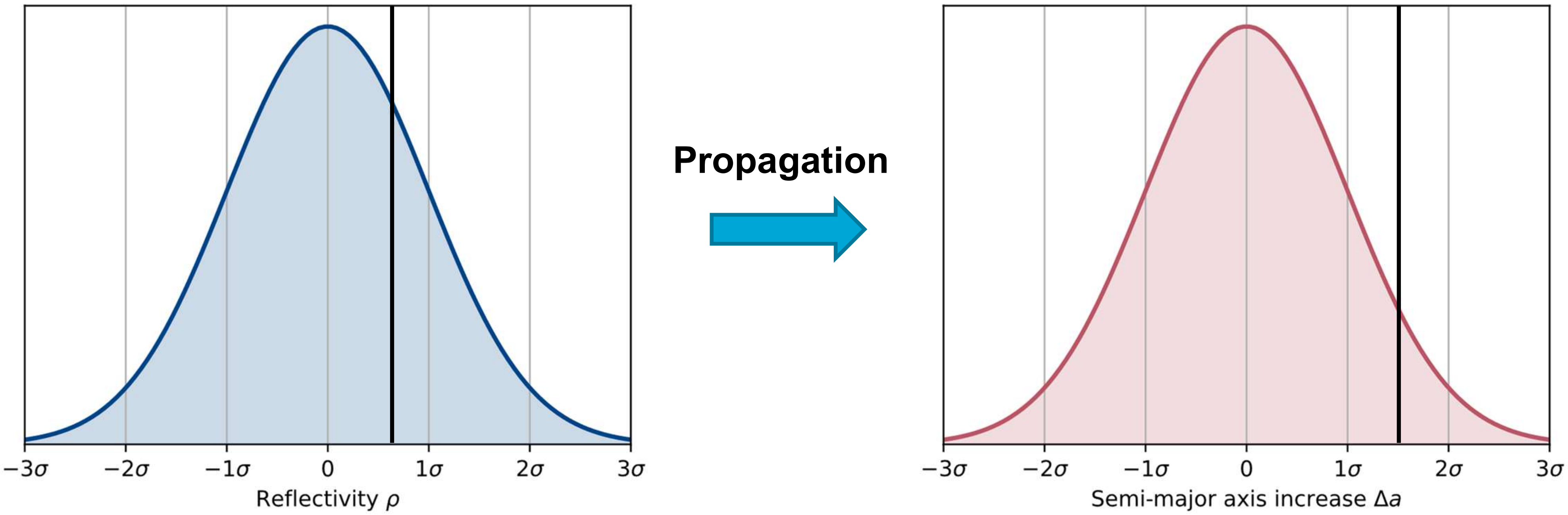
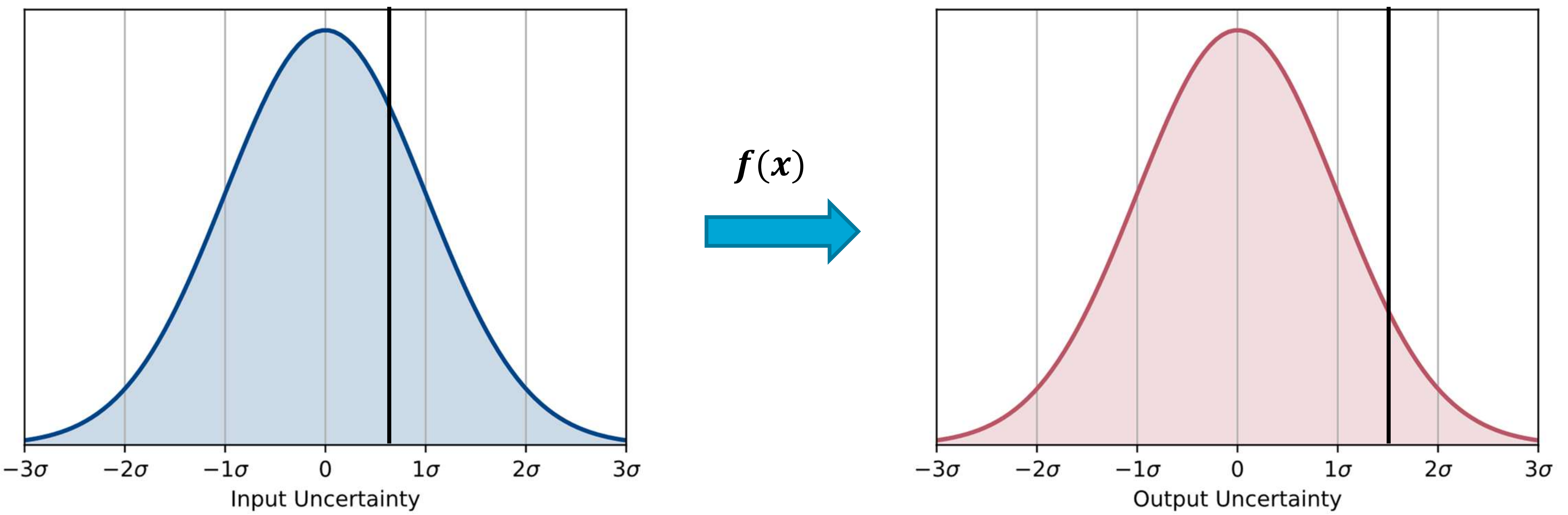
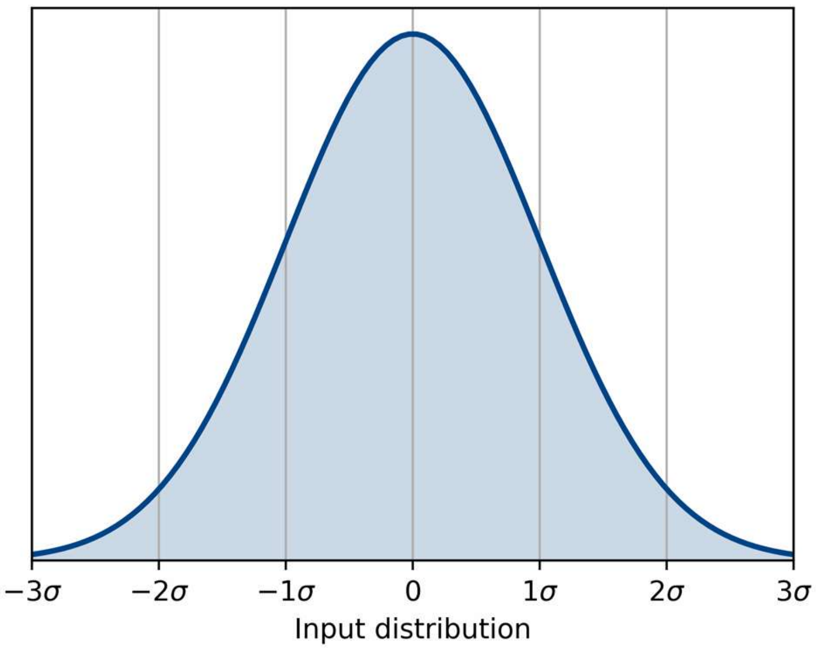
Uncertainty propagation: sampled-based methods



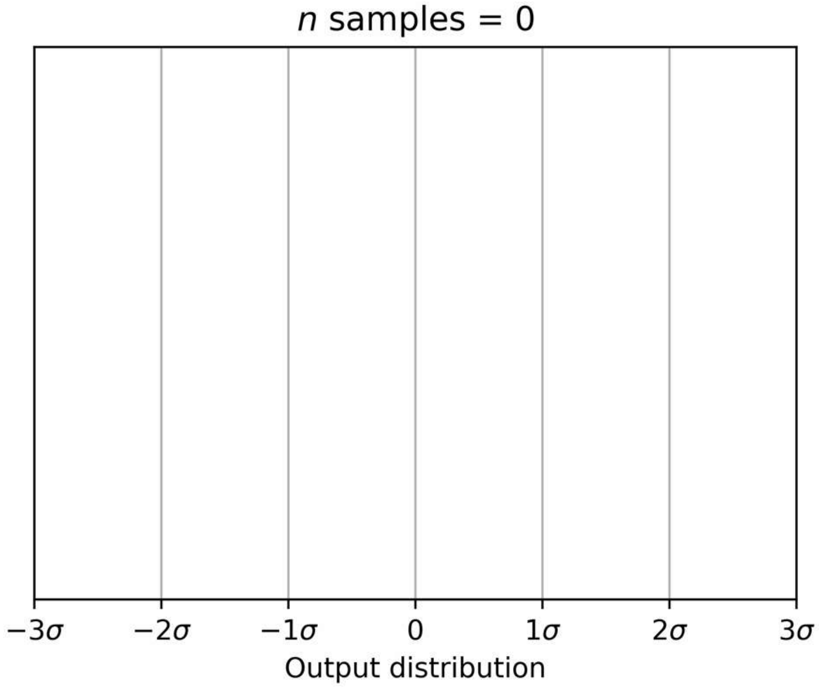
Uncertainty propagation: sampled-based methods



Uncertainty propagation: Monte Carlo



$f(x) = -x$



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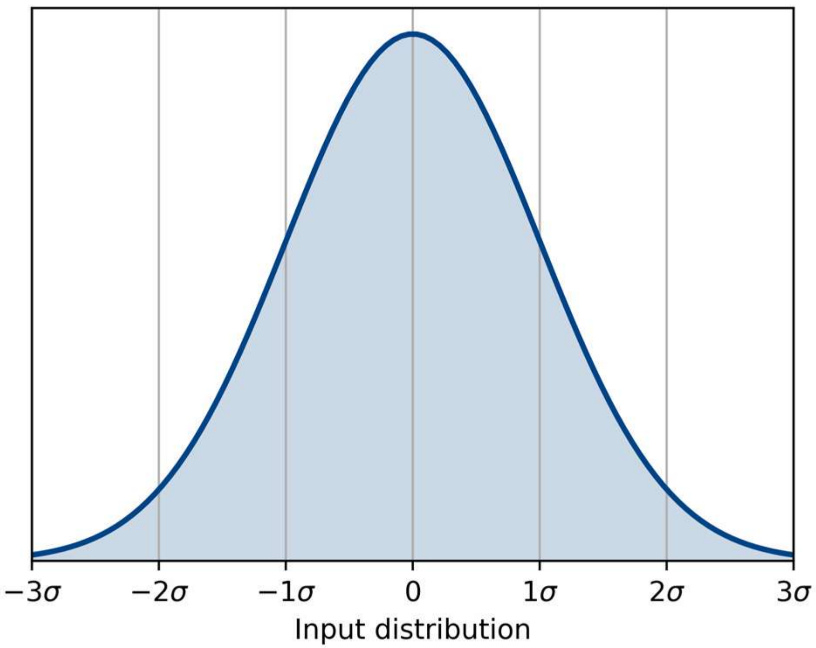
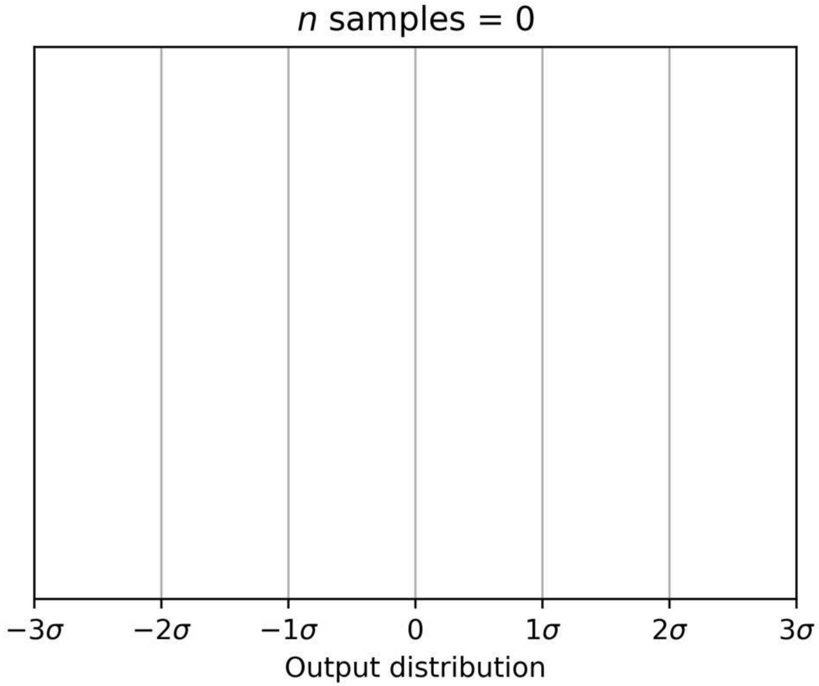
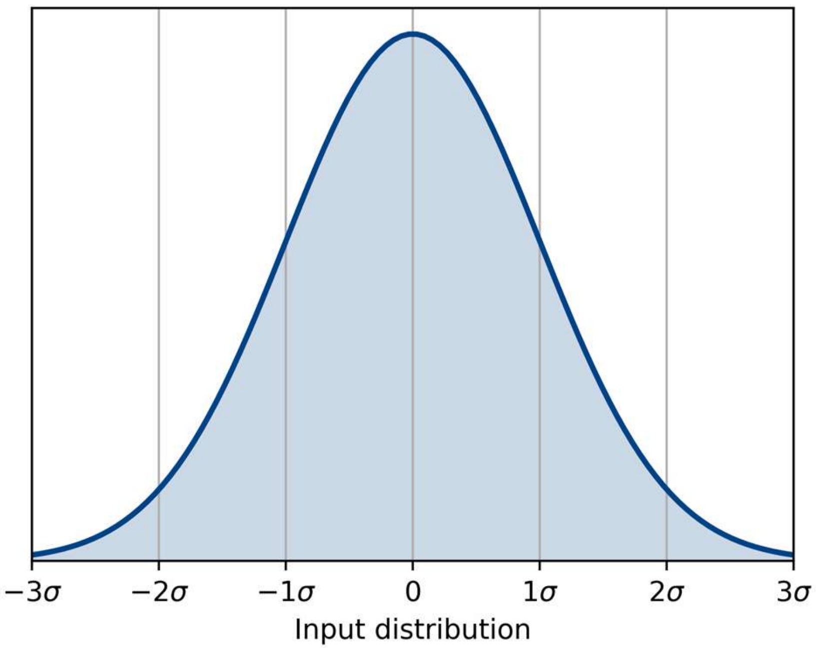
Uncertainty propagation: Monte Carlo



