# A Stochastic Model for the Landing Dispersion of Hazard Detection and Avoidance Capable Flight Systems

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# Overview

- Motivation and Problem Statement
- Model Key Elements
- Application Example
- Conclusions

# Motivation / Problem Statement

- Landing site assessment as part of the mission engineering requires analysis of the risk of terrain related failures,
- State-of-art uses superposition of the landing ellipse on terrain maps to make probability estimates of an encounter with certain terrain features,
- In case of flight systems equipped with Hazard Detection & Avoidance (HDA) functionality the terrain features „drive“ the dispersion pattern.
- The current technique shall be supplemented by a suitable model which captures the key-functionalities of an HDA-subsystem.


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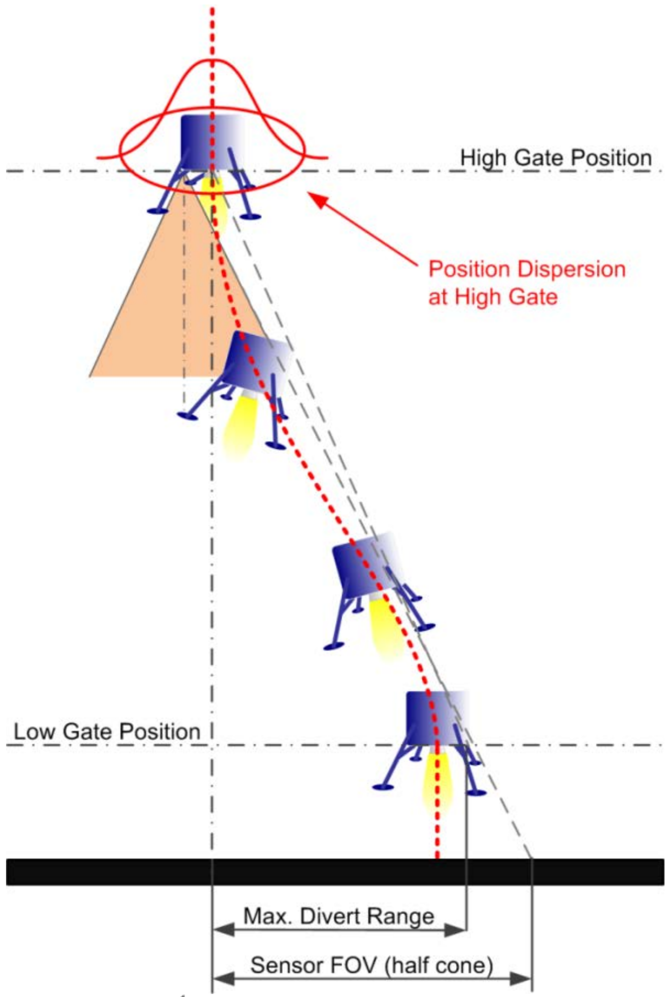
# Motivation / Problem Statement




Grid decomposition of landing area with „per grid-cell“ initial likelihood $\mathbf{P_0}$ ($\mathbf{p_0}$ in a vector notation) to land in that area.

Need to propagate initial dispersion pattern to post HDA maneuver pattern.

