TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry

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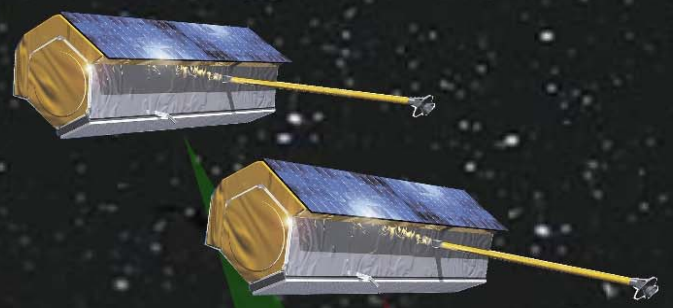
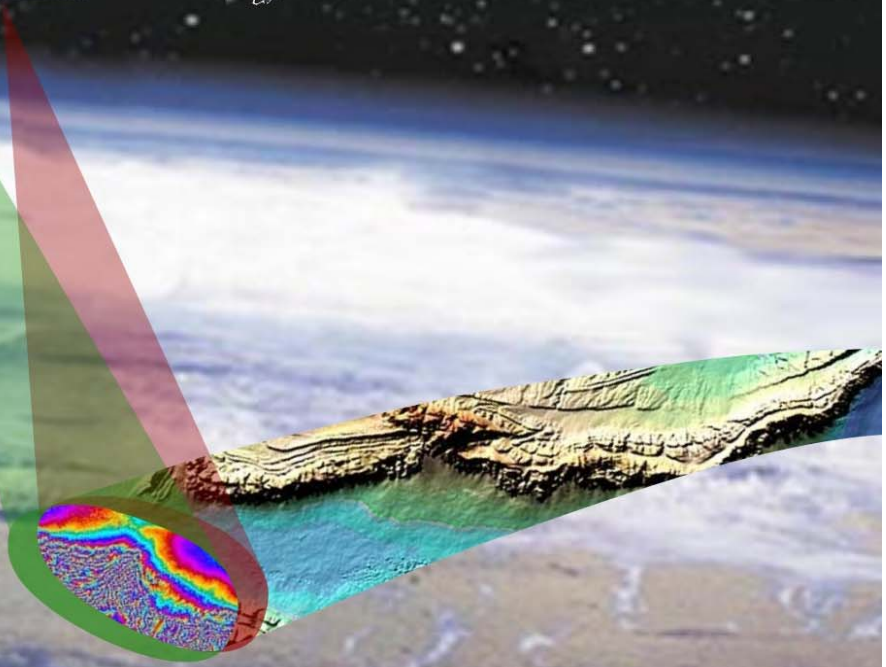
TanDEM-X Mission Goals

DLR EADS ASTRIUM infoterra an astrium company

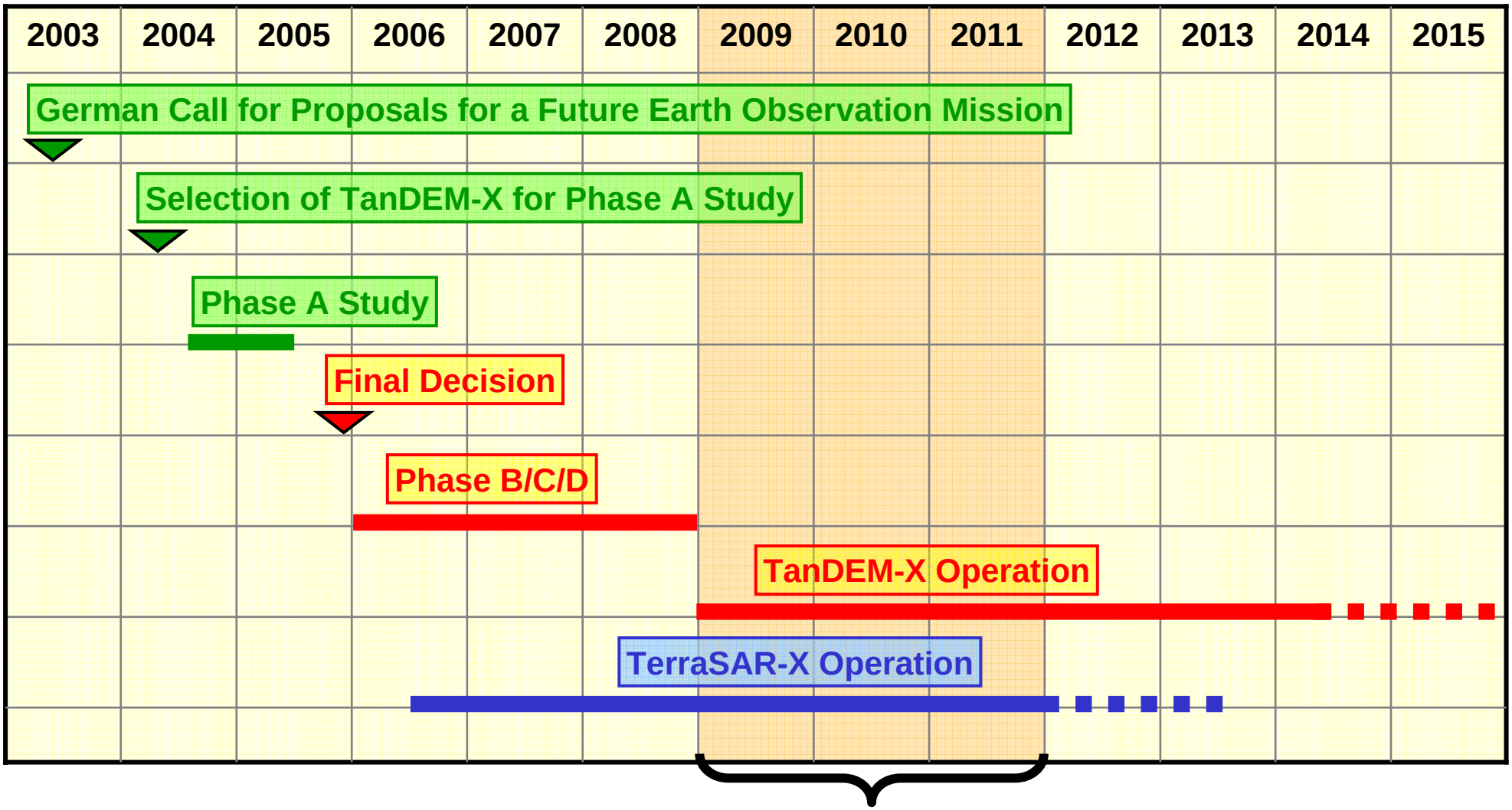


- acquistion of a global DEM according to HRTI-3 standard
- generation of local DEMs with HRTI-4 like quality
- demonstration of innovative bistatic imaging techniques and applications



TerraSAR add-on for Digital Elevation Measurements

TanDEM-X Timeline

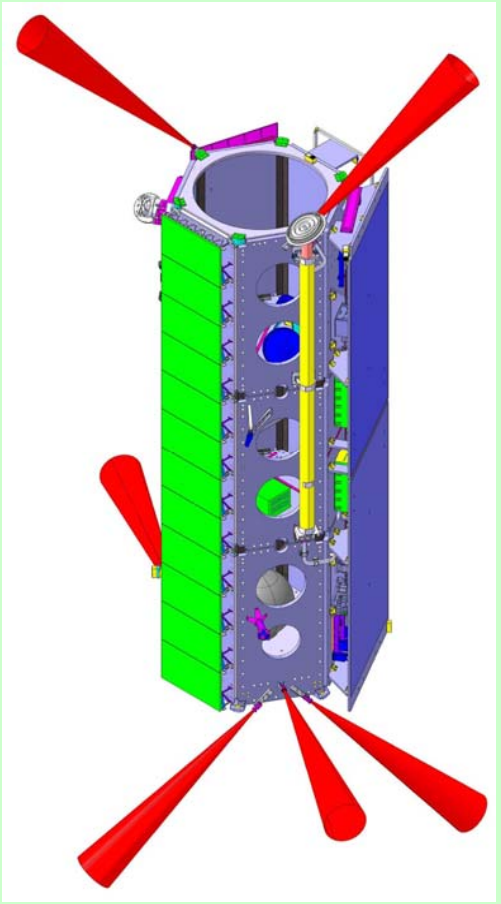


All TanDEM-X mission objectives are achieved within 3 years of joint operation

Investigations in Phase A Study

Derivation of User and Mission Requirements:

- **Organisation of Science Team (currently 97 members)**
- **Scientific and Commercial User Survey**
- **Product Definition (DEM, radar data products, …)**
- **Performance Analyses (DEM, PolInSAR, GMTI, DBF, …)**
- **Mission Planning and Data Management**
- **PRF and Phase Synchronisation (design upgrade)**
- **Close Formation Flying (collision avoidance)**
- **Precise Baseline Determination (double difference GPS)**
- **Bi-Static and Interferometric Data Processing**
- **Interferometric Calibration (tie points, crossing orbits, …)**
- **…**

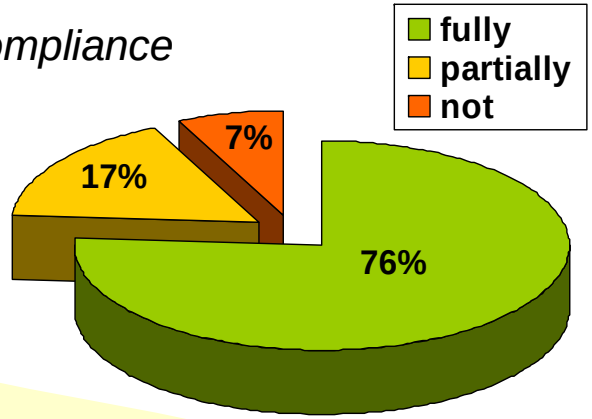


Product and Mission Definition

User Survey:
- application areas
- basic user needs
- technical requirements
- …

Product and Mission Definition

Compliance



Standard DEM (global HRTI)