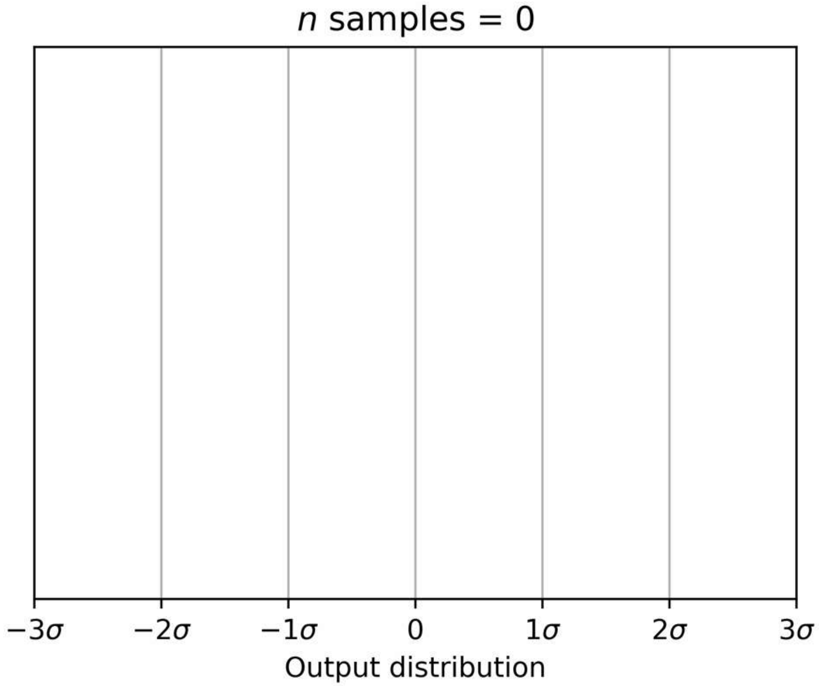
$$f(x) = -x$$



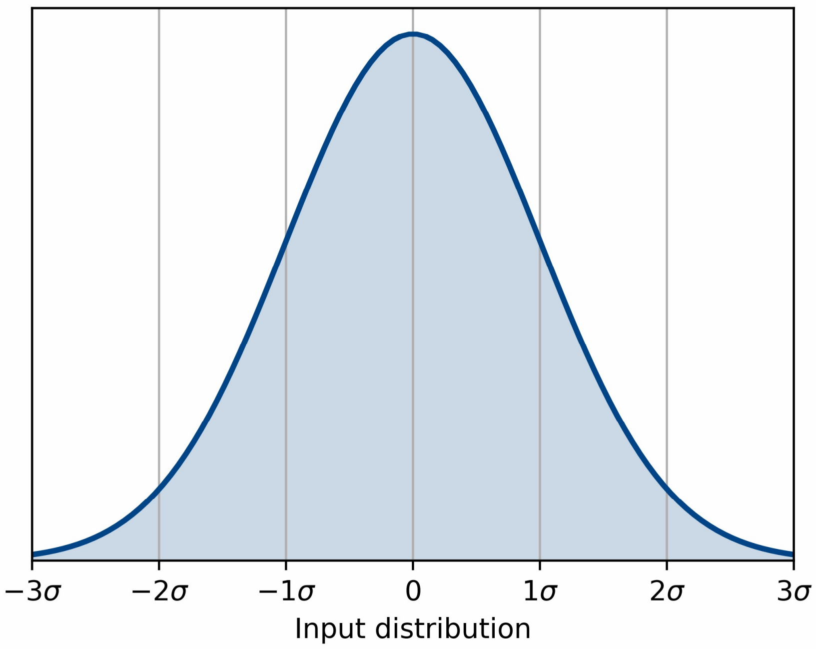
Uncertainty propagation: Monte Carlo



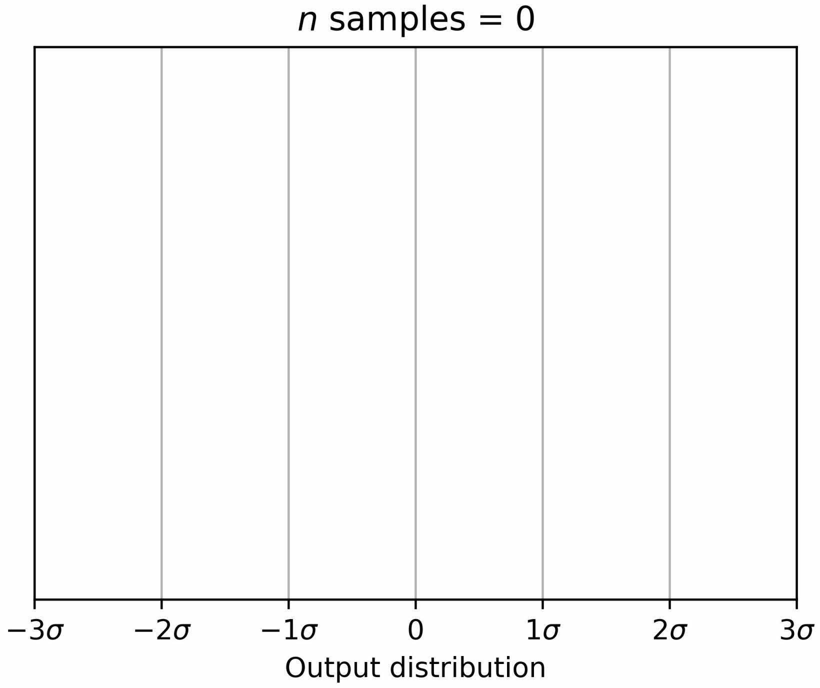
$$f(x) = -x$$



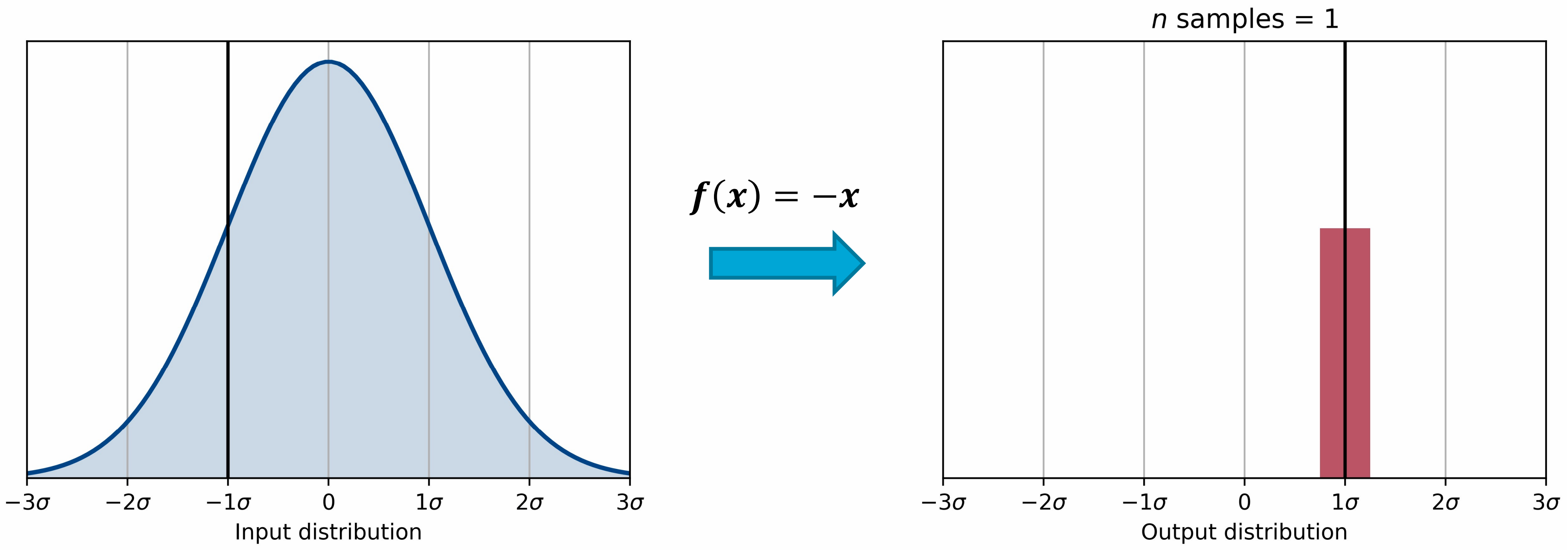
Uncertainty propagation: σ-point methods



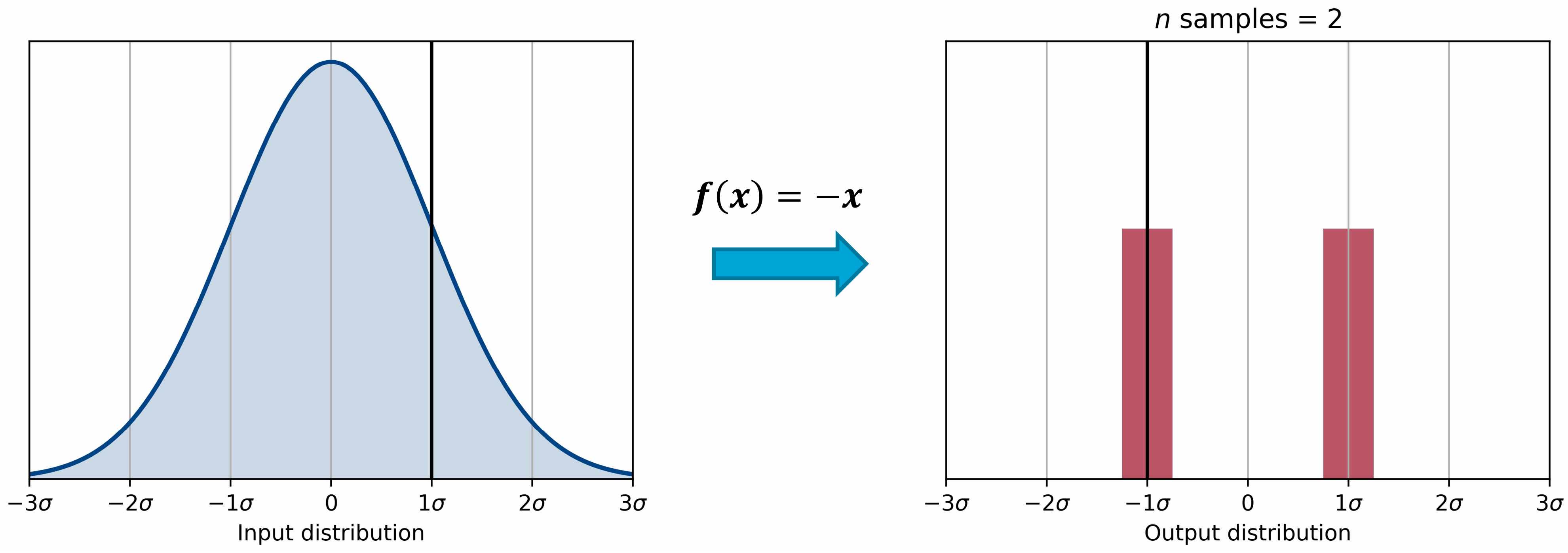
$$f(x) = -x$$



Uncertainty propagation: σ-point methods



Uncertainty propagation: σ-point methods



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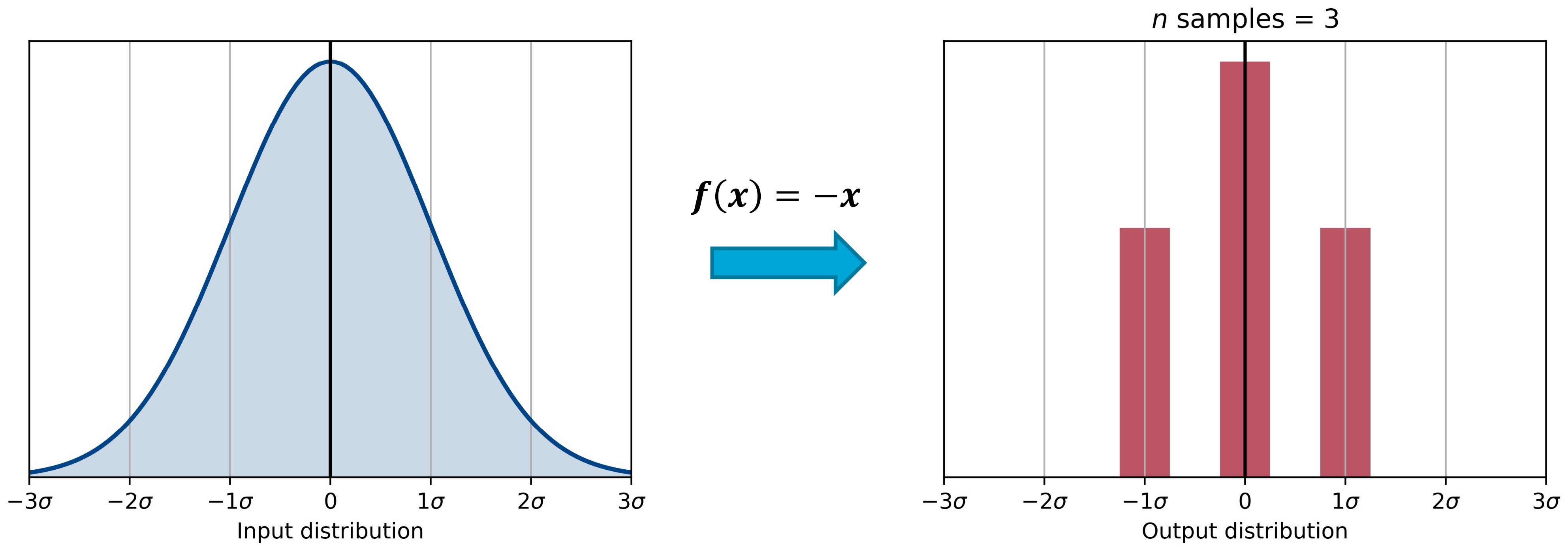

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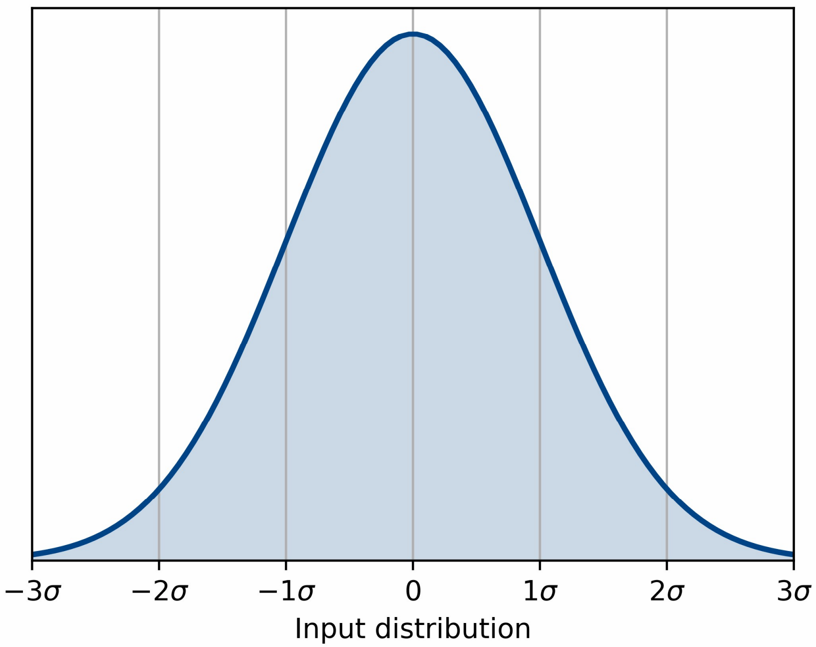