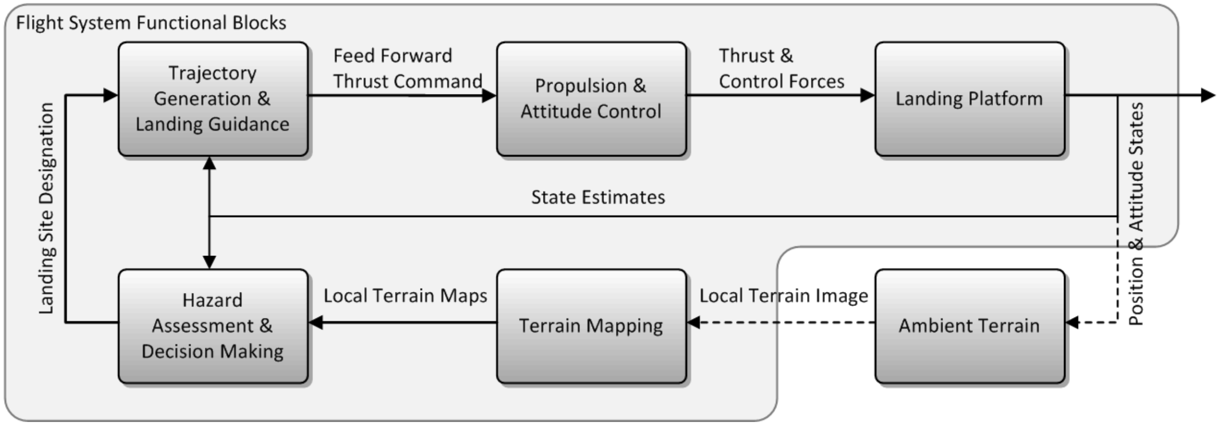
**Idea**: use (Semi-) Marcov chains

$$\mathbf{p_1} = \mathbf{T} \cdot \mathbf{p_0}$$

Need to find a transition matrix **T**, which captures the flight system technical properties!

# Math. Model: What must be modeled (at least)…

- Macroscopic dispersion pattern determined by the site selection of onboard entity,
- HDA subsystem key functionalities considered:
  - *Terrain Mapping* (sensor FOV, sensor errors),
  - *Trajectory Generation* (considering $T_{go}$, propulsion constraints)
  - *Hazard Assessment & Decision-Making* (Cost or Score Function, error propagation into the divert-decision)
- Inner loops of the control cascade not considered, thus the „fine dispersion“ around the commanded trajectory is neglected.

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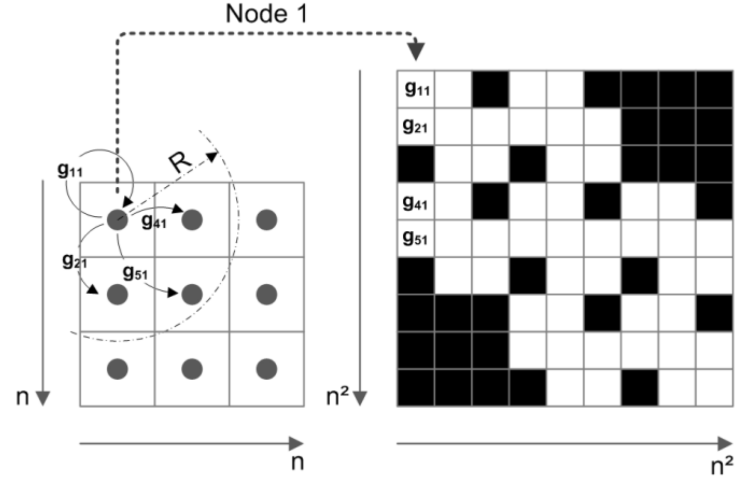
# Math. Model: Field of View and Divert Capability

- The landing zone is represented by gridded data products such as a DTM, providing maps of the size $n \times n$,
- Visibility and accessibility of a particular position on the map from a given position is modeled using a graph,
- The graph connects all nodes within field of view or divert range.
- An $n^2 \times n^2$ adjacency matrices store the visibility and divert range capabilities.
- The adjacency matrix already defines the size and structure of the transition matrix.