- predefined accuracies:
  - Δh = 2 m @ Δx = 12 m
  - Δh = 4 m @ Δx = 6 m
  - Δh = 1 m @ Δx = 25 m
  - Δh = 0,5 m @ Δx = 50 m
- deliverable data:
  - standard DEM
  - detected SAR images
  - coherence maps
  - height error maps

Customised DEM (local)

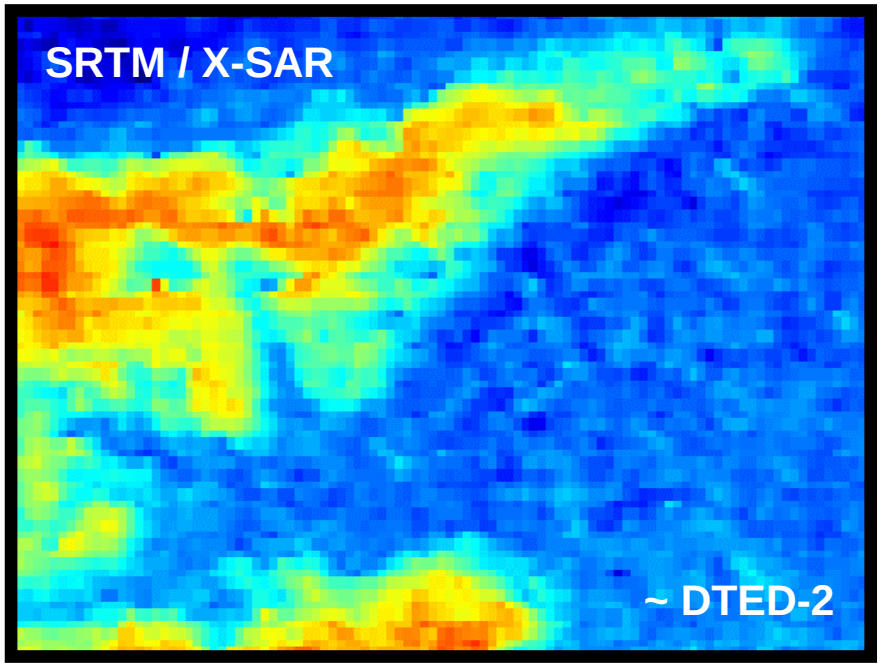
- customised accuracies:
  - Δh = … m @ Δx = … m
- temporal requirements
  - different seasons
  - different years
- deliverable data:
  - customised DEM
  - detected SAR images
  - coherence maps
  - height error maps

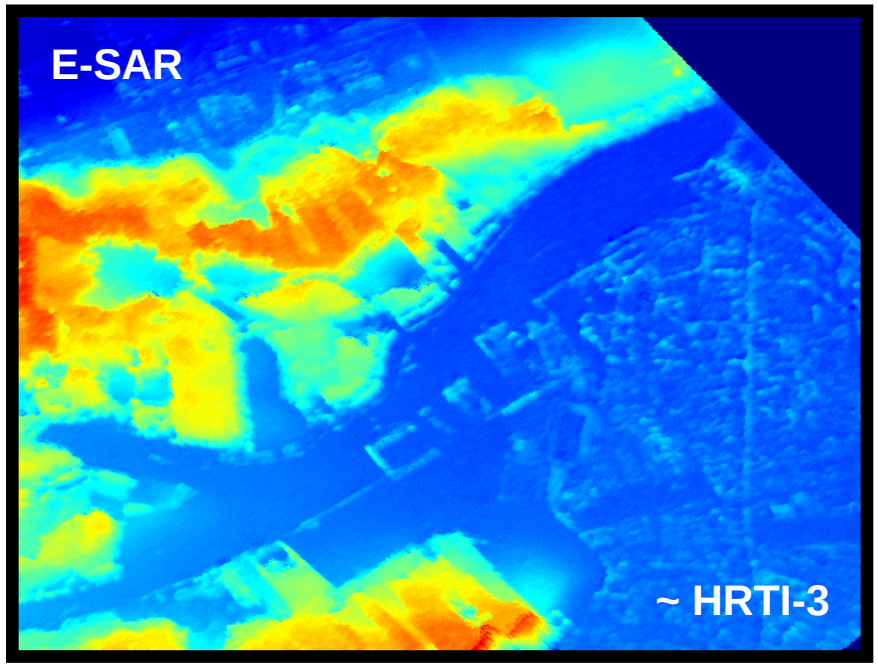
Radar Data Products

- system parameters:
  - B_{cross} = … m
  - B_{along} = … m
  - …
- deliverable data:
  - SLC SAR images
  - SAR raw data
  - TanDEM-X interferograms
  - orbit state vectors

HRTI-3 DEM Definition

	Spatial Resolution	Absolute Vertical Accuracy (90%)	Relative Vertical Accuracy (point-to-point in 1° cell, 90%)
DTED-1	90m x 90m	< 30 m	< 20 m
DTED-2	30m x 30m	< 18 m	< 12 m
HRTI-3	12m x 12m	< 10 m	< 2 m
HRTI-4	6m x 6m	< 5 m	< 0.8 m

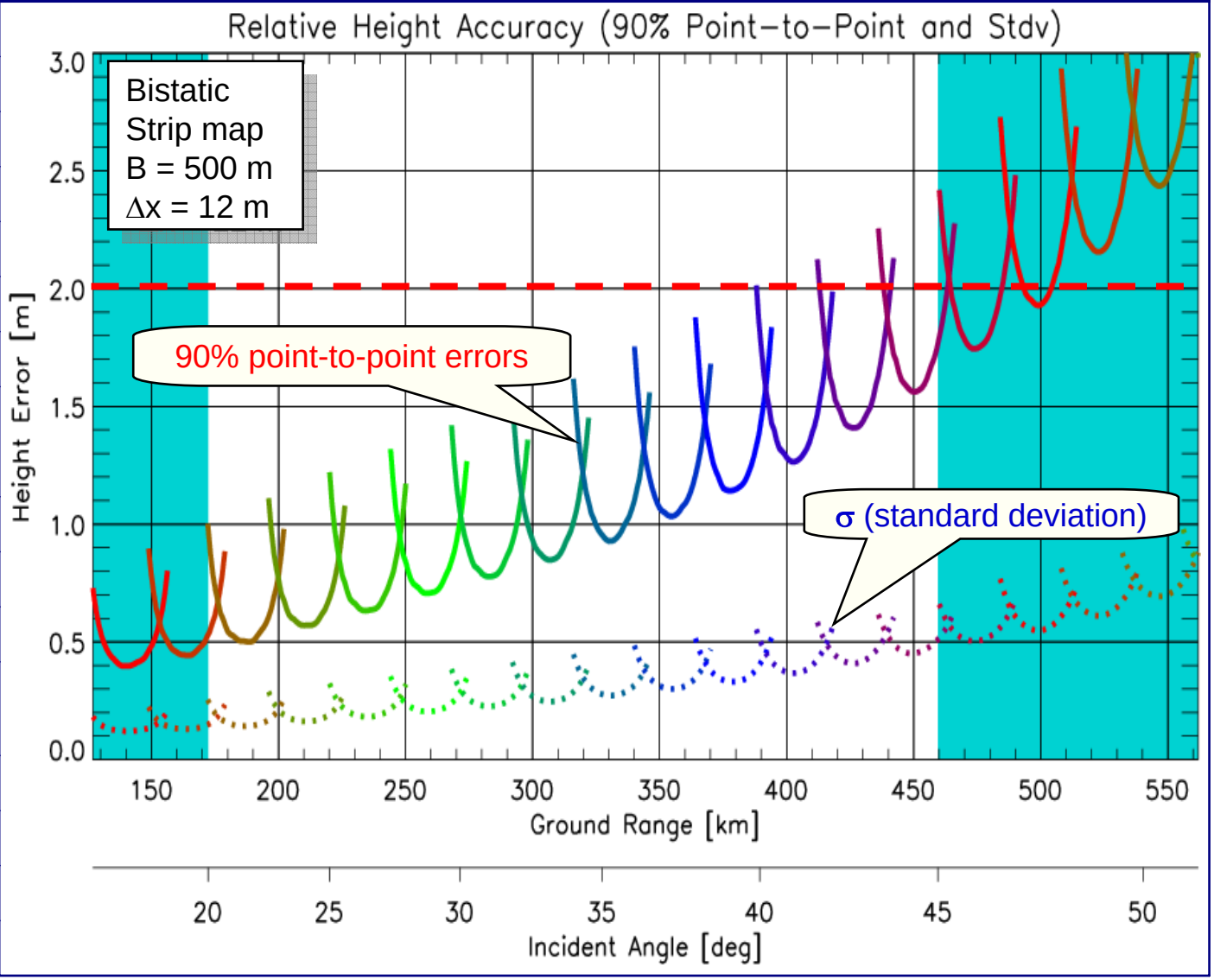




Relative Height Accuracy (B = 500 m)