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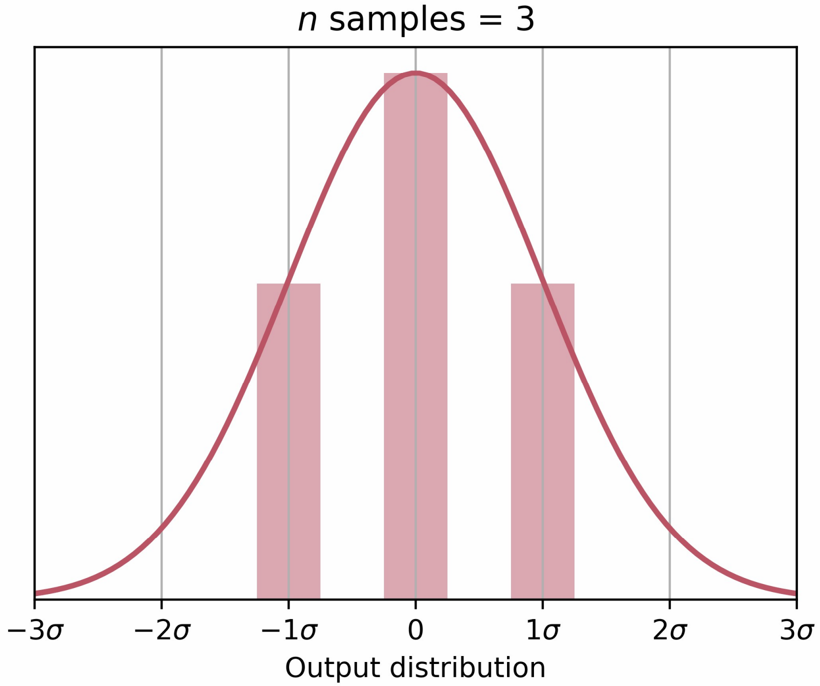
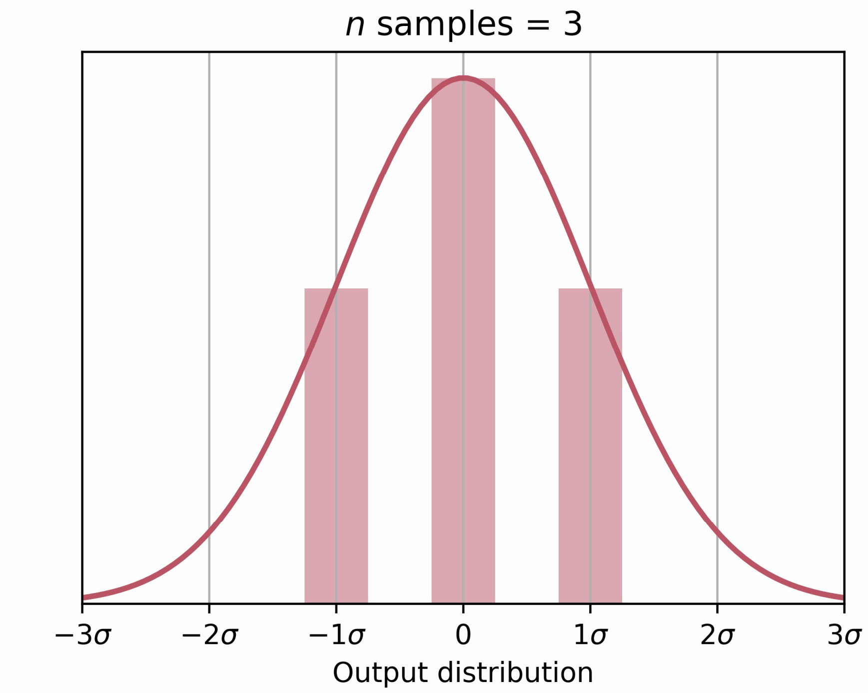


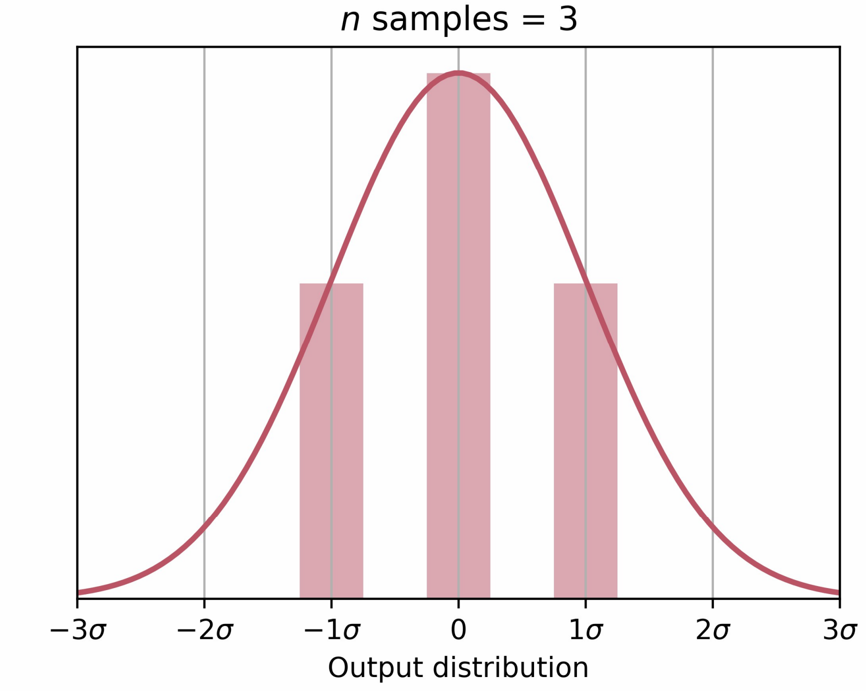
Uncertainty propagation: σ-point methods

- Small amount of samples
- Samples are chosen deterministically
- Each sample has an associated weight
- The output distribution is assumed to have a certain shape



Uncertainty propagation: Gauss von Mises method

- A σ-point method
- Uses $2d + 1$ samples
- Uses orbital elements to represent the spacecraft's state: $\{a, h, k, p, q, \ell\}$
- Assumes that $\{a, h, k, p, q\}$ follow a *Gaussian* (normal) distribution
- Assumes that ℓ follows a *von Mises* distribution



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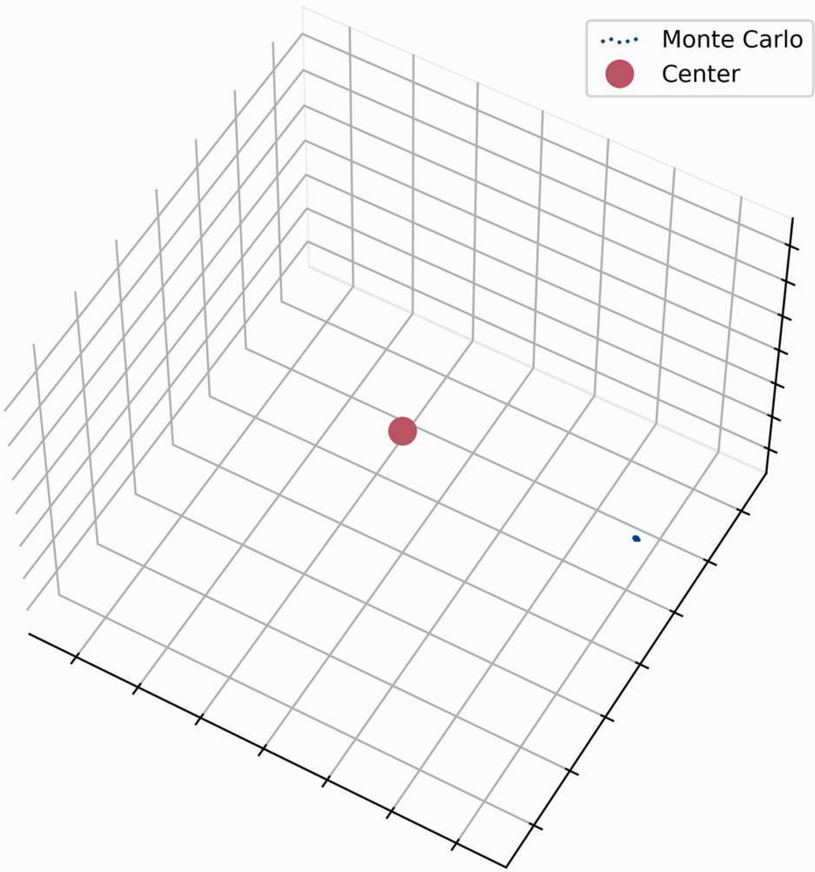
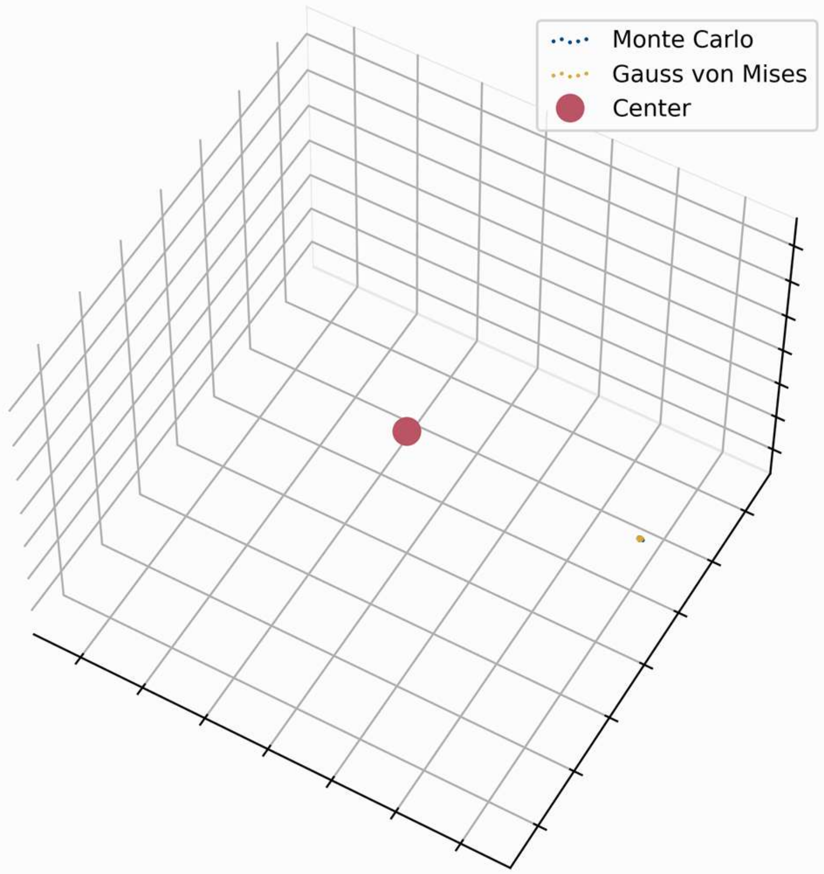
Uncertainty propagation: Gauss von Mises vs Monte Carlo



Uncertainty propagation: Gauss von Mises vs Monte Carlo



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- <u>Test case</u>
- Constant Random Value Uncertainties
- Stochastic Process Uncertainties
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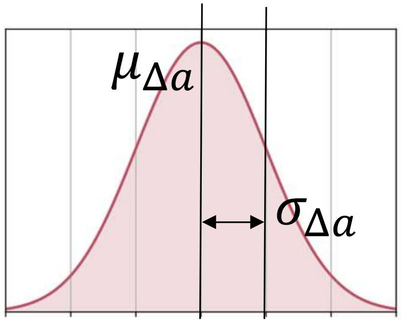
Test case

- **Initial Orbit:** Dawn-Dusk Sun Synchronous Orbit

- **Perturbations:** J_2 + aerodynamic forces

- **Control:** Locally optimal steering law that maximizes the rate of change of the semi-major axis

- **Figure of Merit:** Total increase in semi-major axis after X days of maneuvers



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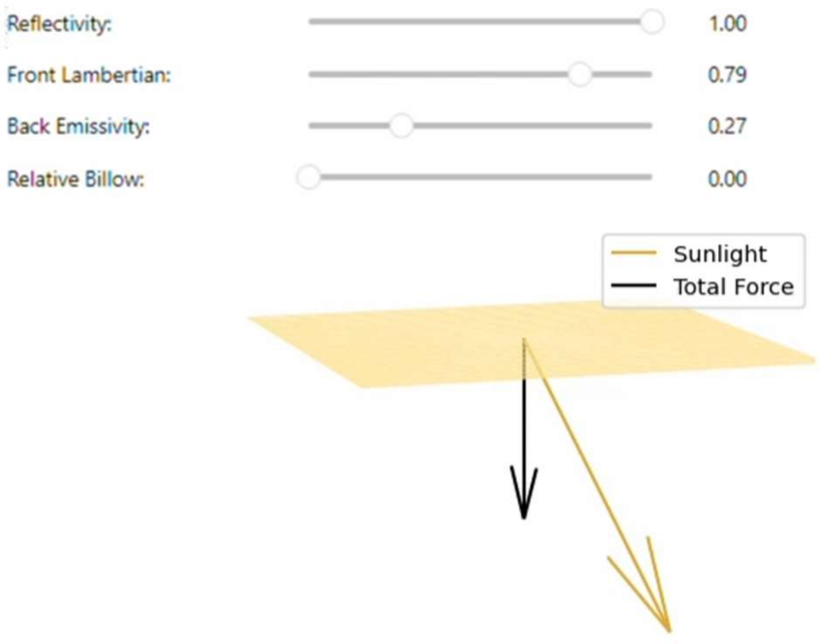
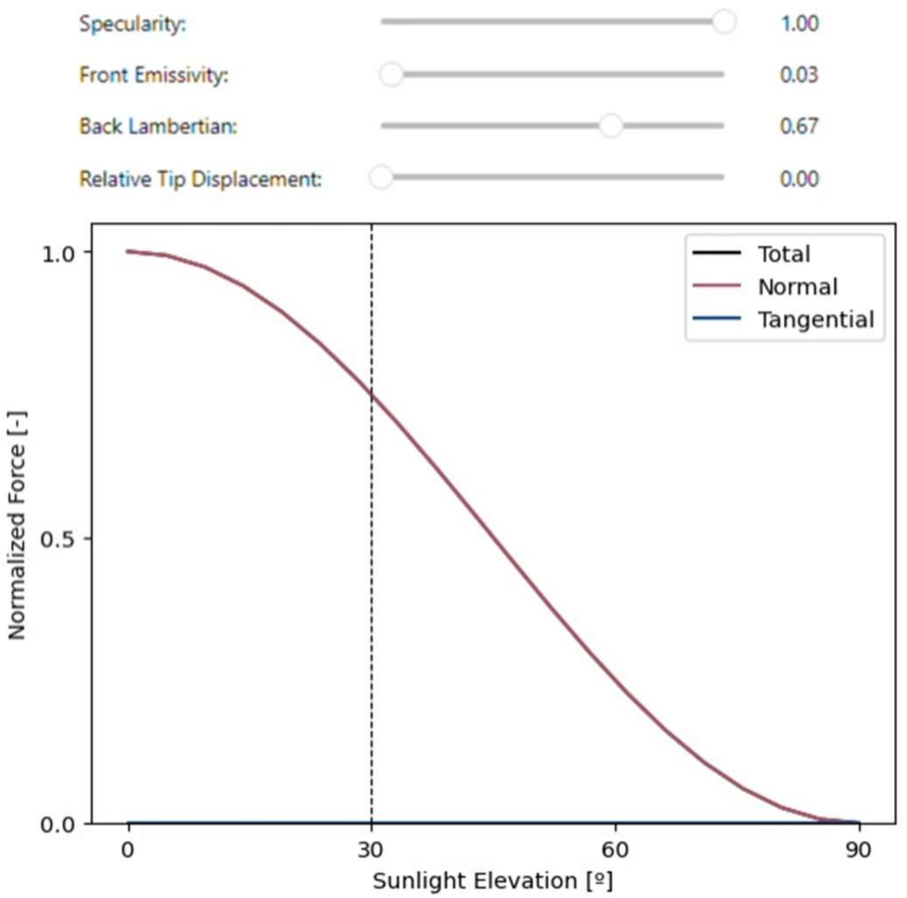
Constant Random Value Uncertainties