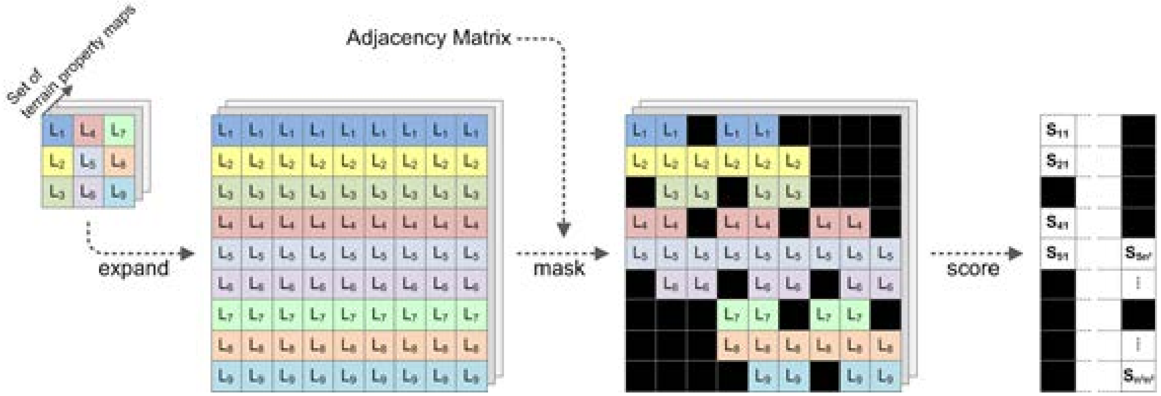
| | Albuquerque | Arches NP | Big Bend NP | Bryce Canyon NP | Capitol Reef | Death Valley |
|---|---|---|---|---|---|---|
| Albuquerque | 0 | | | | | |
| Arches NP | 395 | 0 | | | | |
| Big Bend NP | 630 | 960 | 0 | | | |
| Bryce Canyon NP | 595 | 285 | 1205 | 0 | | |
| Capitol Reef | 495 | 155 | 1115 | 110 | 0 | |
| Death Valley | 720 | 605 | 1265 | 420 | 525 | 0 |
| Denver | 450 | 365 | 865 | 570 | 450 | 890 |
| El Paso | 265 | 670 | 350 | 855 | 740 | 915 |
| Escalante | 560 | 245 | 1175 | 45 | 65 | 445 |
| Flagstaff | 322 | 335 | 925 | 300 | 470 | 395 |



# Math. Model: Local Terrain Property and Score Maps

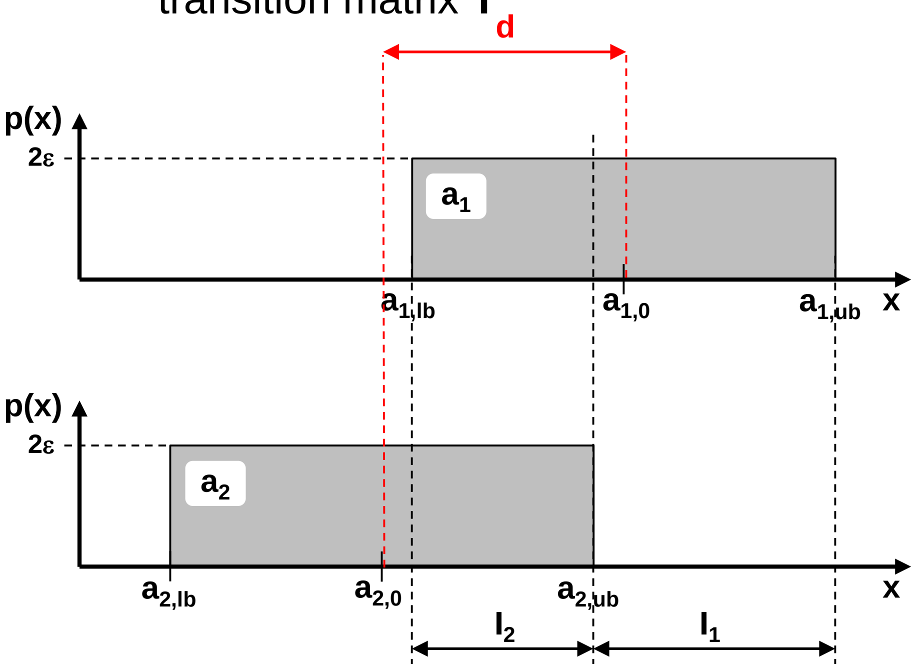
- *Local Terrain Maps* – as imaged by the onboard sensors – are obtained by „masking“ the terrain property maps (slope, roughness, shadow, …) with the FOV adjacency matrix.
- Each column of a $n^2 \times n^2$ terrain matrix contains a local map seen from the associated position.
- The onboard HDA decision-making calculates score or cost values for alternative landing spots:
    - Simple example:

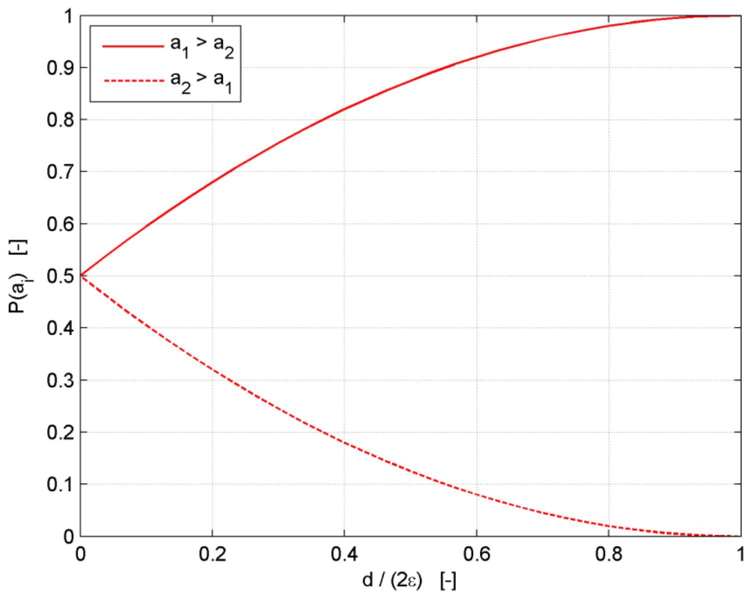
      Score S = f(slope L, roughness R, shadow S) = $1-(L+R+S)/(L_{max}+R_{max}+S_{max})$



# Math. Model: Decision Making under Uncertainty

- In the presence of errors the score values become random numbers,
- Relevant for HDA: what is the likelihood $P(a_2 > a_1)$ that $a_2$ excceds $a_1$ although not representing the true best alternative?
- Probabilities assigned to all score values of the Score matrix, which yields the transition matrix **T**




$$P(a_1 > a_2) = P(a_1 \in l_1) + P(a_1 \in l_2) \cdot P(a_2 \notin l_2) + P(a_1 \in l_2) \cdot P(a_2 \in l_2) \cdot P(a_1 > a_2)$$