Parameter	Value
Wavelength	0.031 m
Chirp Bandwidth	≤150 MHz
Peak Transmit Power	2260 W
Duty Cycle	18 %
Noise Figure TRM	4.3 dB
Losses (rad., atm.,..)	4.1 dB
Antenna Size (Tx, Rx)	4.8 m x 0.7 m
Antenna Tapering	linear phase
PRF (swath variant)	~3500 Hz
Processed Bandwidth	2266 Hz
Mis-Registration	1/10 pixel
Quantization	4 bit (BAQ)
Sigma Nought Model (90% occurence)	Ulaby (X-Band, VV, Soil)
Baseline (perp.)	500 m
Along-Track Displ.	< 1 km
Swath Width	30 km
Post Spacing	12 m x 12 m

Relative Height Accuracy



Relative Height Accuracy (B = 1000 m)

Parameter	Value
Wavelength	0.031 m
Chirp Bandwidth	≤150 MHz
Peak Transmit Power	2260 W
Duty Cycle	18 %
Noise Figure TRM	4.3 dB
Losses (rad., atm.,..)	4.1 dB
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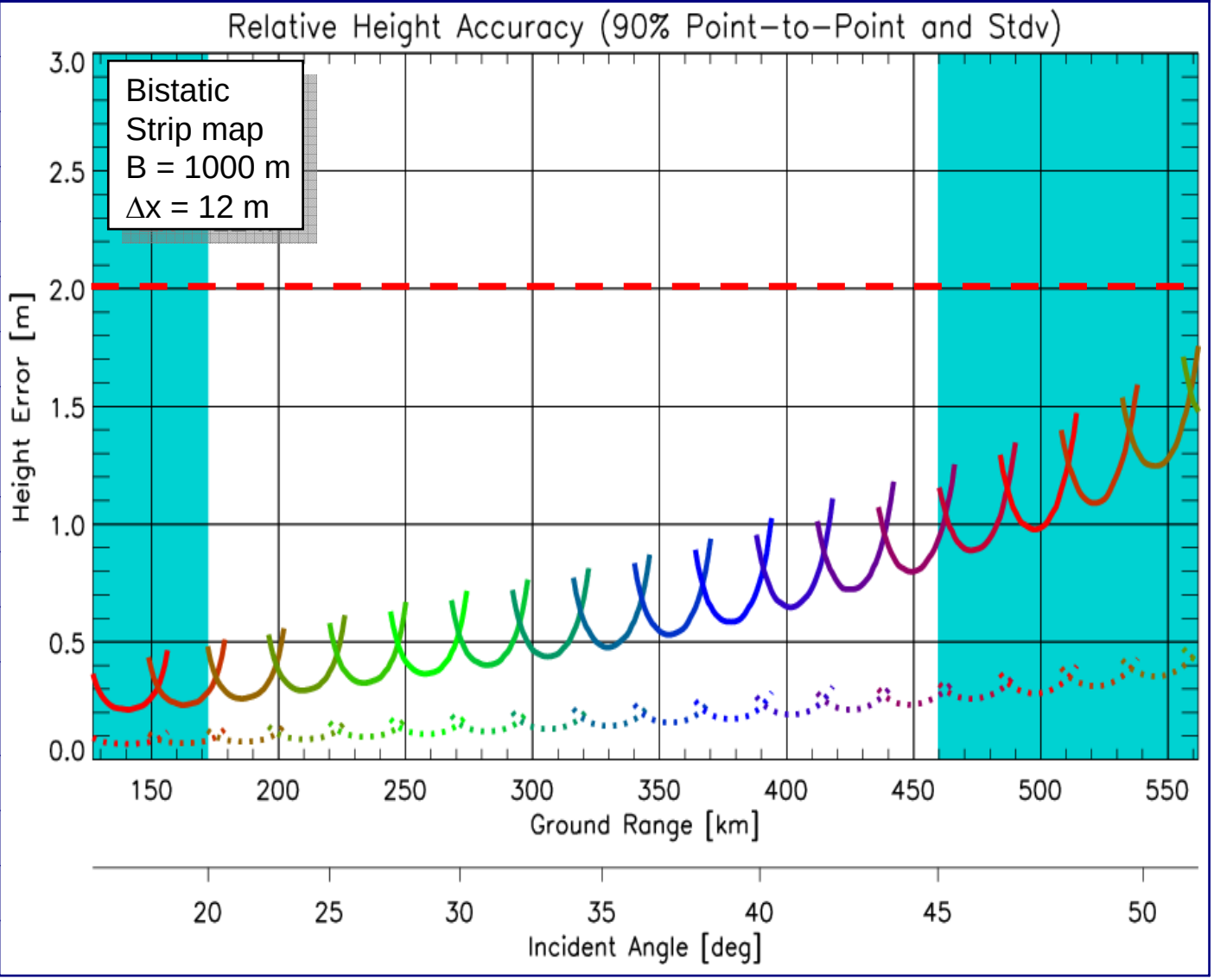
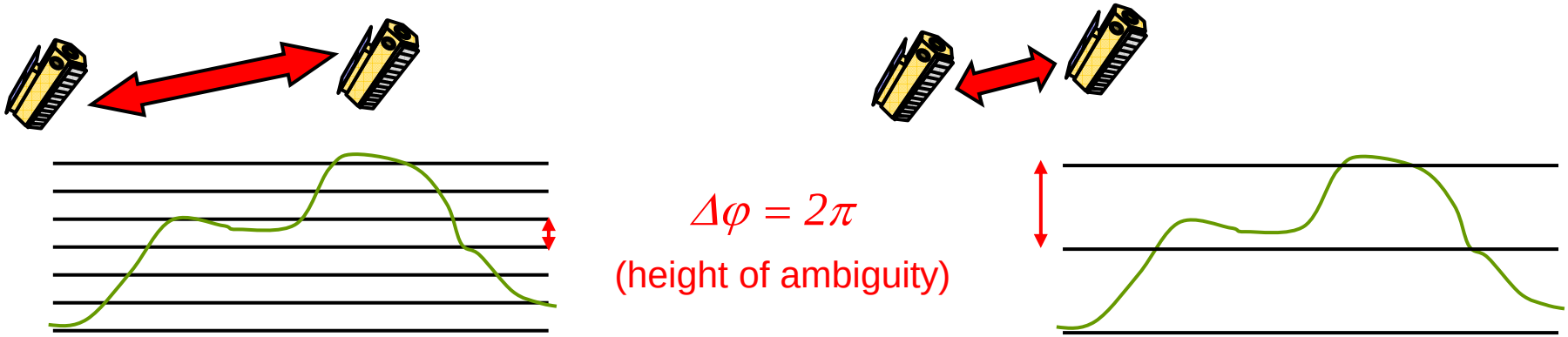
Relative Height Accuracy



Phase Unwrapping

TanDEM-X enables large baselines which allow for ultra high resolution DEMs with height accuracies in the sub-meter range, but …



$$\Delta\varphi = 2\pi$$

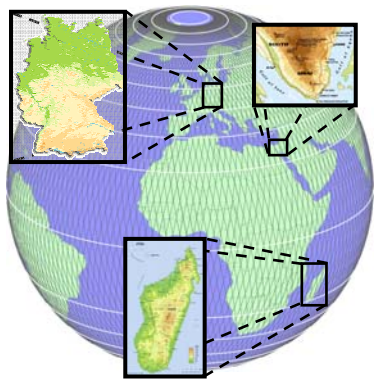
(height of ambiguity)

Compromise on Accuracy for Global DEM

- use reduced baselines
- additional acquisitions for difficult terrain

→ acquisition scenario for global DEM according to HRTI-3

Local/Regional Ultra High Resolution DEMs



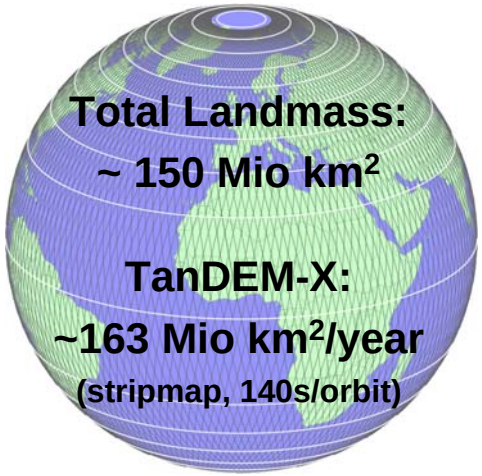
- use multiple data acquisitions with large and small baselines

→ regional DEMs with sub-meter resolution (e.g. HRTI-4)