Optical Coefficients

Reflectivity	ρ	Specularity	s
Front Lambertian Coeff.	B_f	Front Emissivity	ε_f
Back Lambertian Coeff.	B_b	Back Emissivity	ε_b

Constant Random Value Uncertainties





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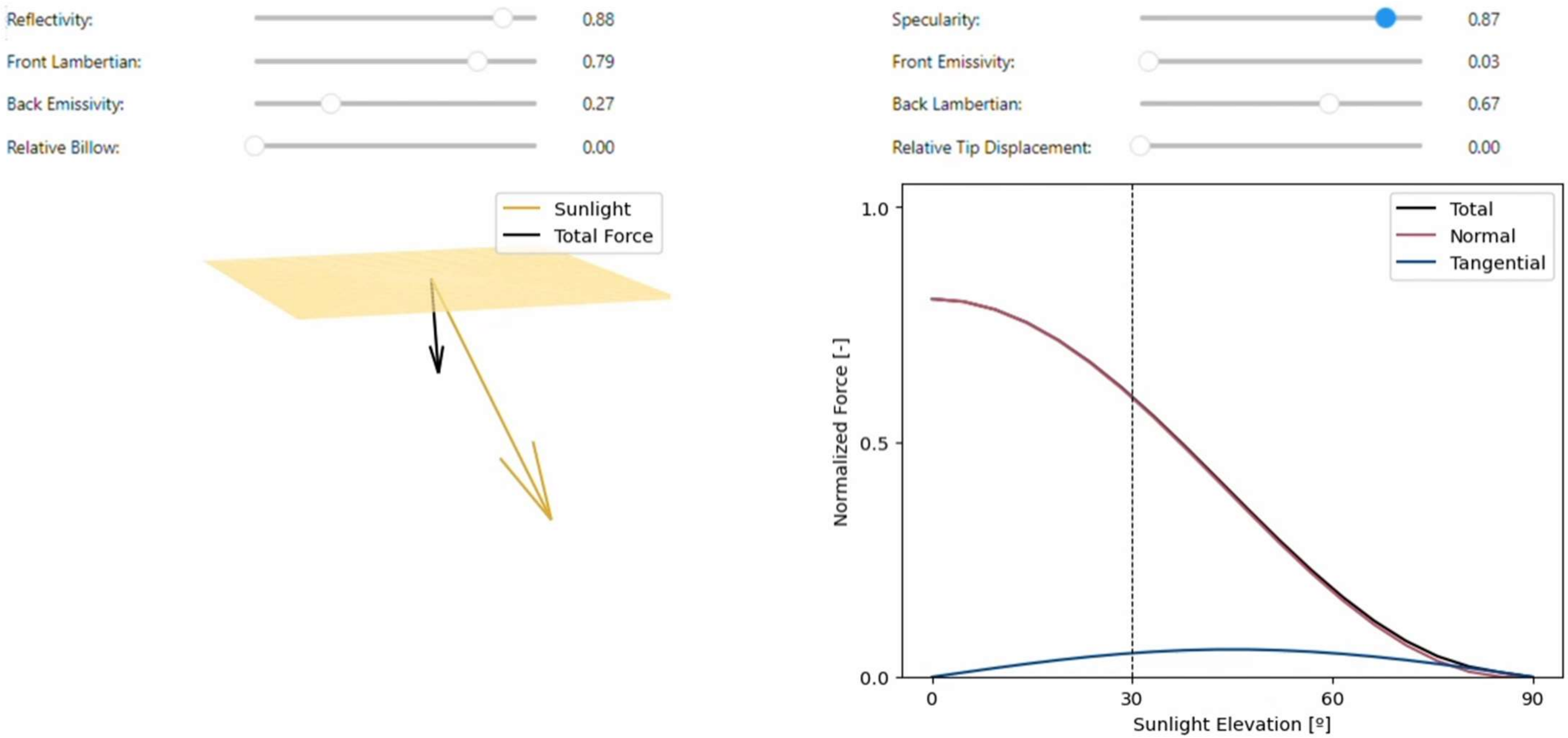
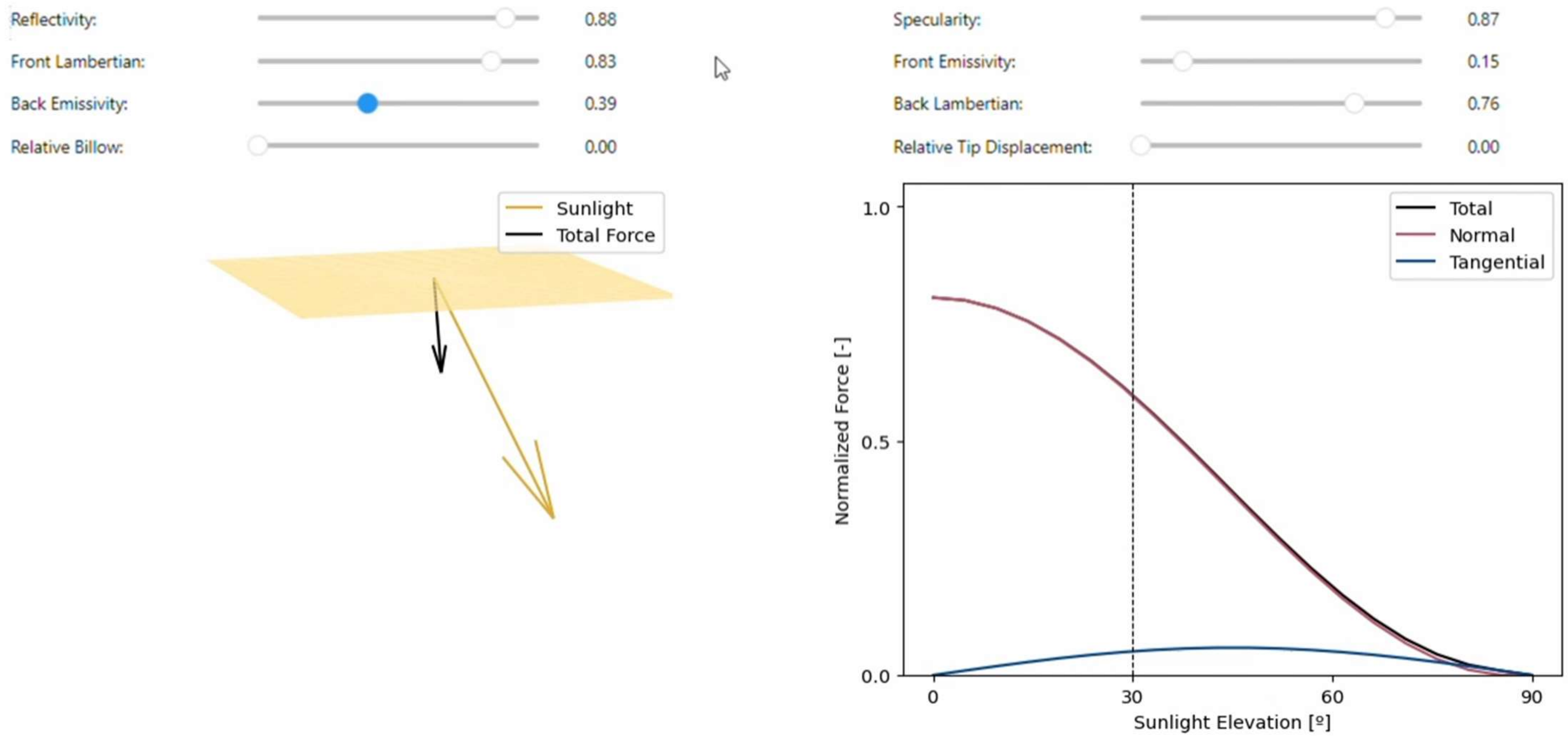


Constant Random Value Uncertainties



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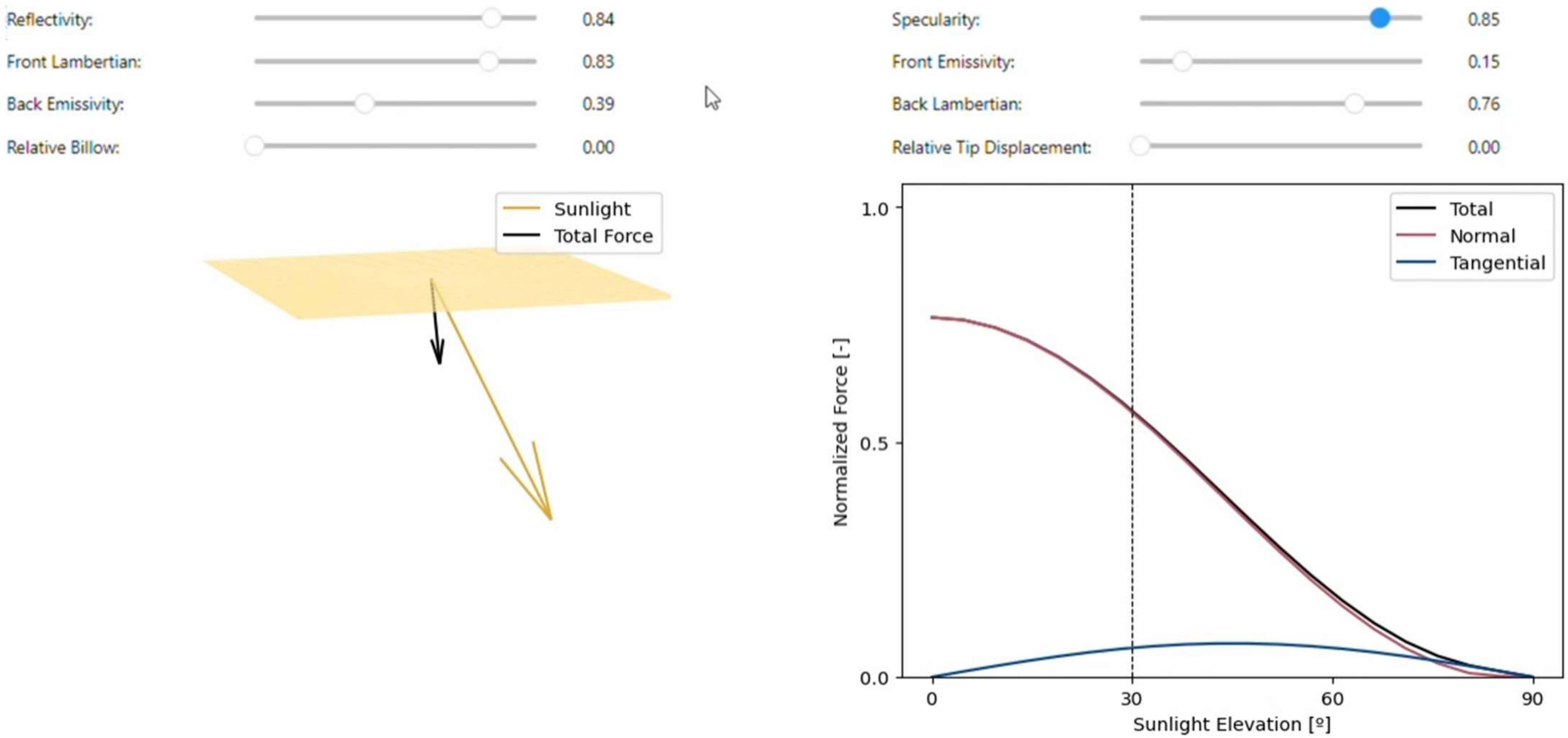

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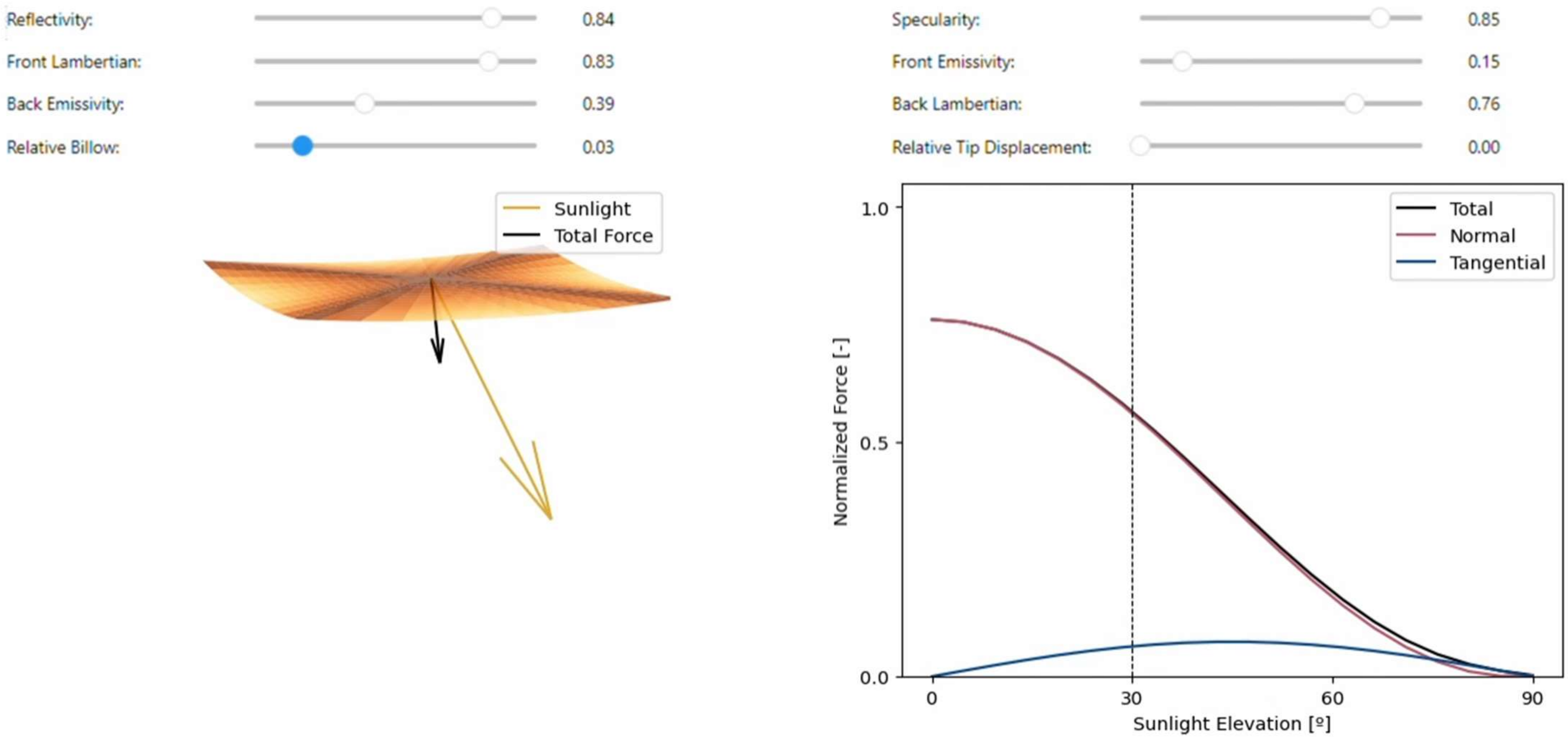