$$P(a_2 > a_1) = P(a_1 \in l_2) \cdot P(a_2 \in l_2) \cdot P(a_1 > a_2)$$

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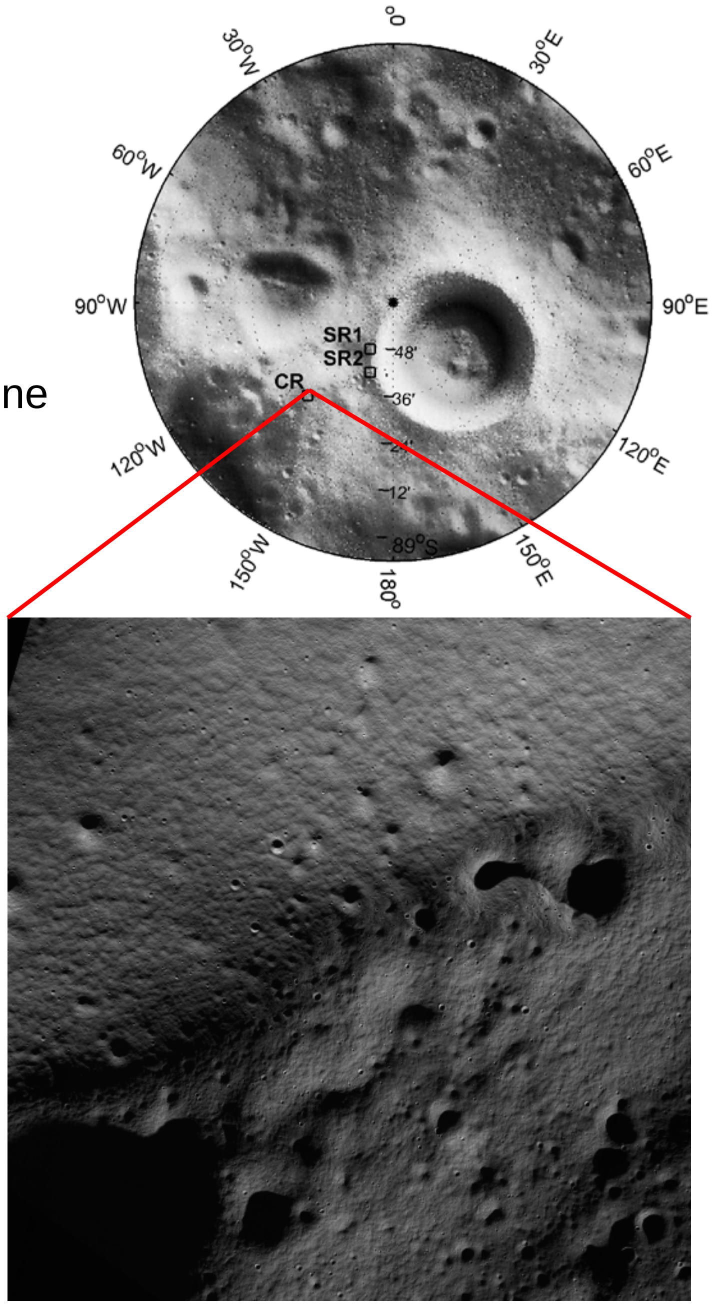
# Application Example

**A robotic lunar lander**

- Flight system (not exactly ESA LL): capable of one HDA maneuver, performances: Table below
- Landing Site: Lunar South Pole »Connecting Ridge«, DTM[1] from stereo images 5×5km² @ 2m/px

| Parameter | Value |
|---|---|
| Nominal Landing Site Coordinates, Lat/Lon [°] | 89.4S / 137.4W |
| Along Track Error (3σ) at High Gate [m] | 360 |
| Cross Track Error (3σ) at High Gate [m] | 240 |
| Ground Track Azimuth [°] | 180 |
| Divert Distance Capability, omnidirectional [m] | 170 (from 1000m) |
| LIDAR Field of View [°], resolution [px] | 20, 700x700 |
| Camera FOV [°], res. [px] | 70, 1024x1024 |
| Slope Determination Error [°] | 2.5 |
| Roughness Determination Error [m] | 0.35 |
| Illumination Determination [bit grayscale] | 10 |

[1] F. Scholten, et.al, NAC_DTM_ESALL_CR1, Connecting Ridge Potential Landing Site for ESA Lunar Lander, [http://wms.lroc.asu.edu/lroc/view_rdr/NAC_DTM_ESALL_CR1], 2012