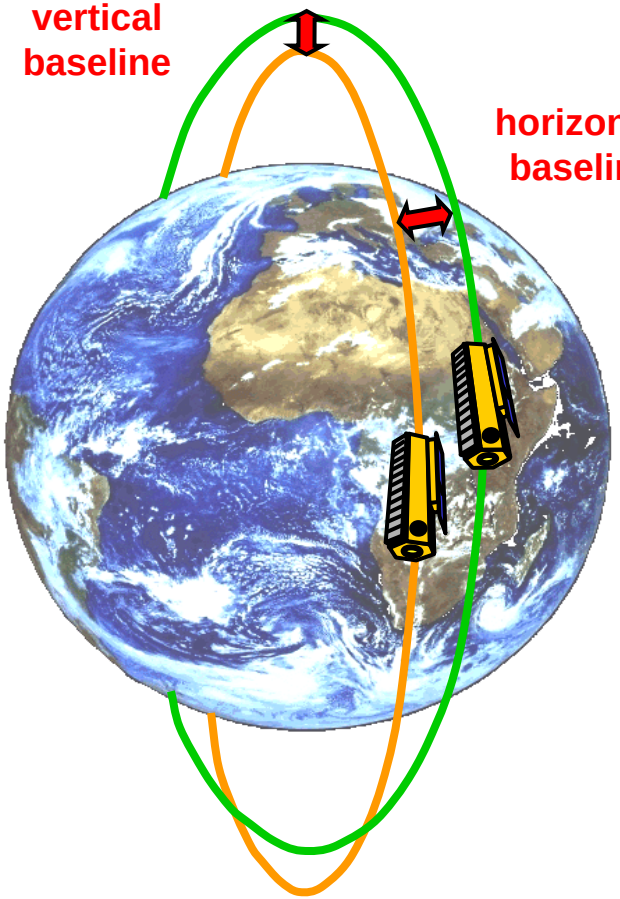
TanDEM-X Data Acquisition Strategy

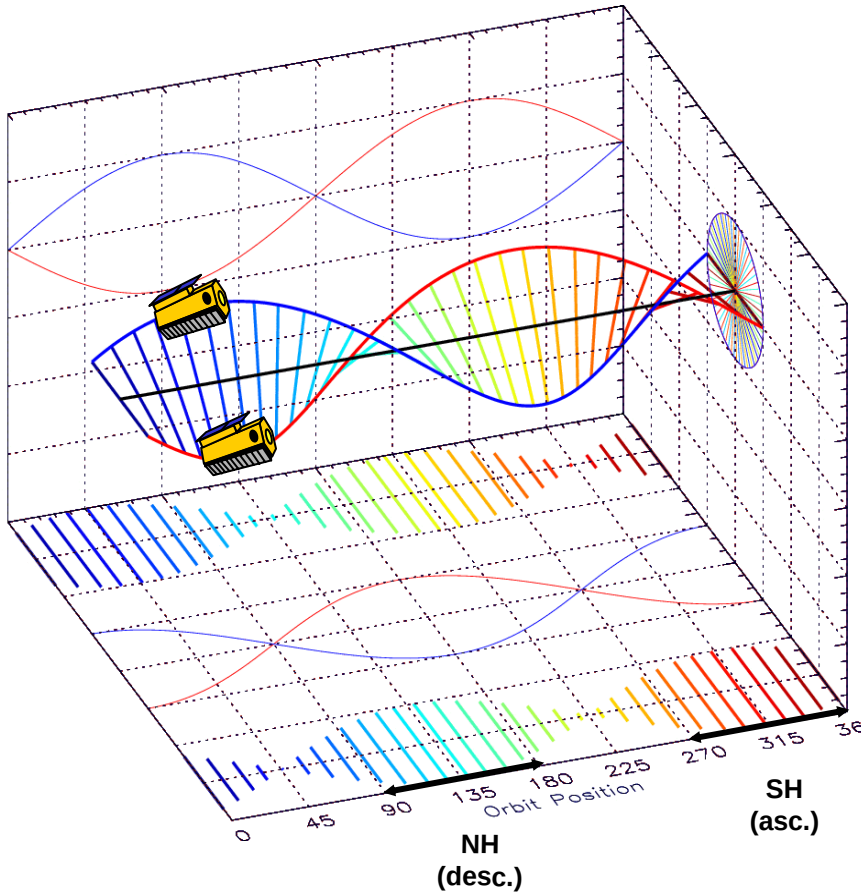
Terrain Type	Percentage of Total Landmass	Number of Acquistions	Required Time (without RDP)
Moderately Sloped Areas	50 %	**1** (h_{amb} ~ 35 m)	~ 7 months
Hilly Areas, Tall Forests	30 %	**2** (+ different h_{amb})	~ 8 months
Mountainous Areas	< 20 %	**4** (+ asc. / desc.)	~ 11 months
Total	100 %	**1 - 4**	~ 26 months (incl. margin)

TanDEM-X Mission Scenario for 3 Years	
Global HRTI-3 DEM (incl. multiple acquisitions for difficult terrain)	**~ 70 %**
Additional Applications (local HRTI-4, ATI, new techniques, …)	**~ 30 %**



TanDEM-X Satellite Formation: HELIX





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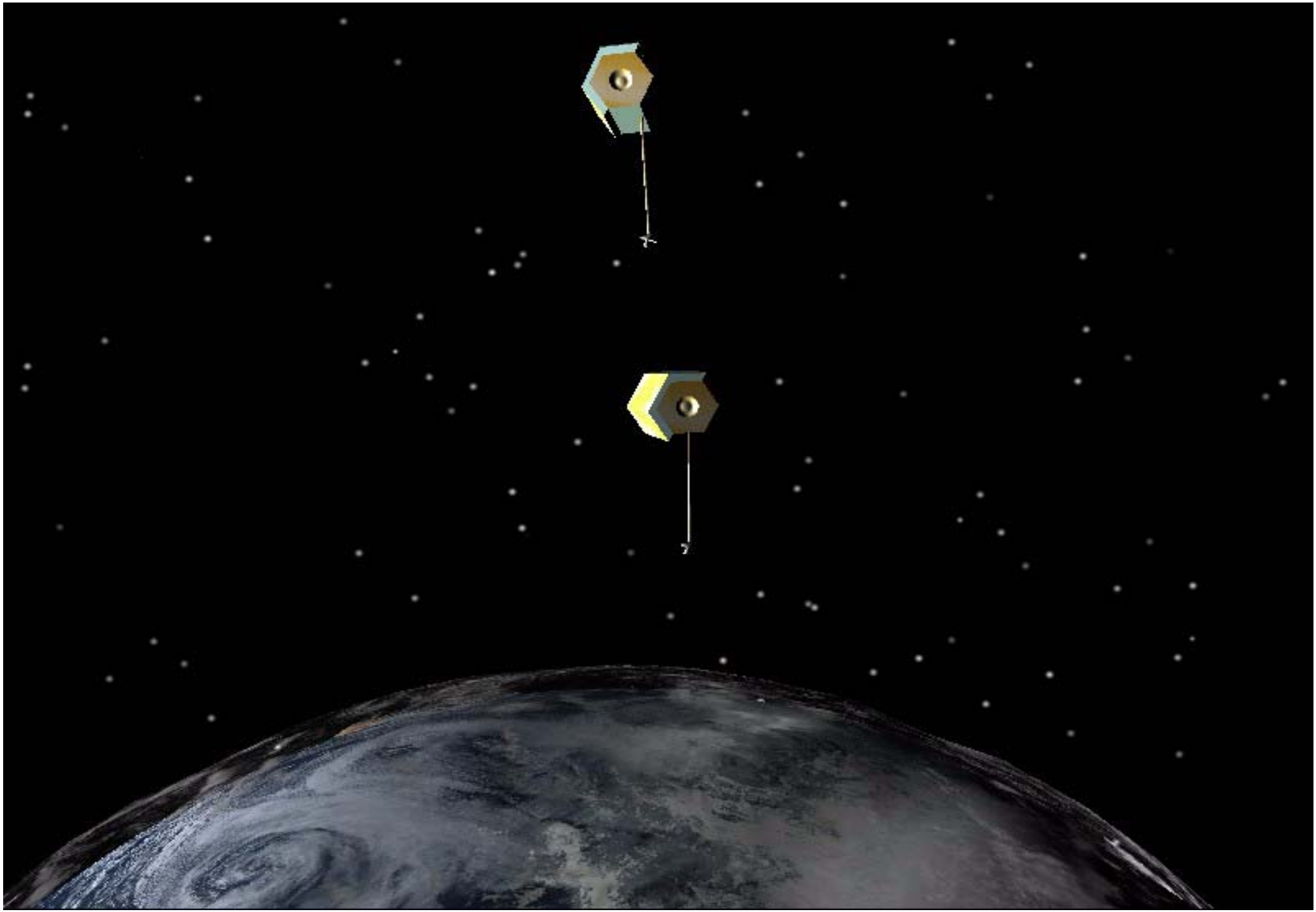
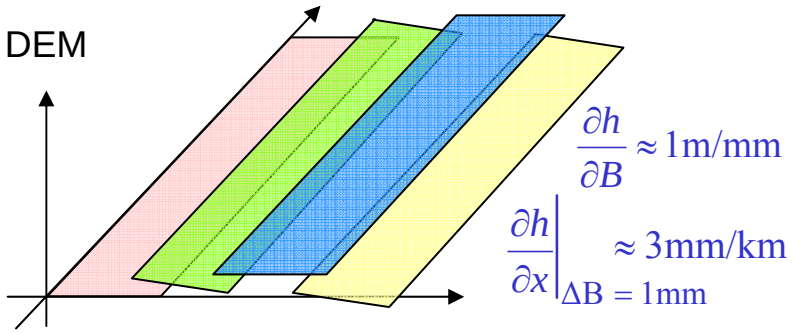
HELIX satellite formation enables safe operation

- *horizontal cross-track separation at equator by different ascending nodes*
- *vertical (radial) separation at poles by orbits with different eccentricity vectors (periodic motion of libration is compensated by regular manoeuvres)*