Constant Random Value Uncertainties

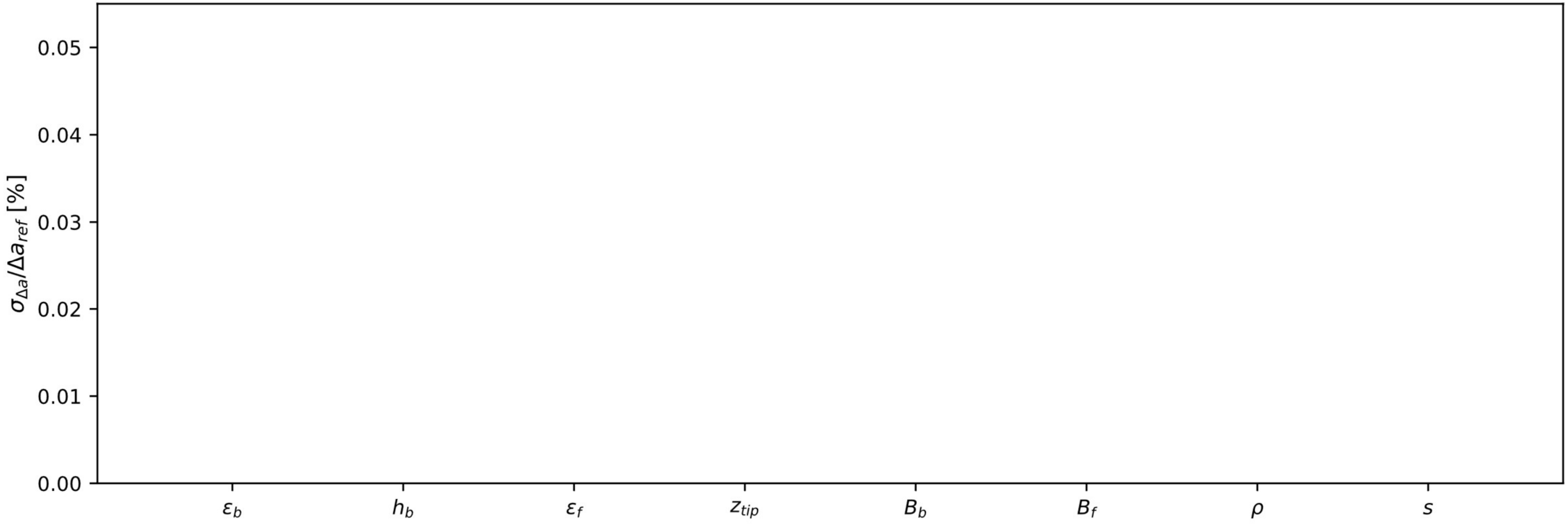
Optical Coefficients

ρ	0.91	$\pm$	0.005	s	0.89	$\pm$	<u>0.045</u>
B_f	0.79	$\pm$	<u>0.05</u>	ε_f	0.025	$\pm$	0.005
B_b	0.67	$\pm$	<u>0.05</u>	ε_b	0.27	$\pm$	0.005

NEA Scout Thrust and Torque Model, Heaton et al., 2017

Constant Random Value Uncertainties

Results for 1 day of propagation using Monte Carlo with 10,000 samples



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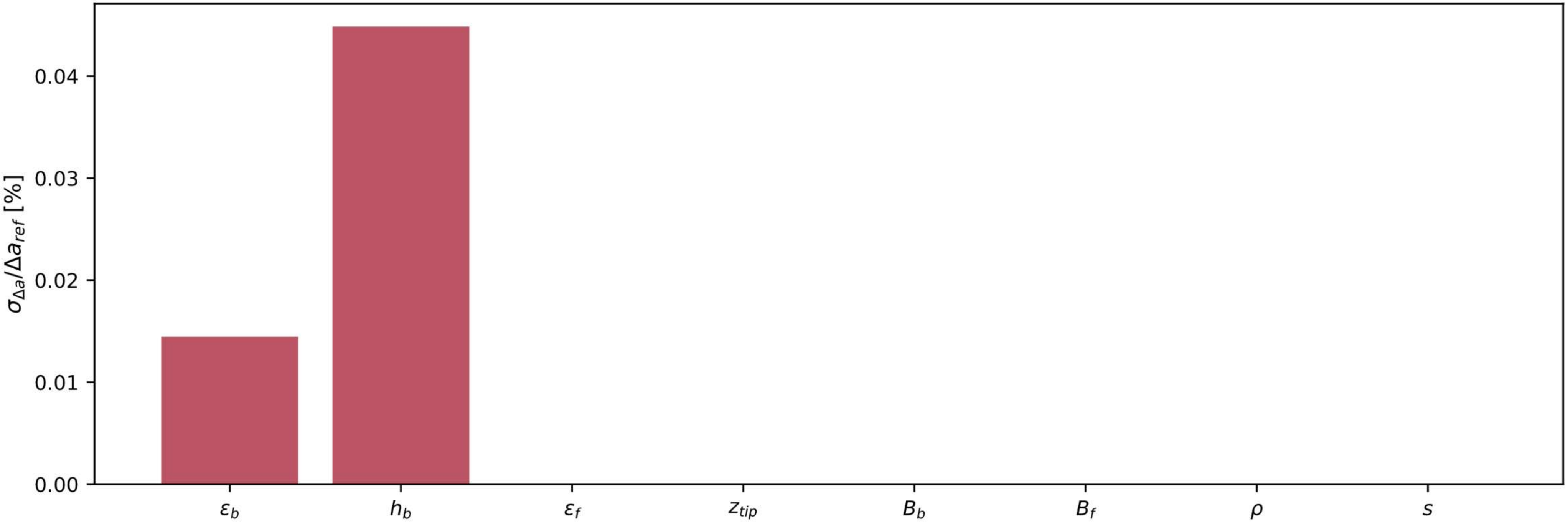

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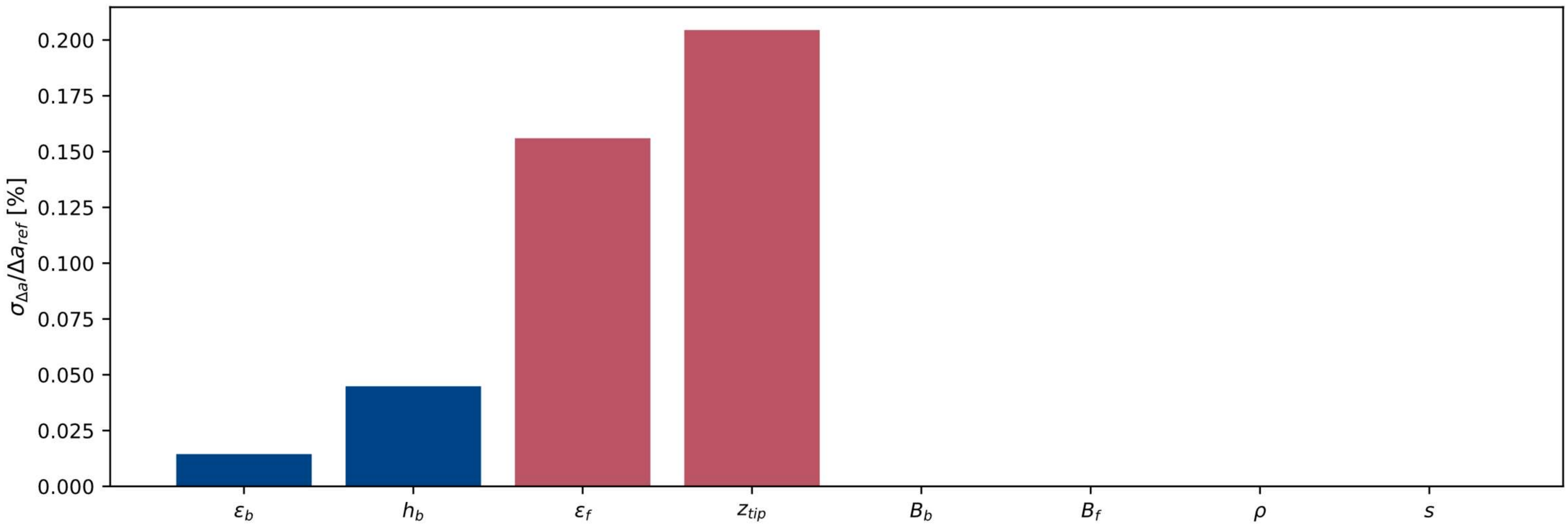

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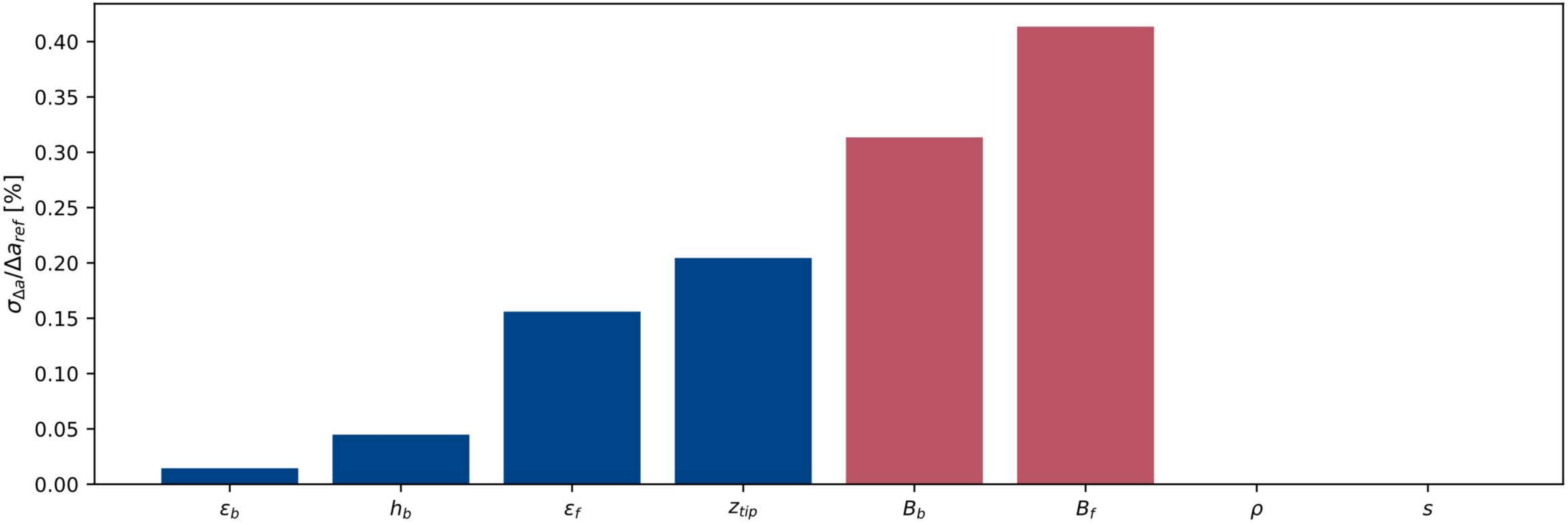

Constant Random Value Uncertainties

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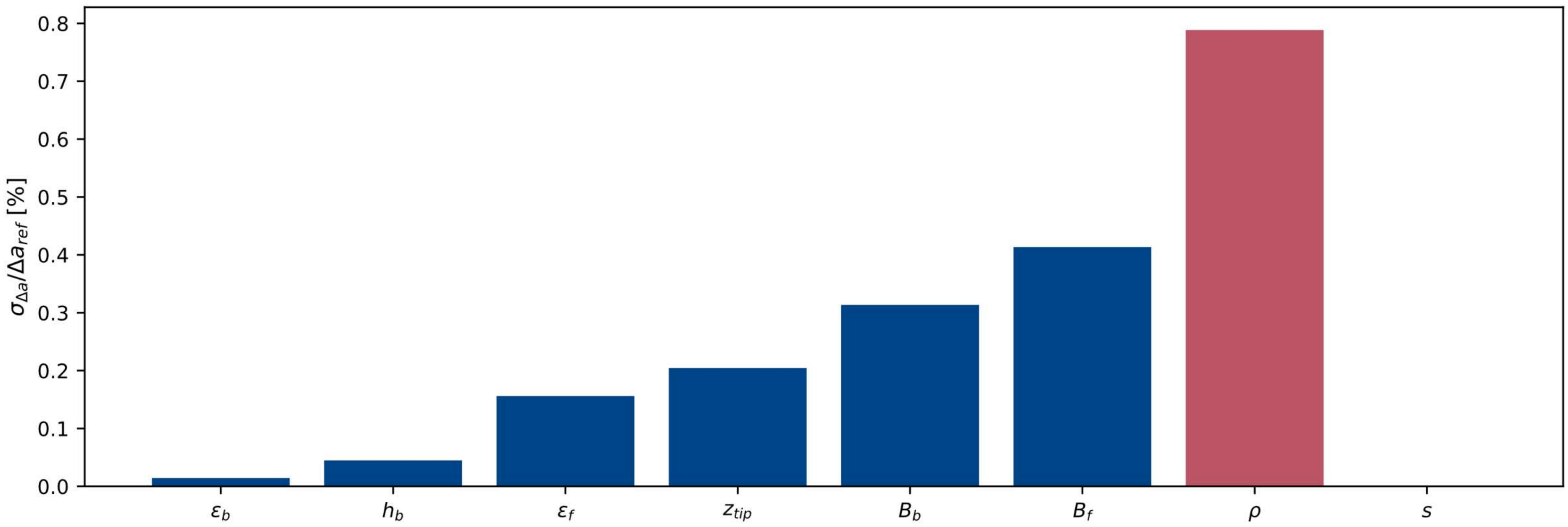
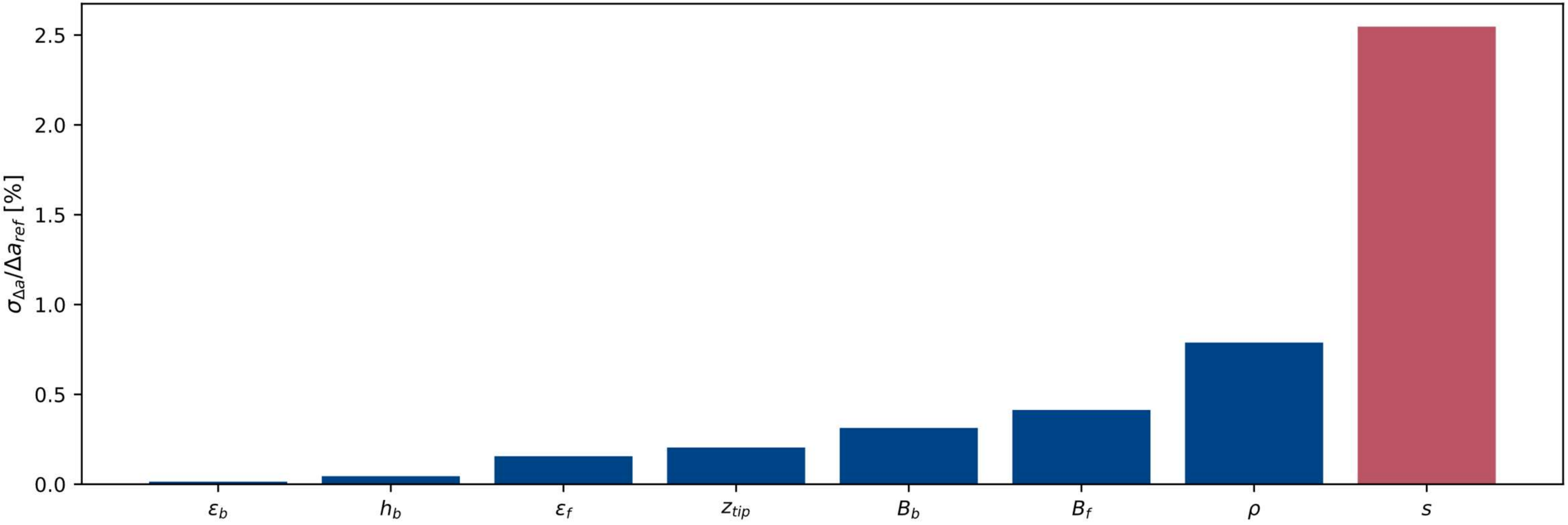