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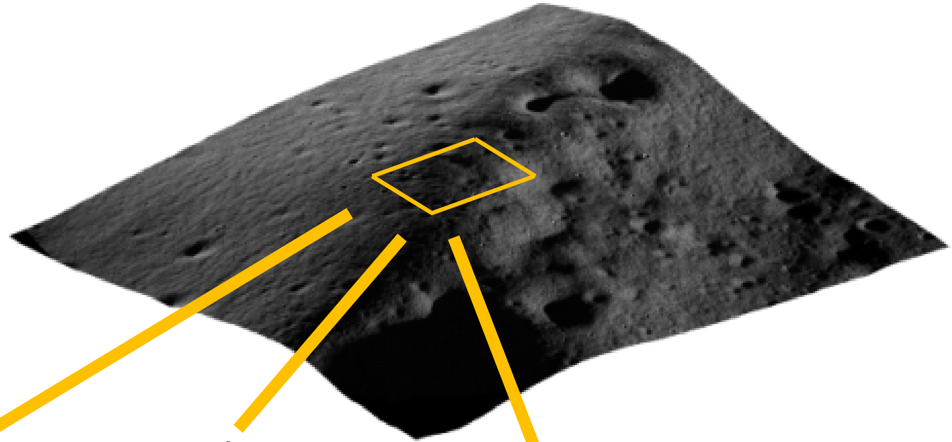
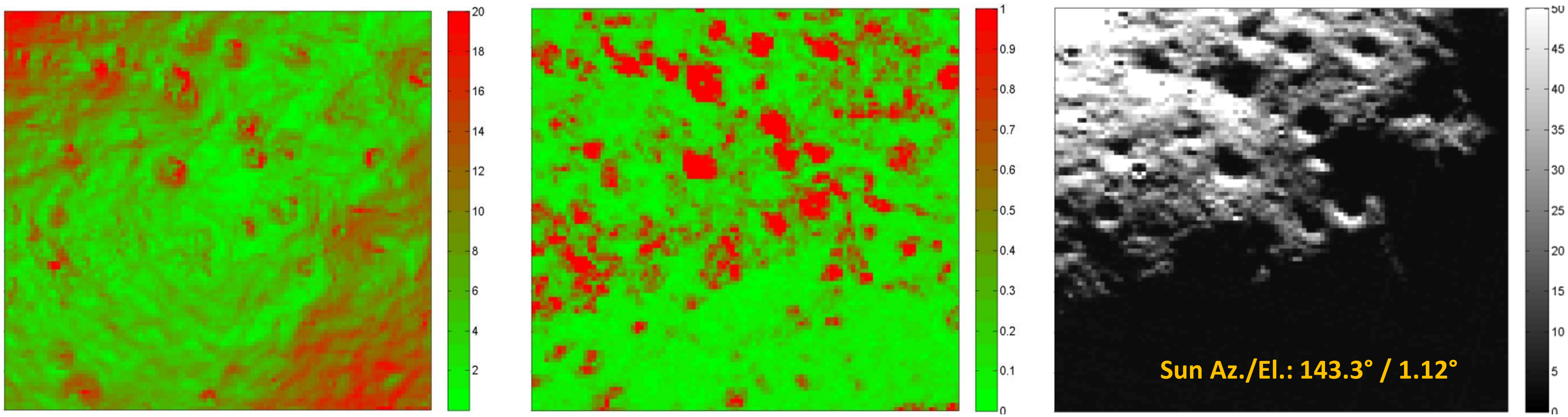
# Application Example

- High resolution DTM data is used to derive terrain property data.
- Used to „mimic“ the onboard sensor based mapping.
- Landing zone is 1×1km²