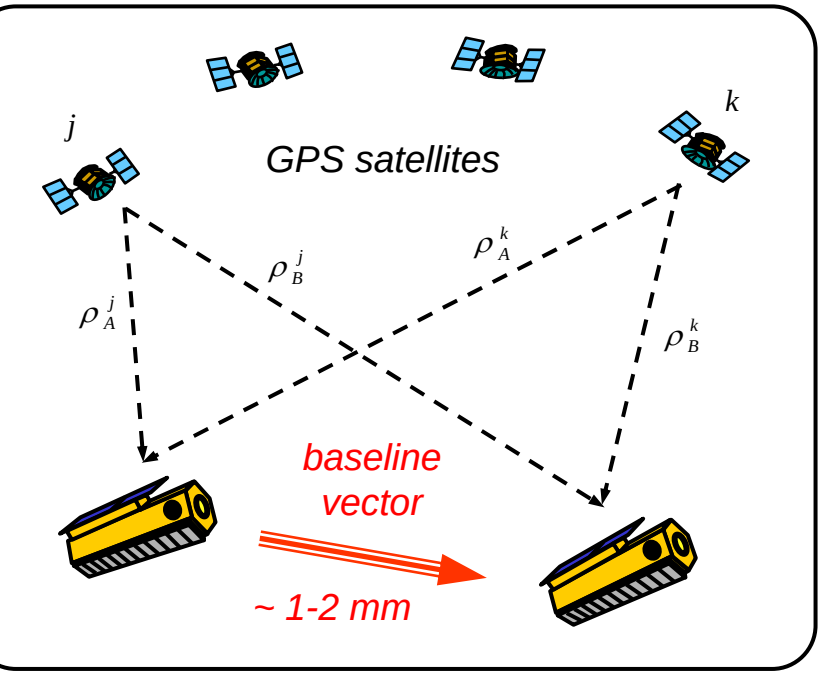


Baseline Estimation and DEM Calibration

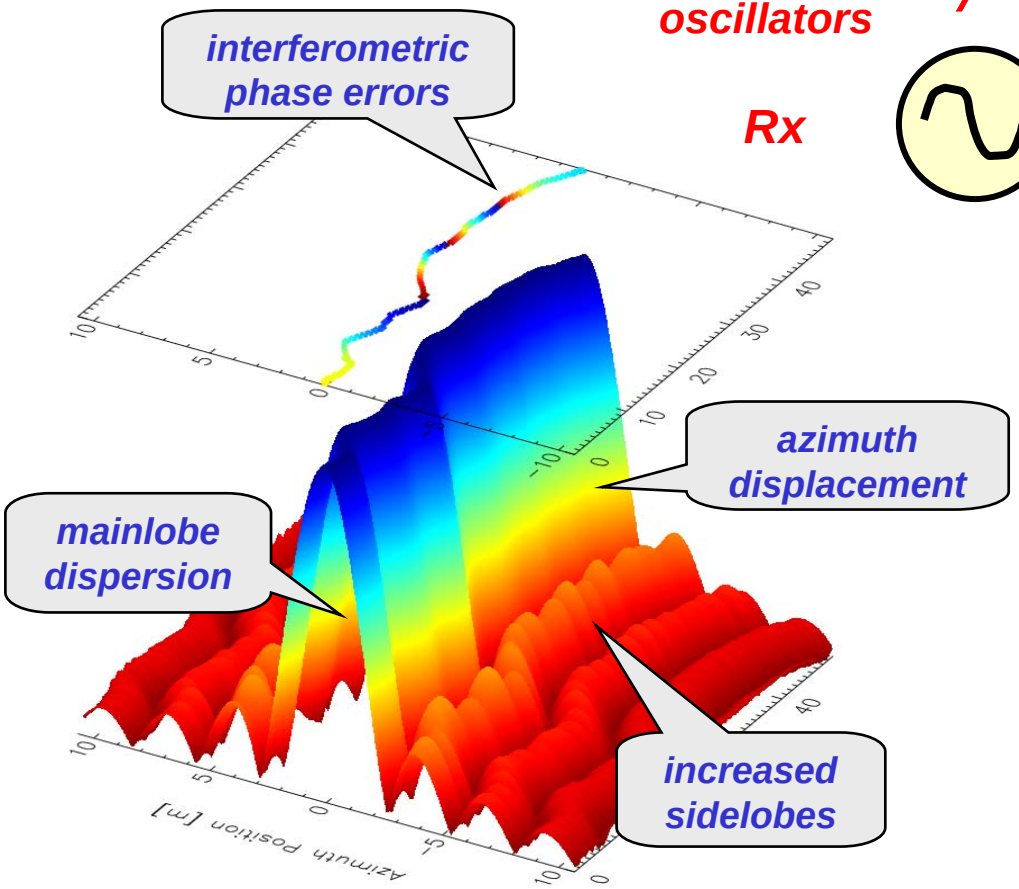
- ***Both satellites are exposed to almost identical orbit perturbations***
  - *negligible azimuth modulation / twisting of DEM swath ($\Delta B < 0.25$ mm for 500 km swath and 'unmodelled' $\delta a < 100$ nm/s^2)*
  - *vertical bias and tilt of raw DEM swaths due to initial baseline estimation errors*
- ***Precise baseline estimation by***
  - *double-difference GPS carrier-phase measurements*
  - *accurate orbit propagation model*
  - *several studies predict a 3-D accuracy in the order of 1-2 mm*

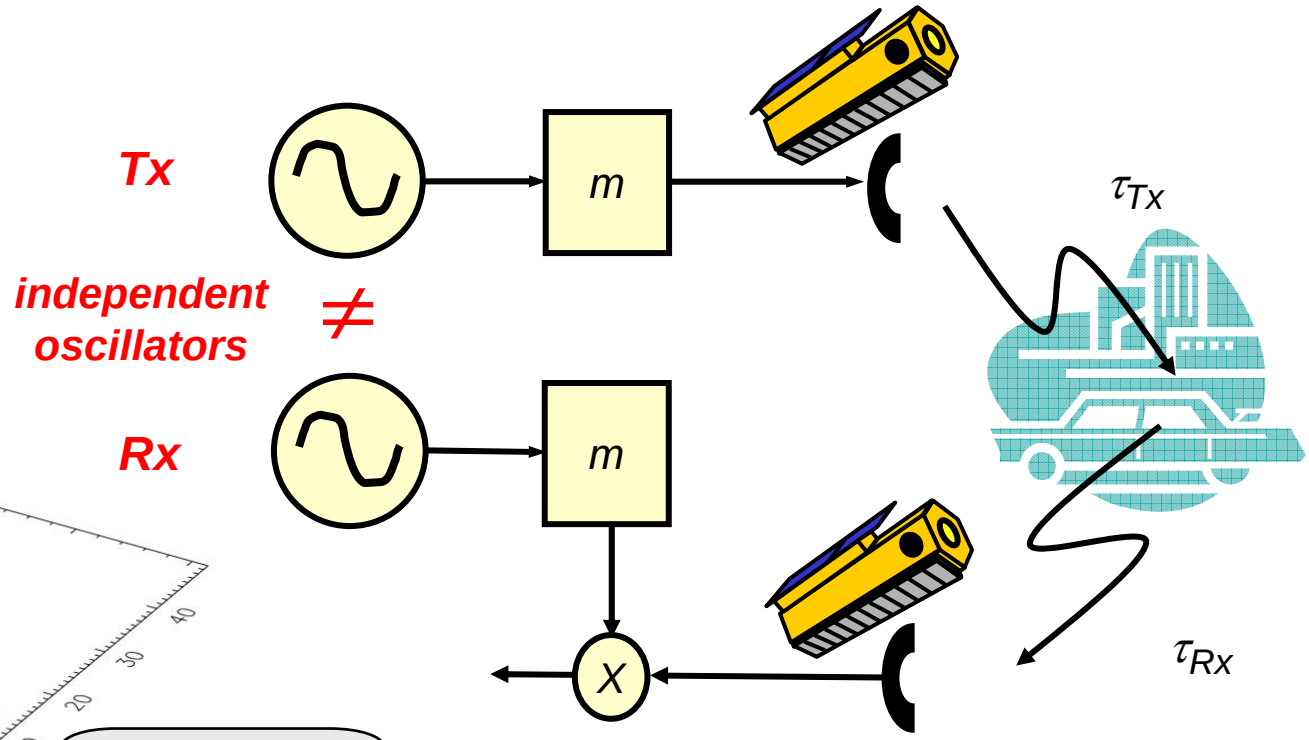


calibration with overlapping swaths, crossing orbits, external references, etc.



Impact of Oscillator Noise



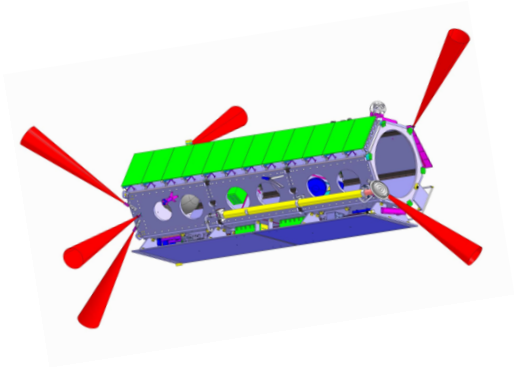


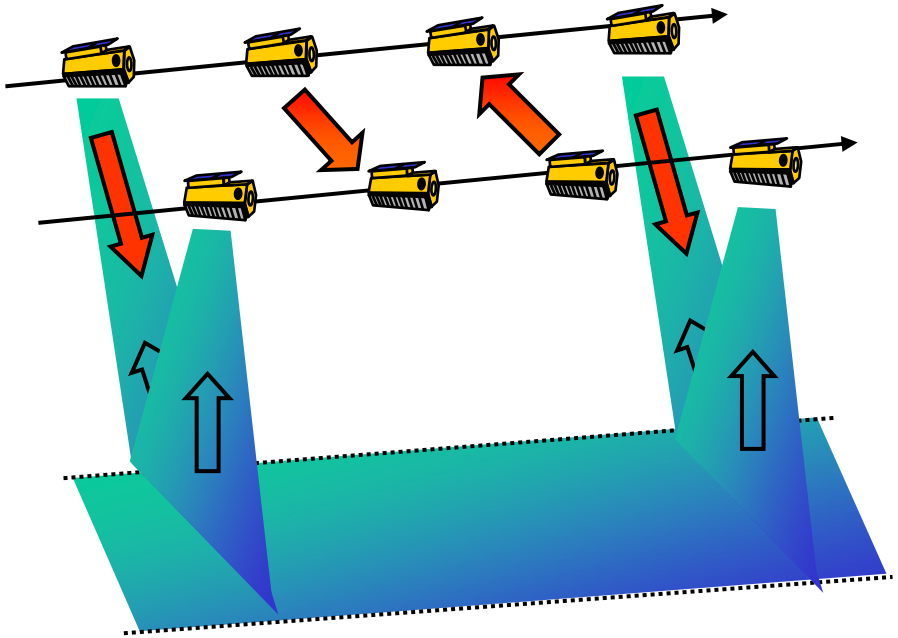
Major effects:

- **interferometric phase errors (azimuth 'modulation' of DEM)**
- **azimuth displacement**
- **increased azimuth sidelobes**
- **range drift (walk of receiving window)**

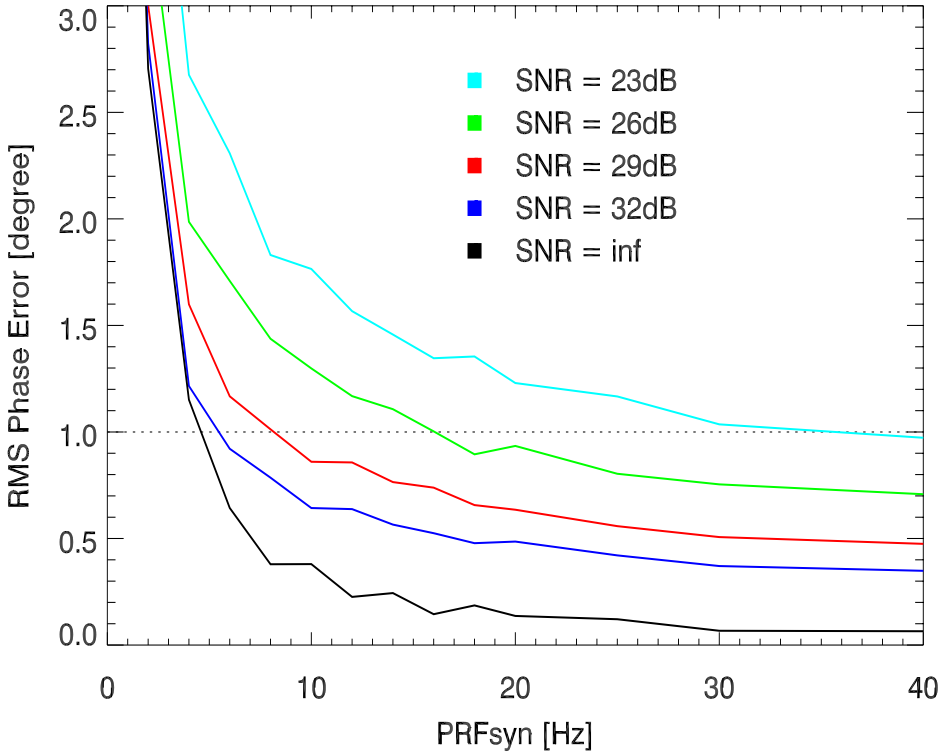
Phase Referencing in TanDEM-X

Synchronisation Link





Analysis of Residual Errors



⟹ *phase referencing can achieve a short term rmse below 1° in standard DEM acquisition mode by integrating multiple sync pulses (for B < 1 km)*

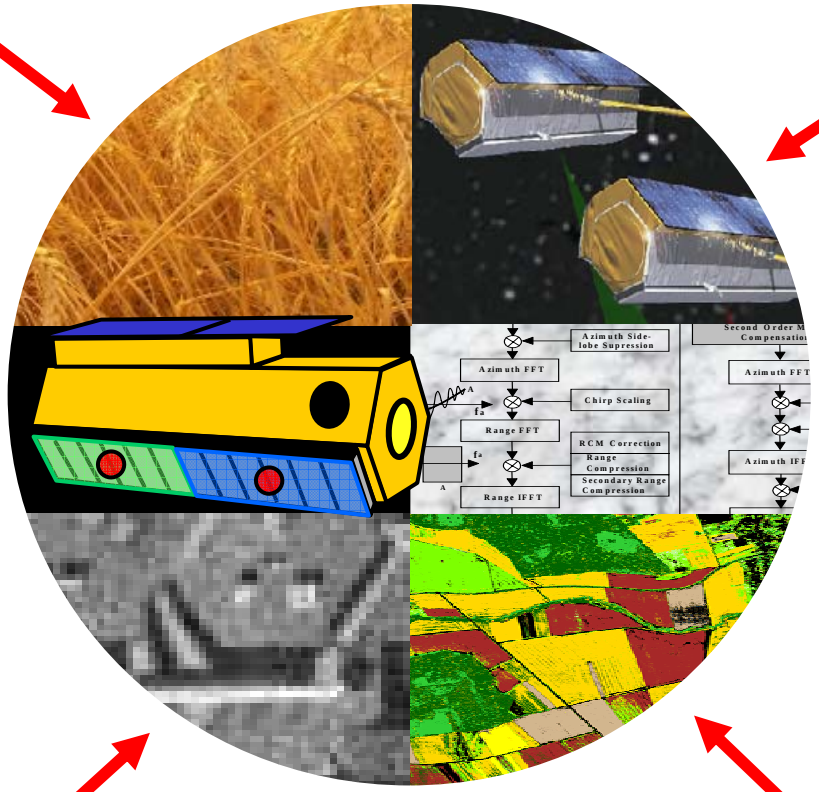
Secondary Mission Goals & New Techniques

Pol-InSAR

(fully polarimetric !)

Along-Track Interferometry

(HELIX formation !)



Digital Beamforming

(4 phase centres !)

Multi Baseline InSAR

(flexible baselines !)

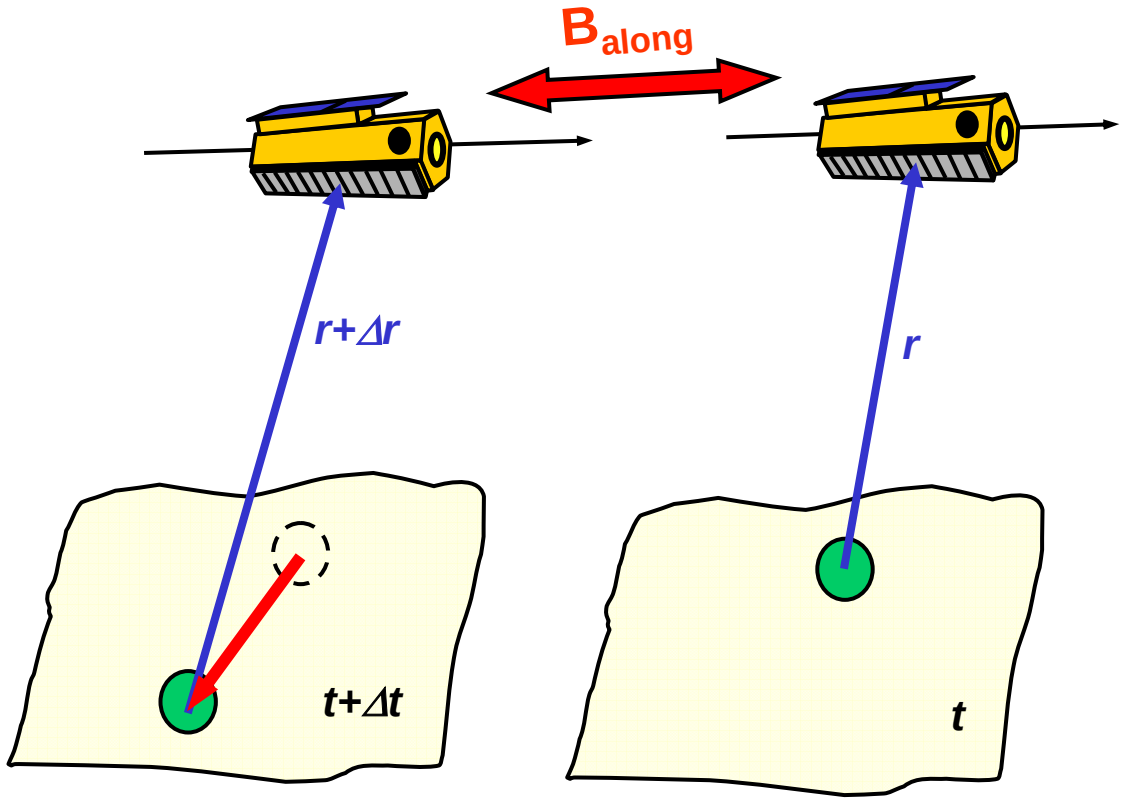
Super Resolution

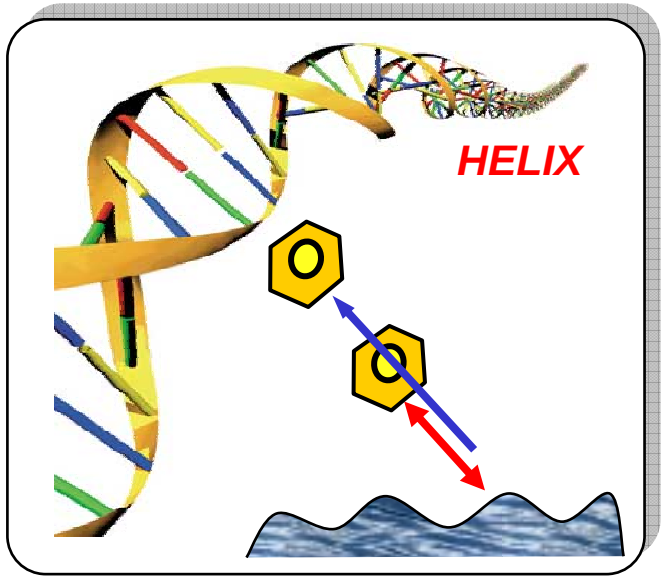
(large bandwidth !)