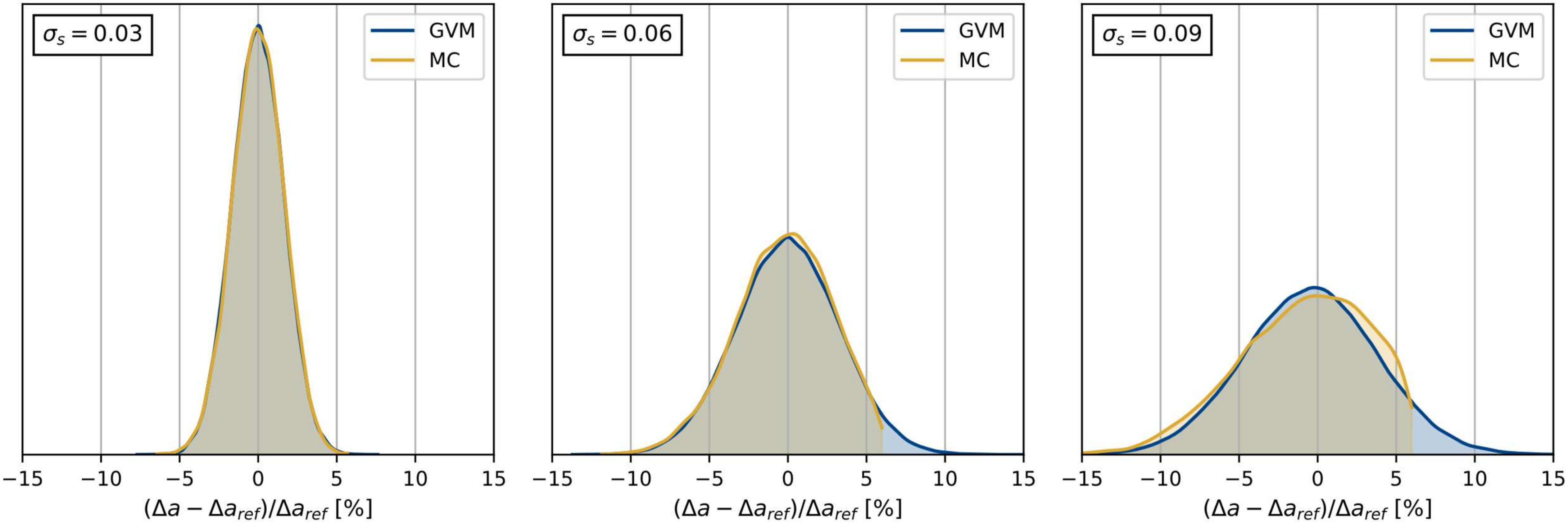
Constant Random Value Uncertainties

Results for 1 day of propagation using Monte Carlo with 10,000 samples



Constant Random Value Uncertainties

Results for 10 days of propagation



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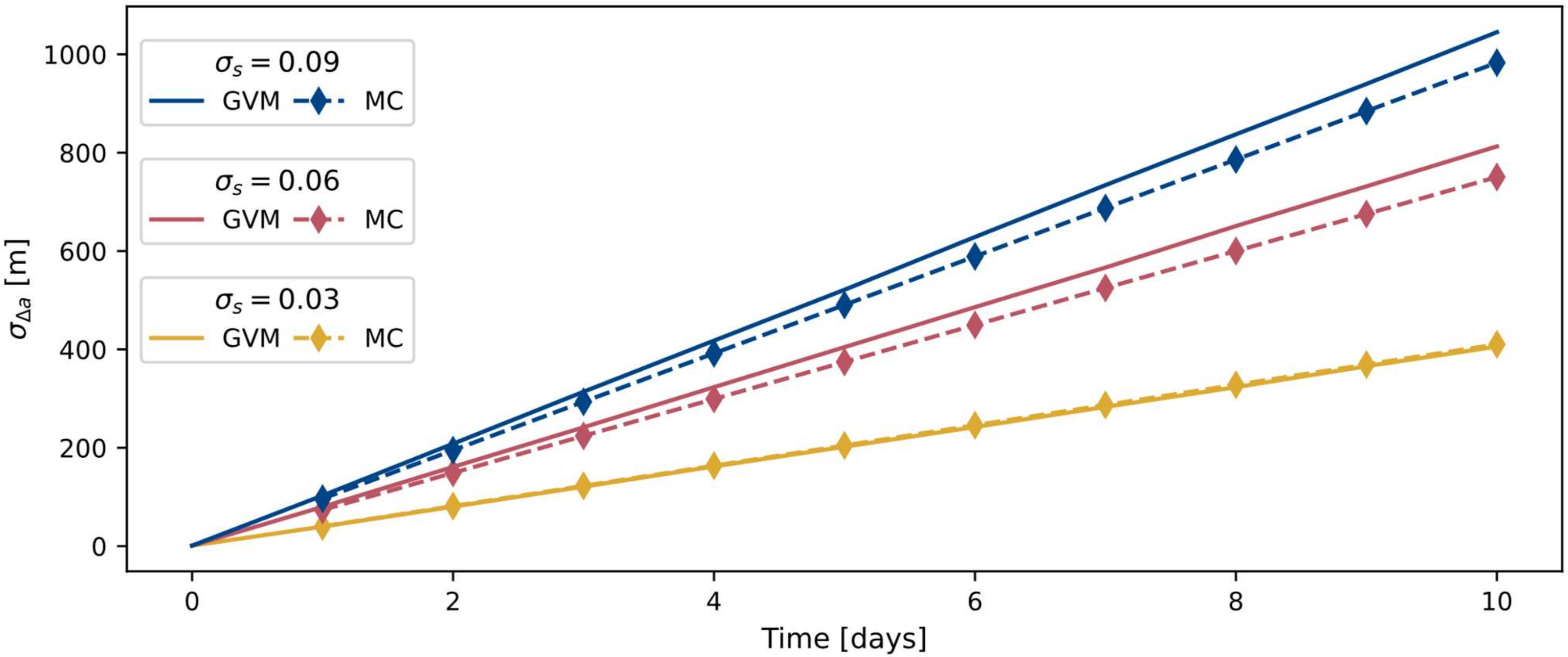
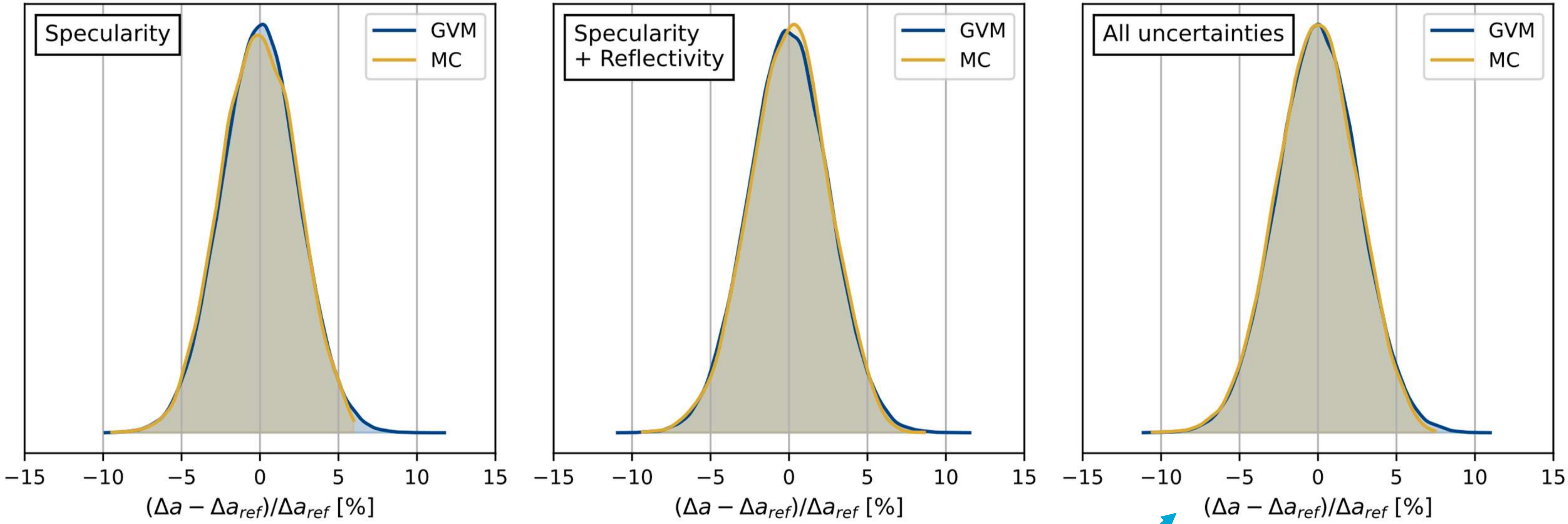
Constant Random Value Uncertainties



Constant Random Value Uncertainties

Results for 10 days of propagation



3σ uncertainty of ~7.5%

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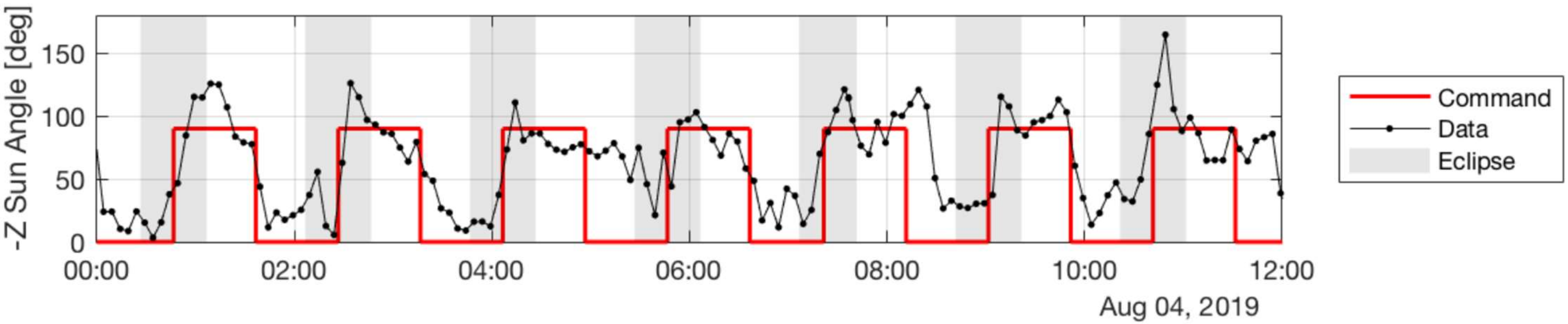
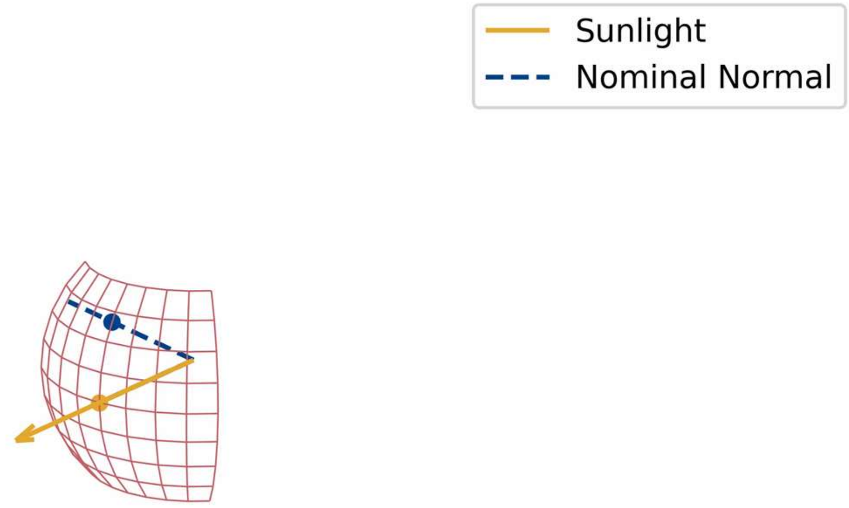
Stochastic Process Uncertainties



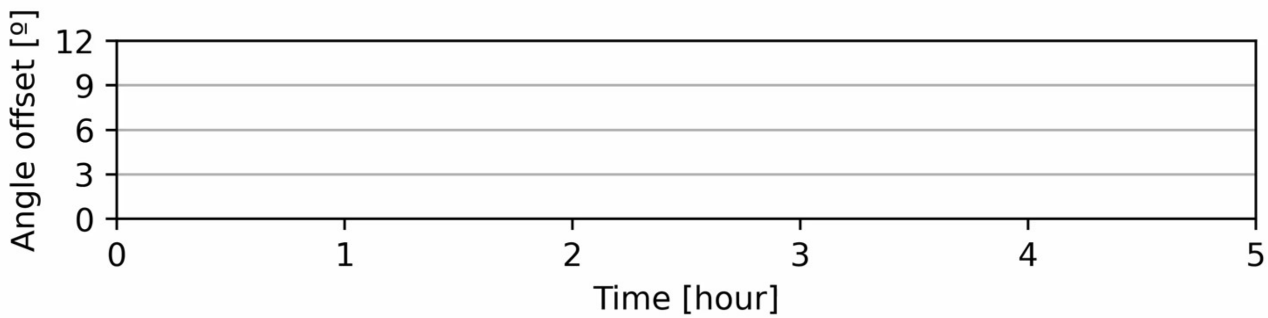
Orbit and Attitude Performance of the LightSail 2 Solar Sail Spacecraft, Mansell et al., 2020

Stochastic Process Uncertainties



Nominal Normal:

$\alpha = 30º$



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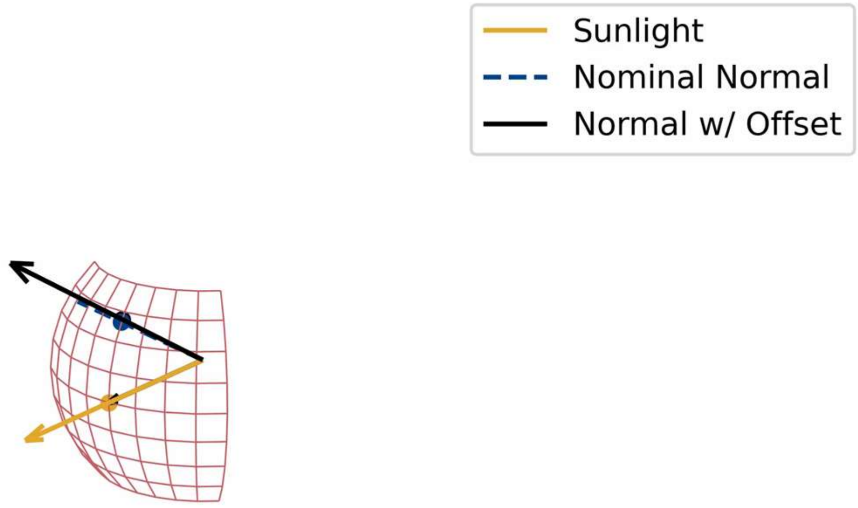
Stochastic Process Uncertainties