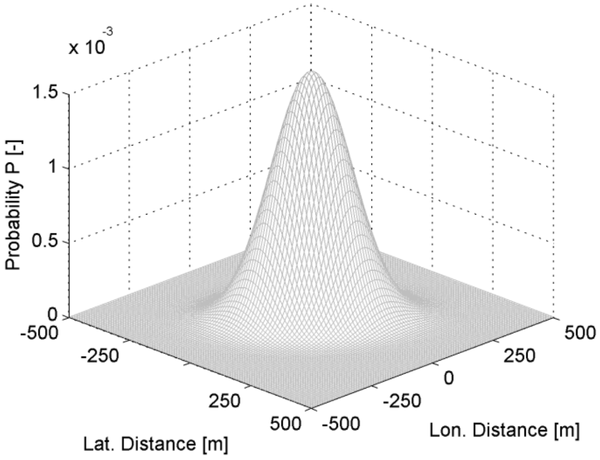



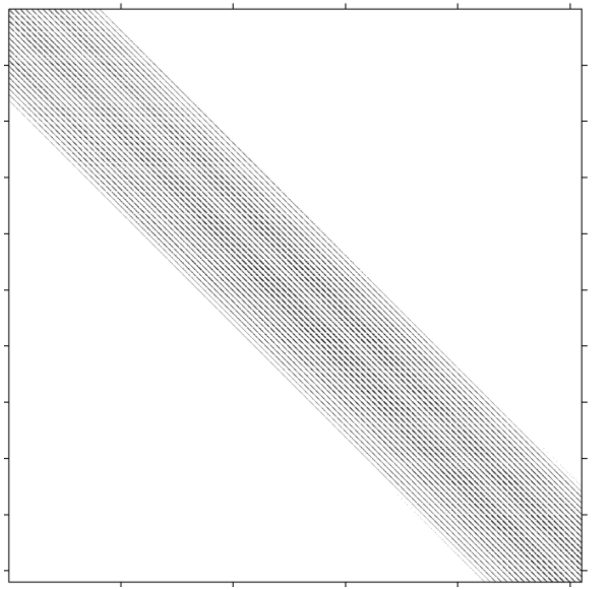
# Application Example

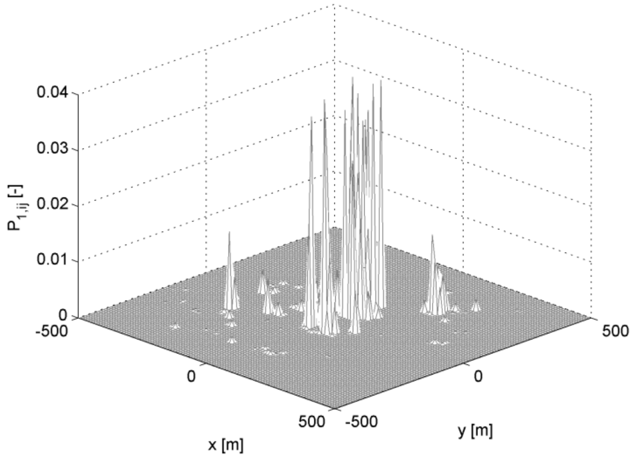
Initial dispersion $\mathbf{P}_{0}$,

in a vector notation: $\mathbf{p}_0$ → Transition Matrix **T** → Post HDA-dispersion $\mathbf{p}_{1}$,