Bistatic Observations

(bistatic angle !)

Along-Track Interferometry





HELIX formation enables:

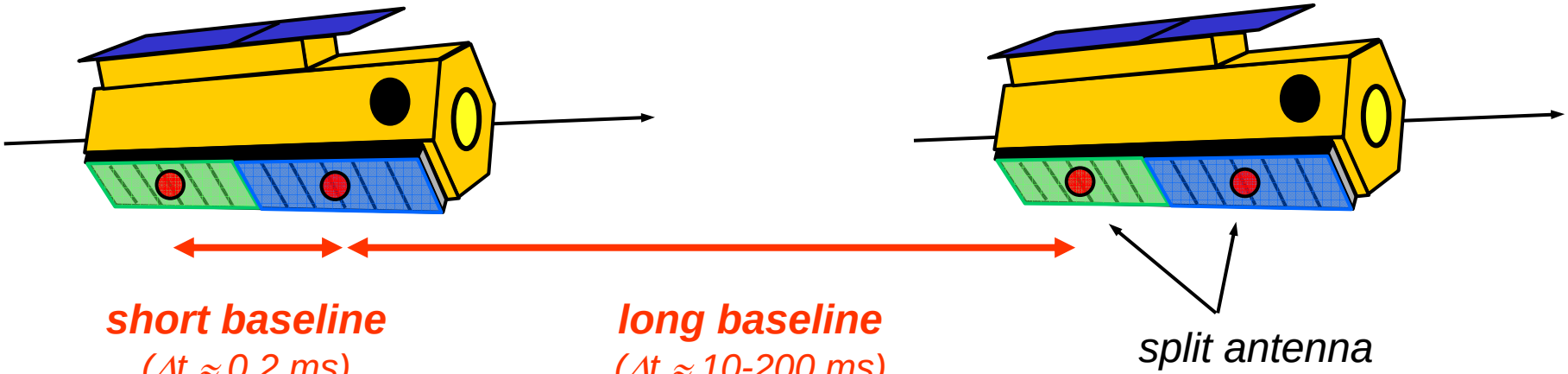
- *short along-track baselines*
  (arbitray satellite shifts along the orbits)
- *vanishing cross-track baselines*
  (for specified latitude/incident angle combinations)

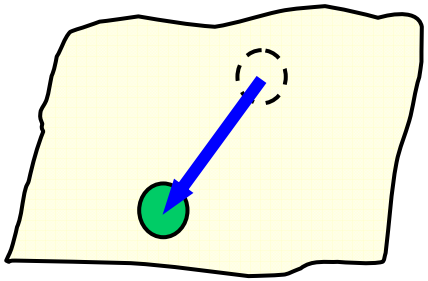
Example (bistatic mode):

- B_{along} = 100 m
- posting = 10 m
- σ^0 = -12 dBm^2/m^2
- θ_{inc} = 45°
- v_{amb} = 11 km/h