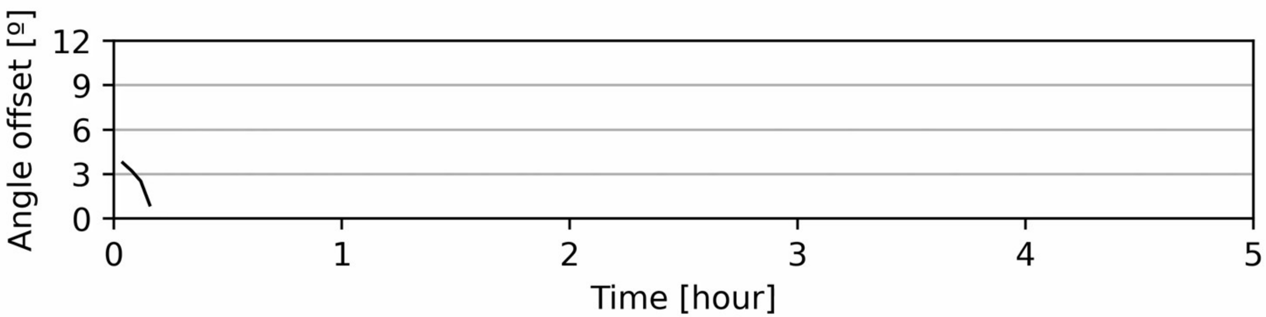
Nominal Normal:

$\alpha = 30º$

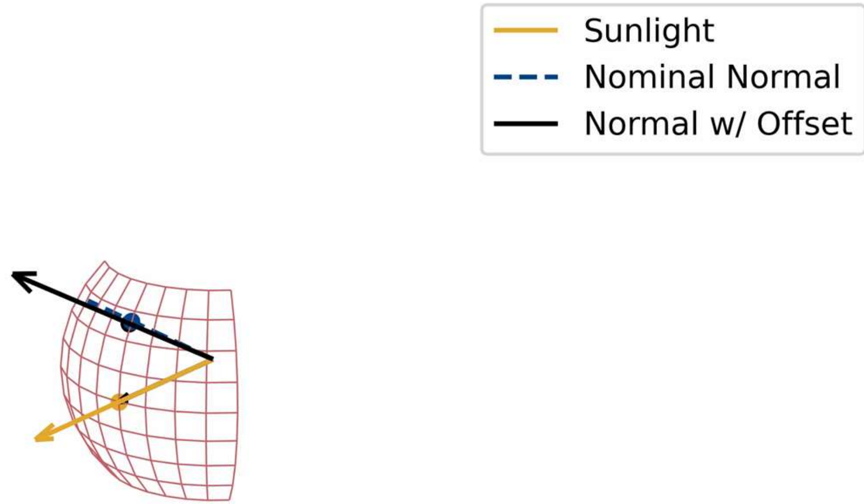
Offset:

$\sigma_{st} = 3º$

$\theta = 10^{-4}$



Stochastic Process Uncertainties



Nominal Normal:

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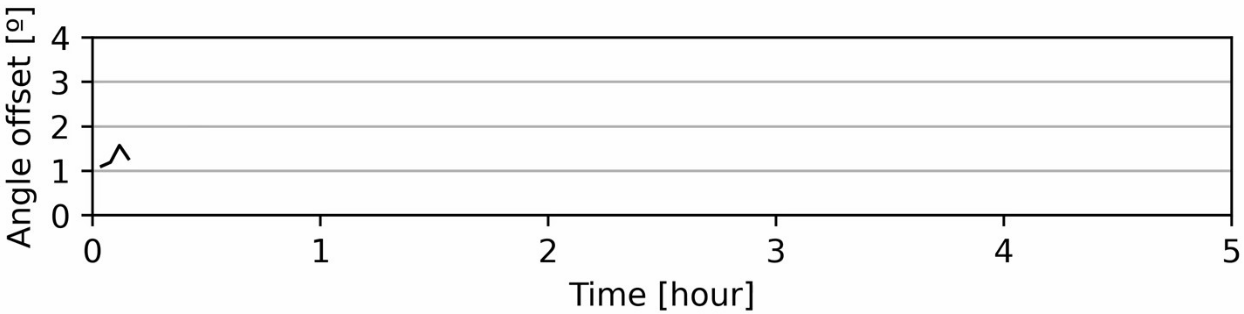
Offset:

$\sigma_{st} = 1º$

$\theta = 10^{-4}$



Stochastic Process Uncertainties

Nominal Normal:

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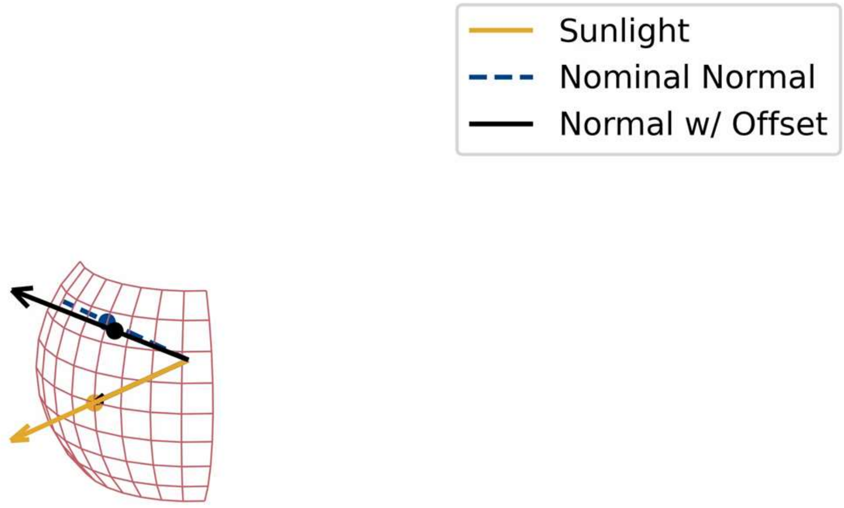
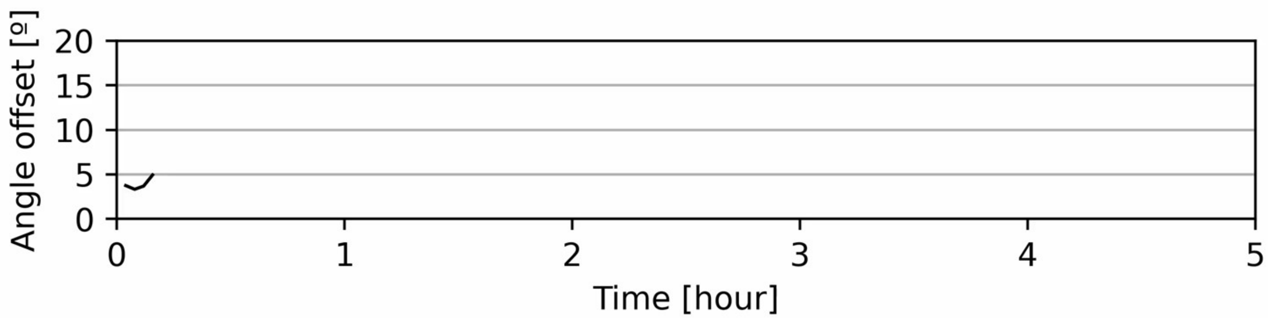
Offset:

$\sigma_{st} = 5º$

$\theta \quad = 10^{-4}$





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Stochastic Process Uncertainties

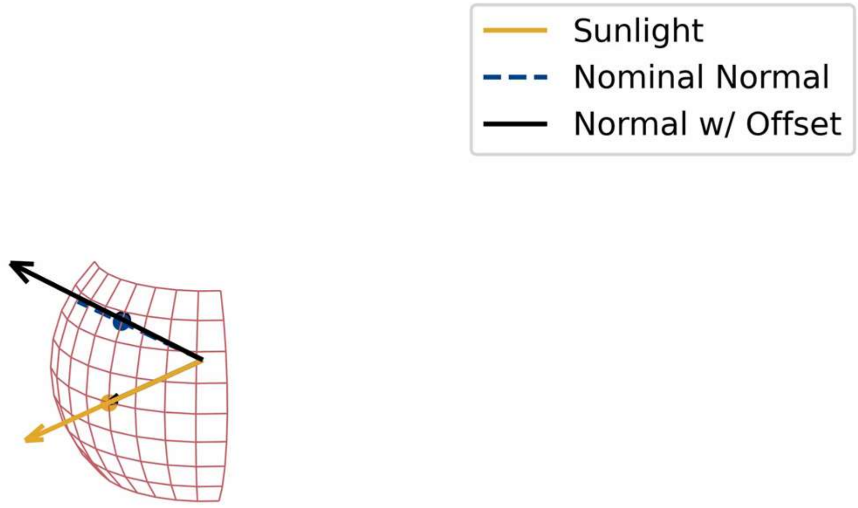
Nominal Normal:

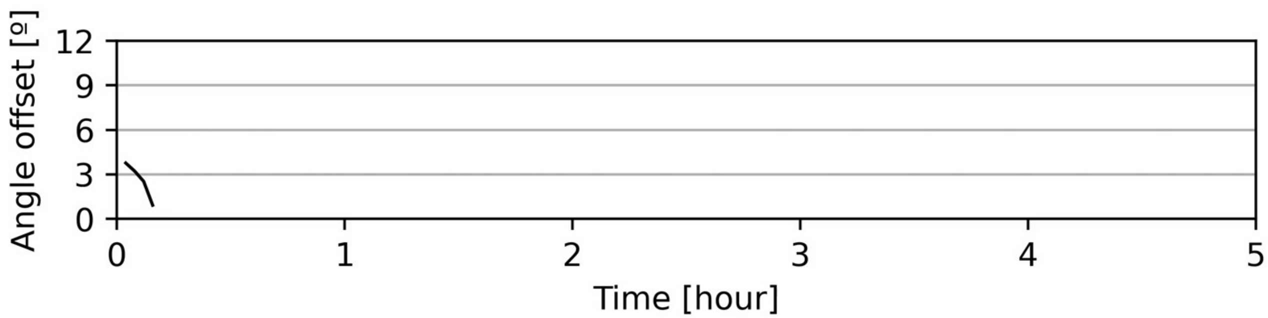
$\alpha = 30^{\circ}$

Offset:

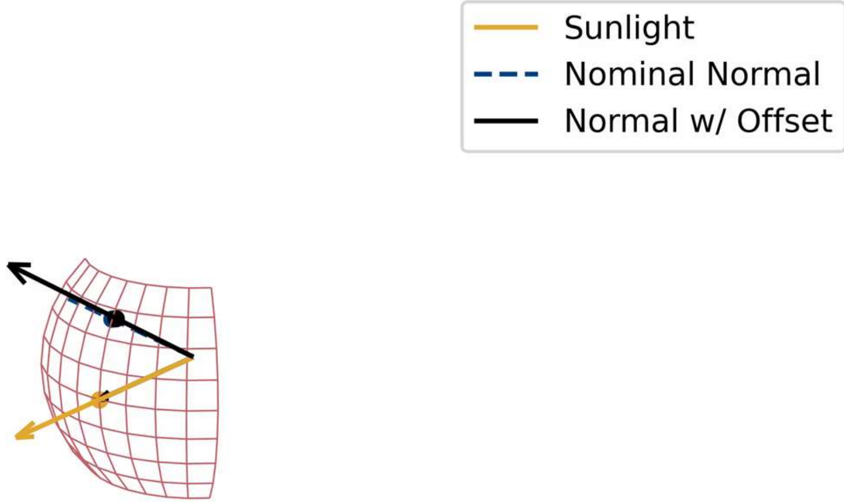
$\sigma_{st} = 3^{\circ}$

$\theta \quad = 10^{-4}$





Stochastic Process Uncertainties



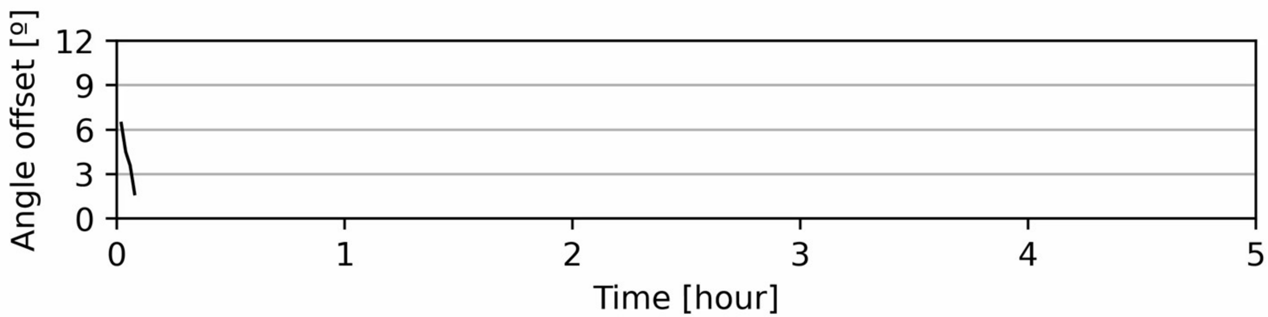
Nominal Normal:

$\alpha = 30º$

Offset:

$\sigma_{st} = 3º$

$\theta \quad = 10^{-2}$



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Stochastic Process Uncertainties

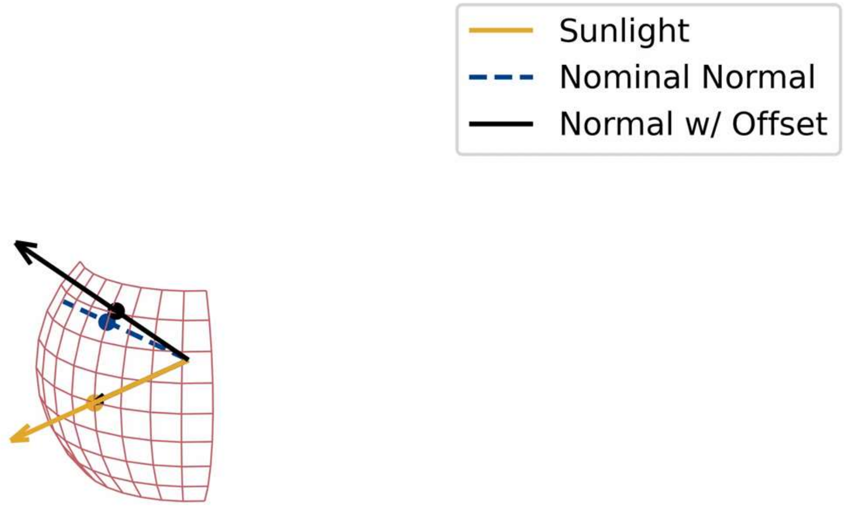
Nominal Normal:

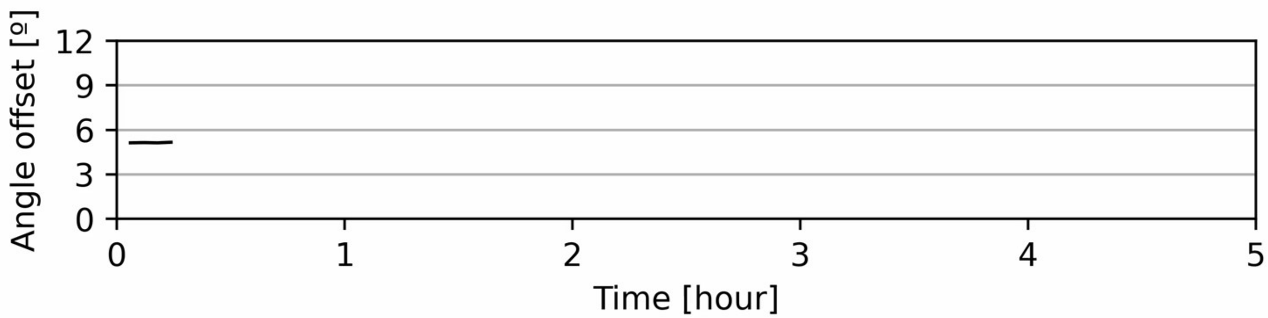
$\alpha = 30º$

Offset:

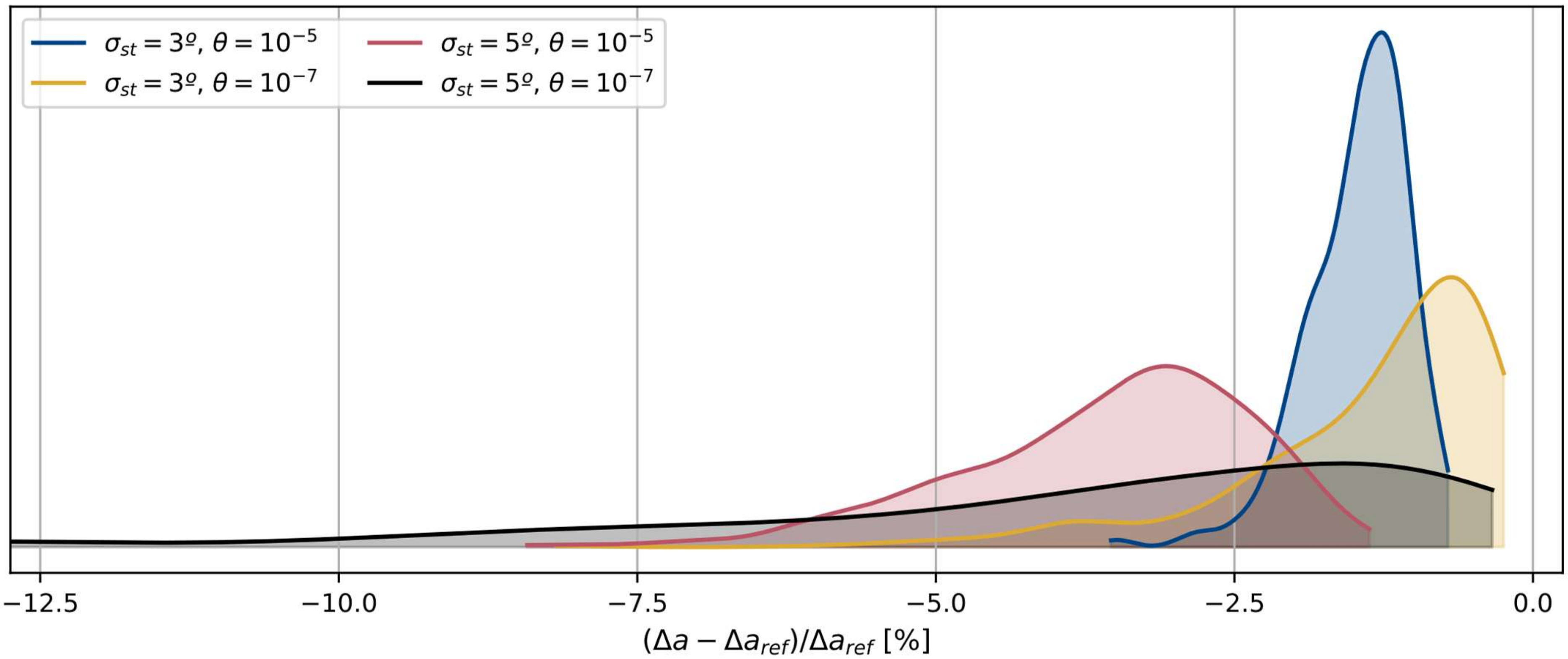
$\sigma_{st} = 3º$

$\theta \quad = 10^{-6}$





Stochastic Process Uncertainties



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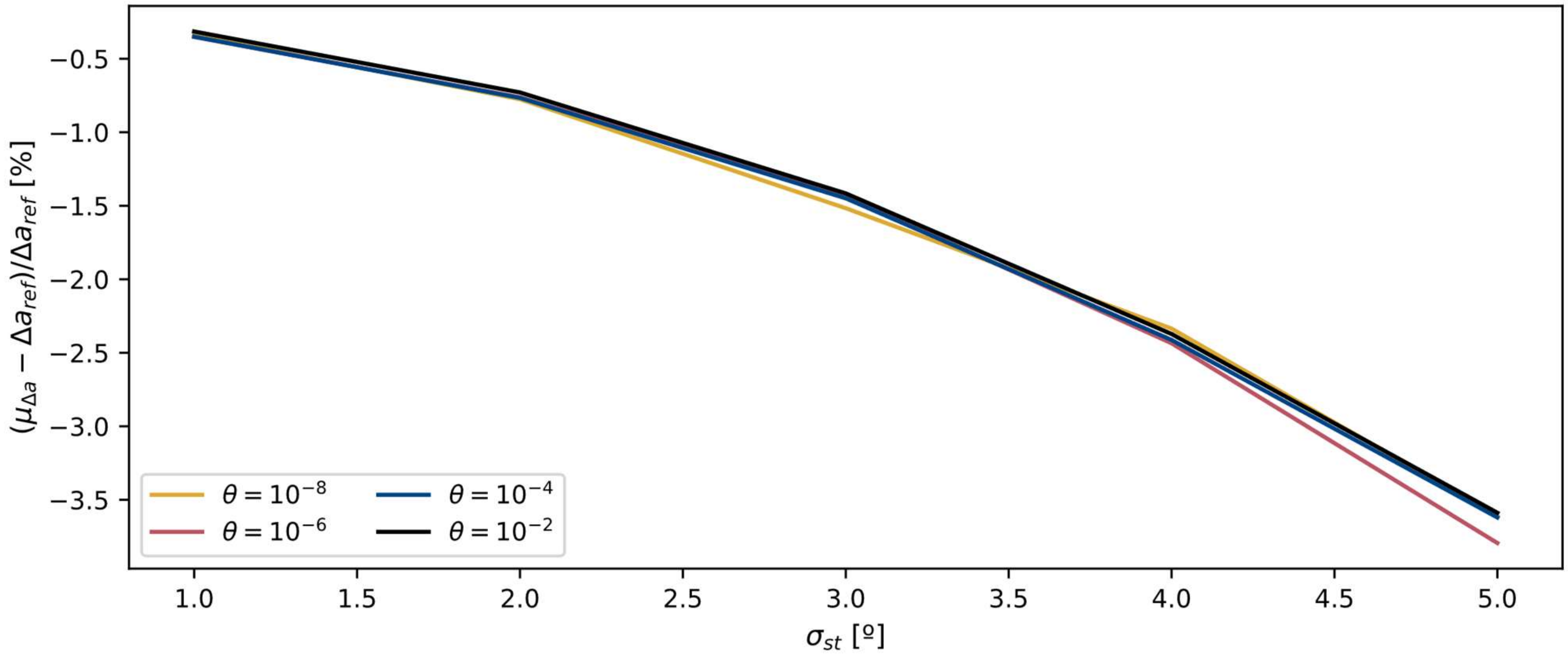
Stochastic Process Uncertainties



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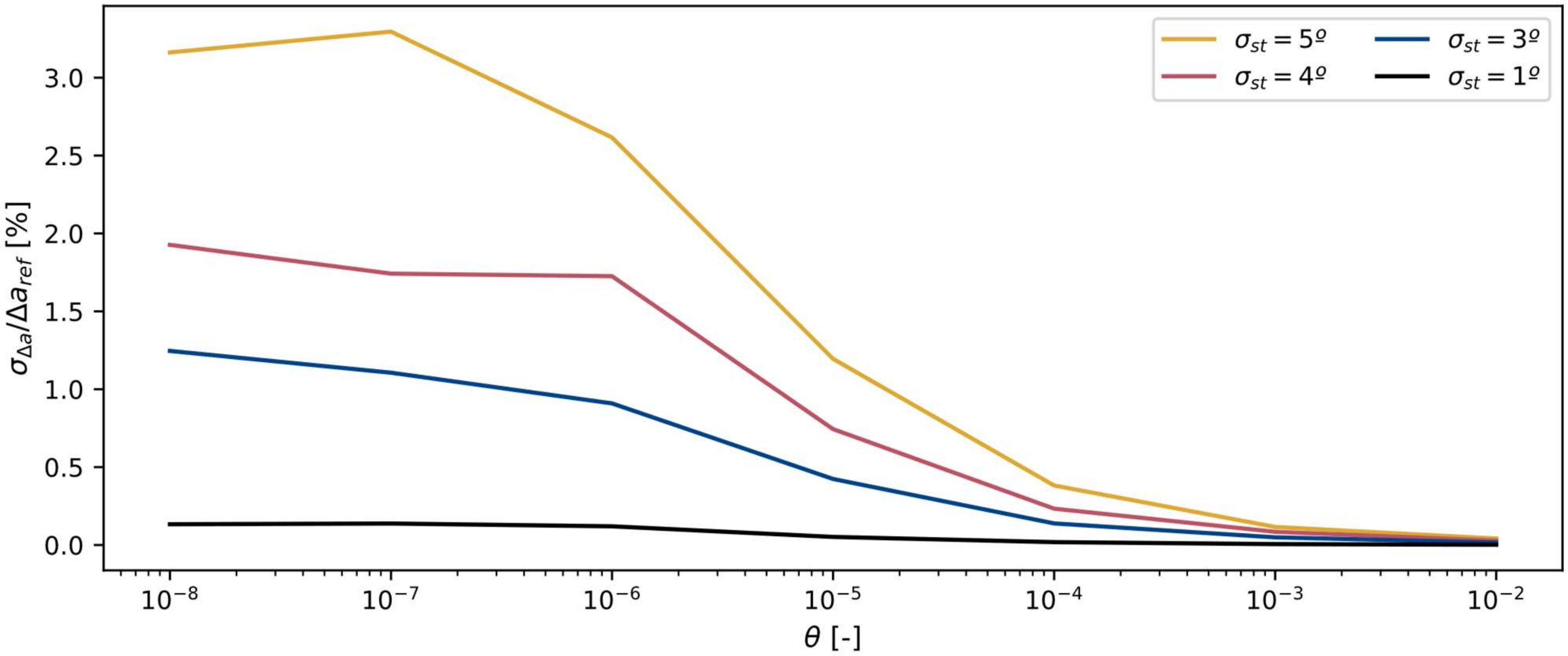
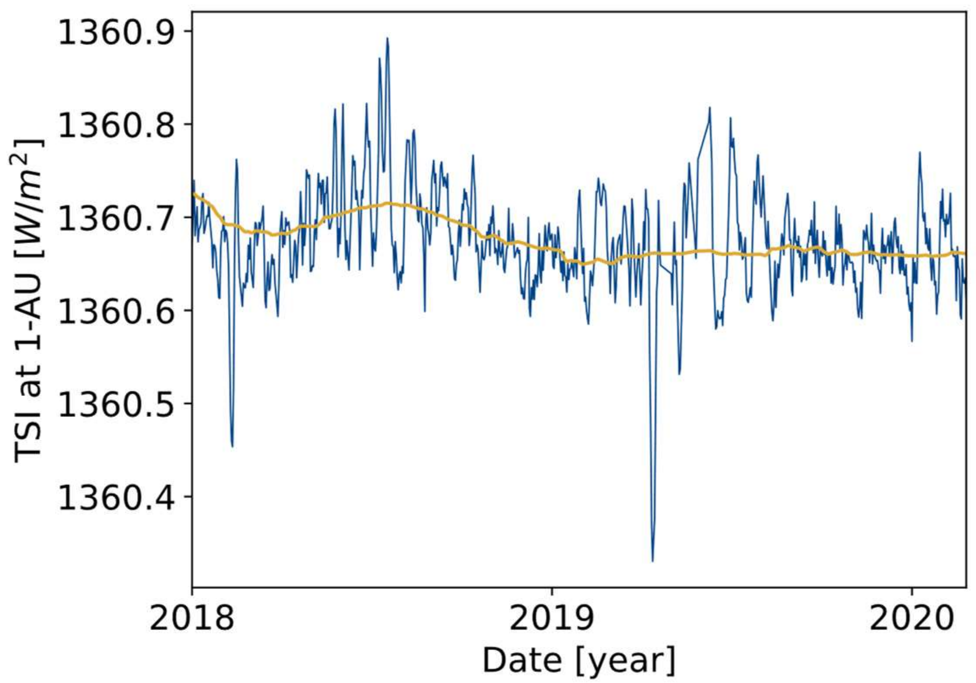
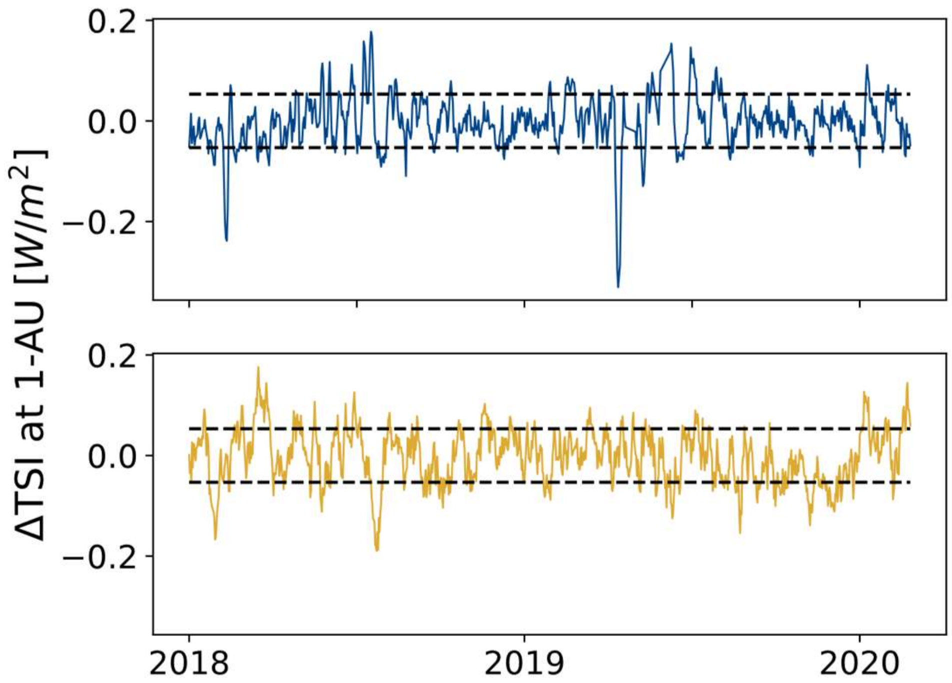
Stochastic Process Uncertainties



Ornstein-Uhlenbeck processes are versatile





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Conclusions

- Uncertainty in solar-sail optical coefficients and deformation has significant impacts on mission design
- Uncertainty in the specularity coefficient is the largest source of uncertainty
- The Gauss von Mises method is an accurate and performant alternative to Monte Carlo simulations
- A flexible method to model attitude uncertainty was demonstrated
- Attitude uncertainty affects mean and deviation of mission performance

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Uncertainty quantification for solar sails in the near-Earth environment

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