back into matrix notation $\mathbf{P}_1$



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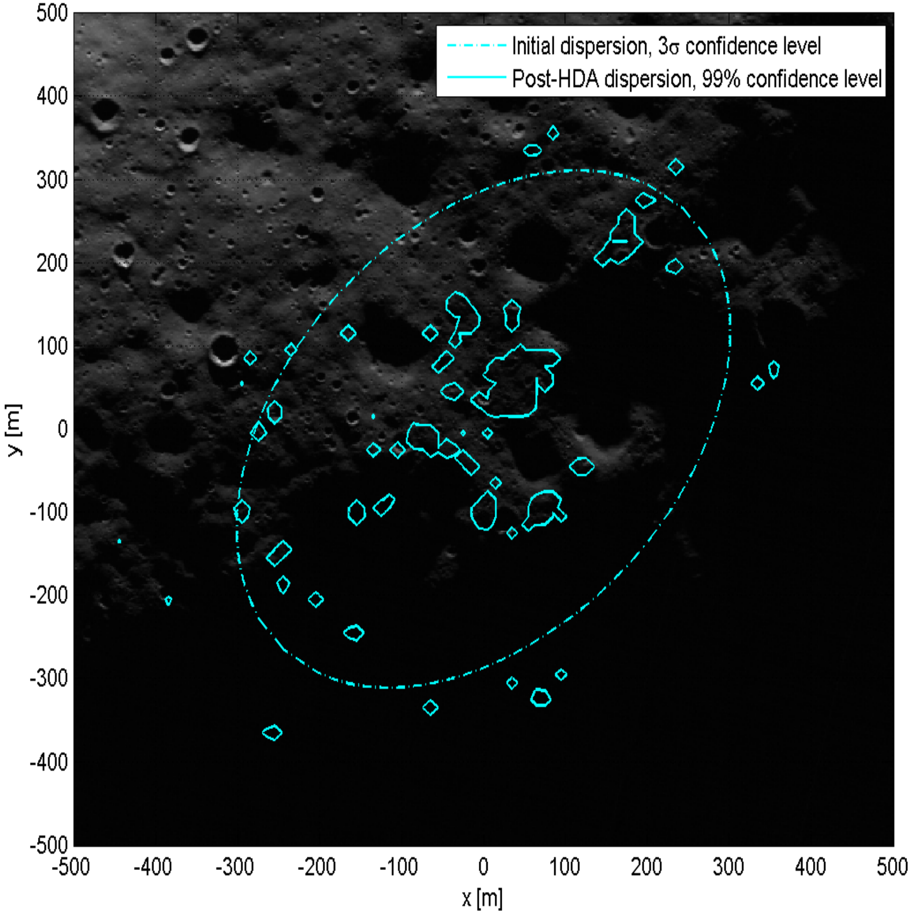
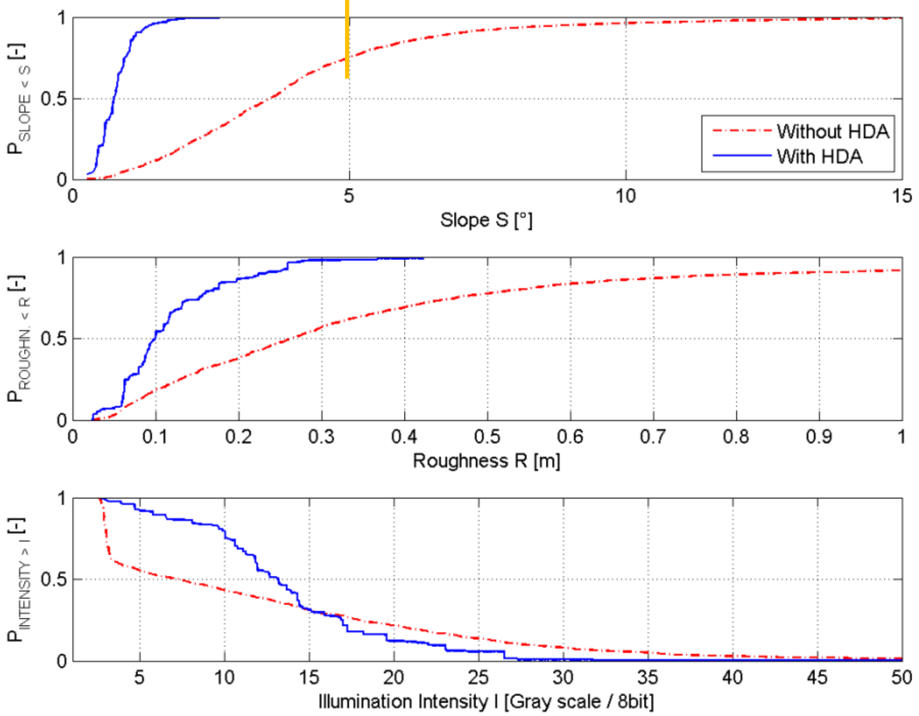
# Application Example

Probability to land on slope less than 5°:
74.9% w/o HDA
99.9% with HDA

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# Conclusions

- A stochastic model to predict landing dispersion pattern for HDA-capable flight systems has been developed,
  - It integrates key functional elements of a HDA architecture,
  - Nevertheless, the model is low fidelity, but calculates dispersion pattern on “one shot”,
  - Numerical efficient if implemented correctly (this example: ~5min on an PC, using MATLAB).

- The use of this method is intended in:
  - an early mission study phase to analyze mission requirements or system baselines and their effect on the risk of terrain related failure.
  - later study phases – after being validated by or calibrated against high-fidelity simulations – as efficient tool to estimate landing success probabilities.

- This talk omitted most of the mathematical details and its numerical implementation, but the method is peer-reviewed and published:
  - Witte, L., Stochastic Modeling of a Hazard Detection and Avoidance Maneuver – The Planetary Landing Case, Reliability and System Safety 119 (2013)

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