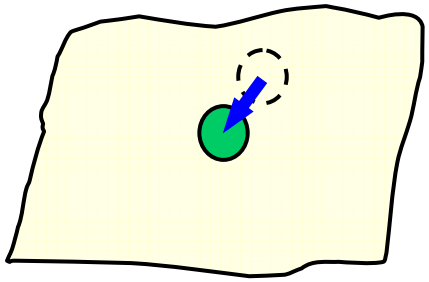
→ **dv ~ 0.15 km/h (stdv.)**

SAR Imaging with four Phase Centres





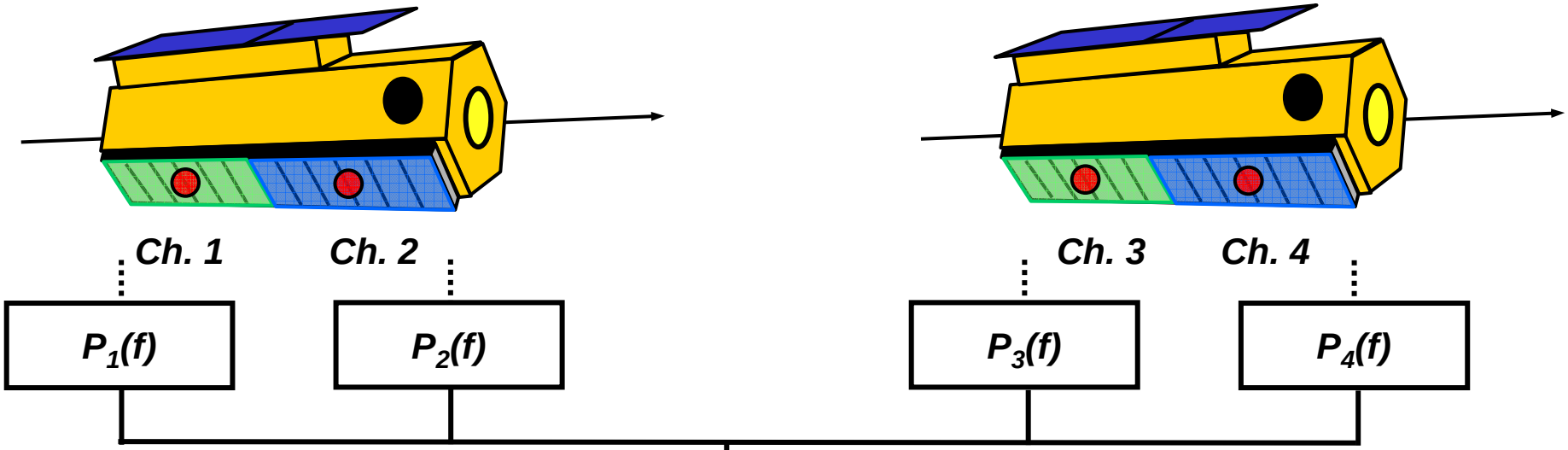
sensitive to
fast movements



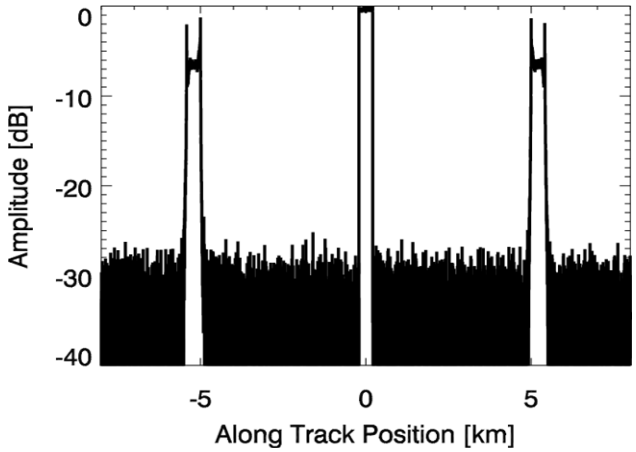
sensitive to
slow movements

⇨ ***highly accurate velocity estimates for slow and fast object movements***

SAR Imaging with four Phase Centres

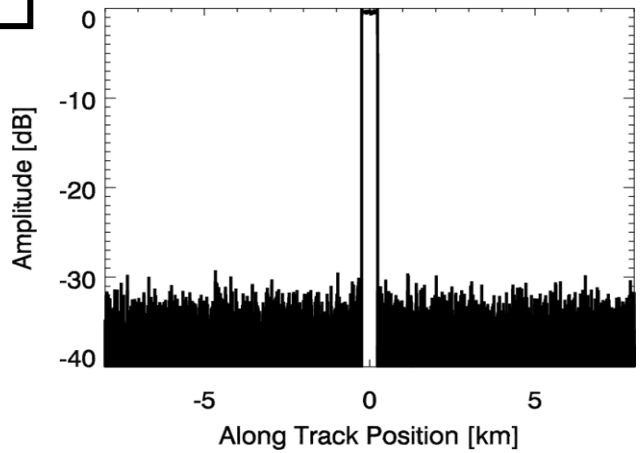


without reconstruction



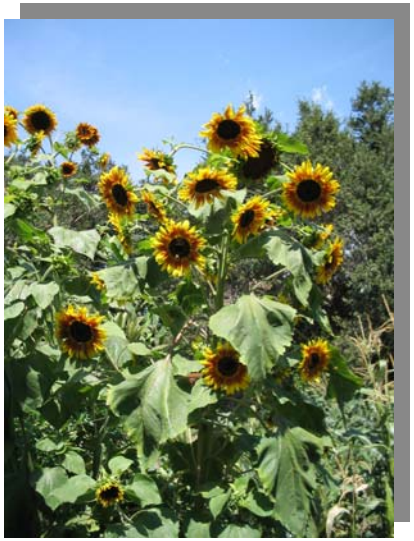
Ambiguity Suppression

with reconstruction



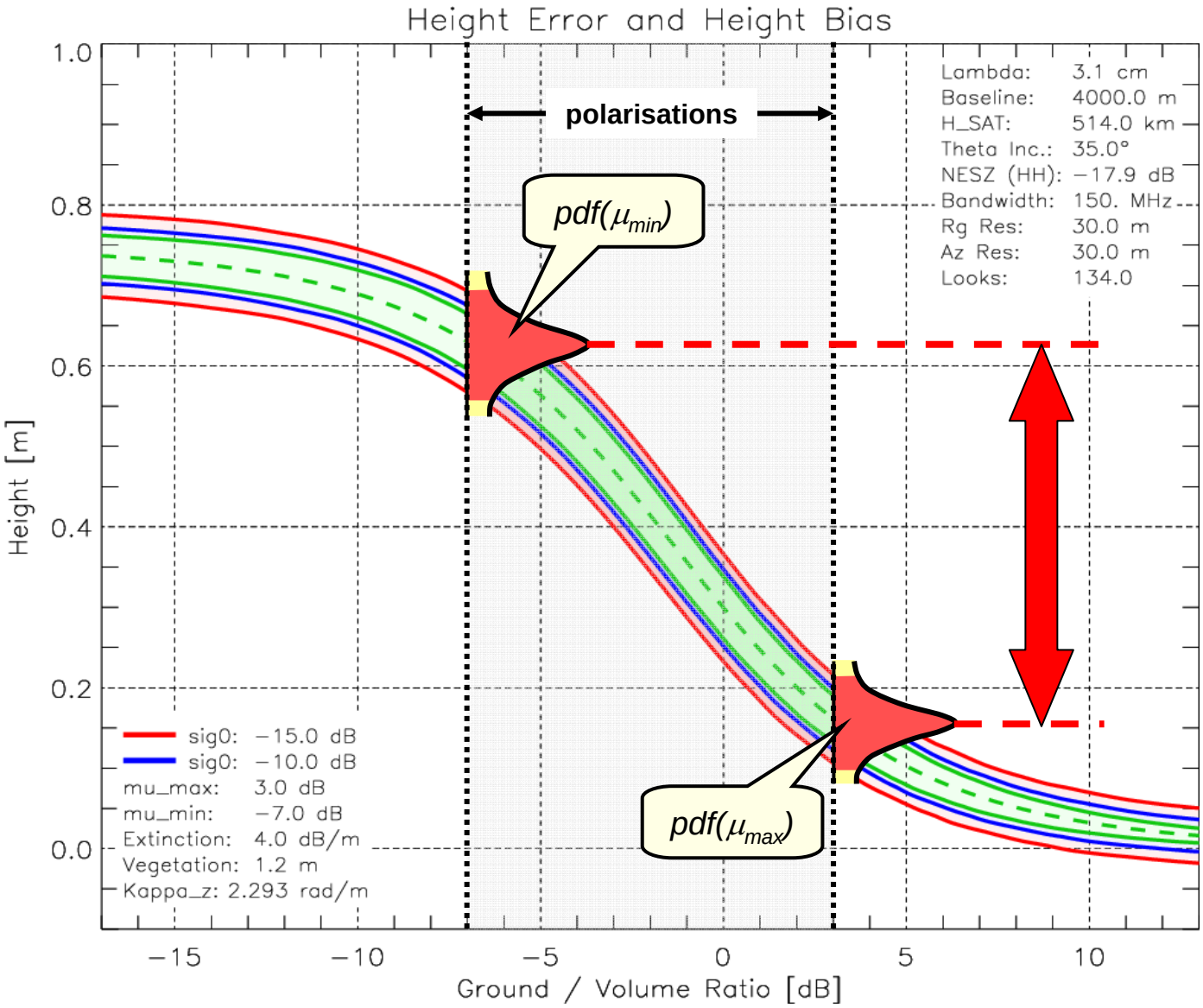
Enables High Resolution Wide Swath Imaging

PolInSAR Example: Sunflower



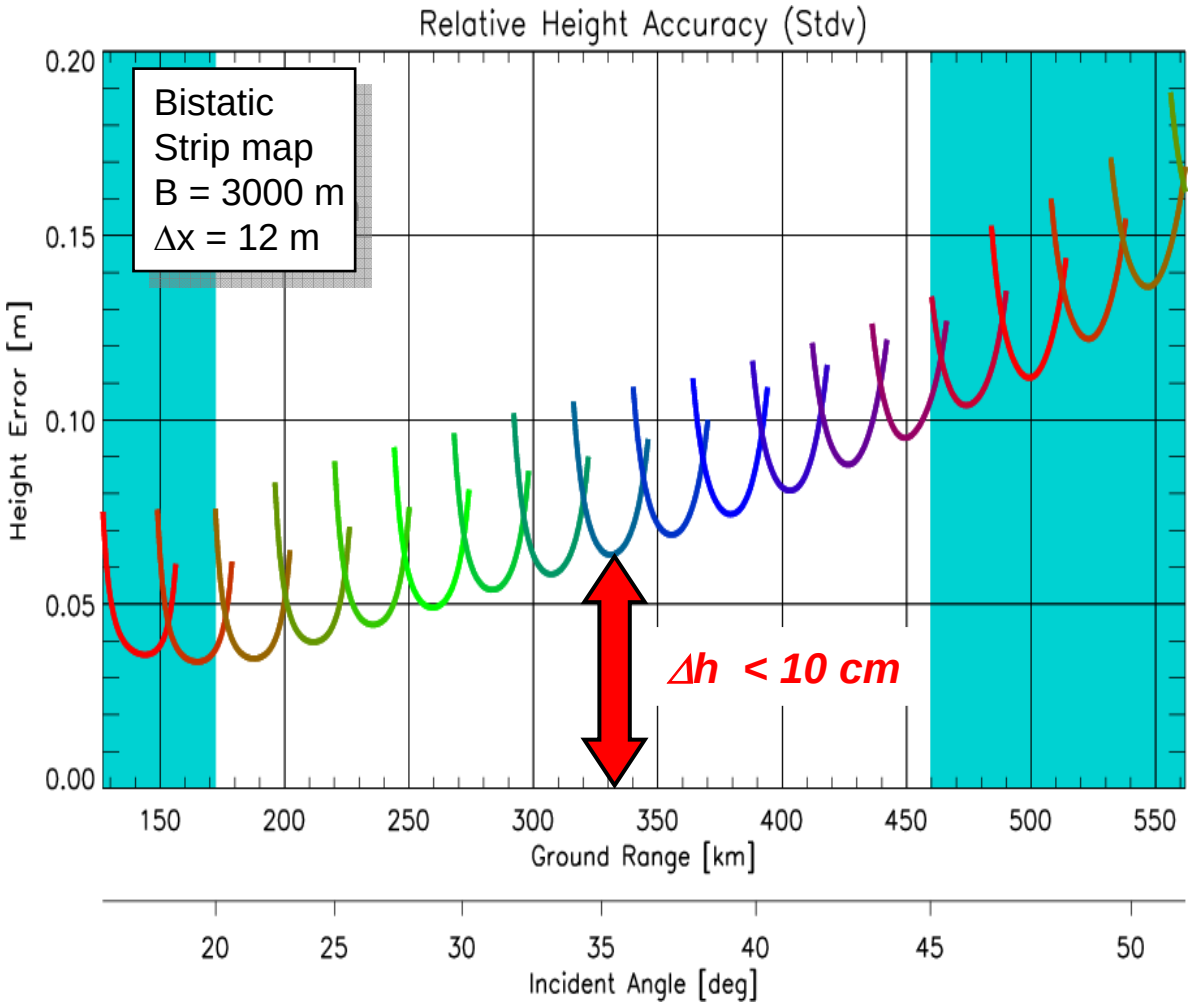
Parameters

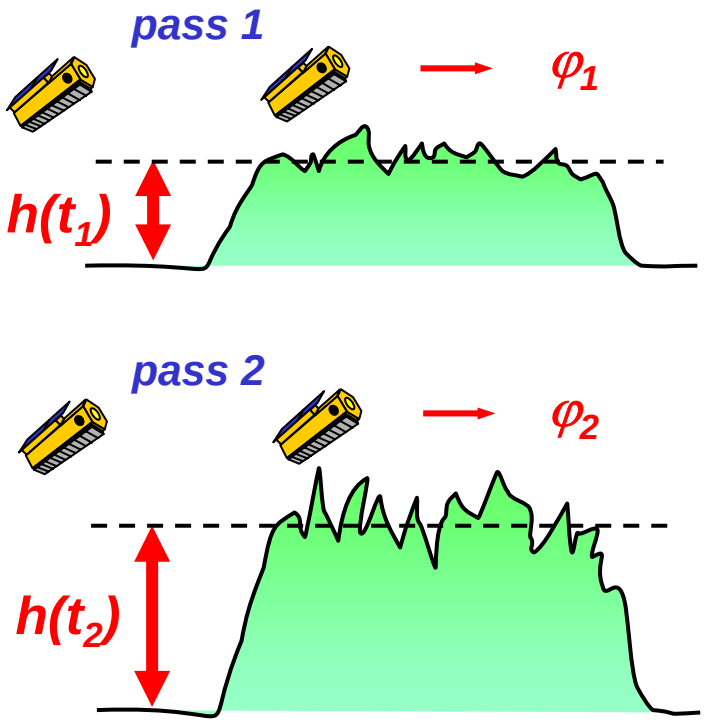
$h = 1.2$ m
$\beta = 4.0$ dB/m
$\mu_{min} = -7.0$ dB
$\mu_{max} = 3.0$ dB
$B_{\perp} = 4$ km
$\theta_{inc} = 35°$
$\Delta x = 30$ m



"Double Differential SAR Interferometry"

e.g. difference between two single-pass cross-track interferograms





→ $\Delta h \sim \varphi_2 - \varphi_1$

coherence between passes not mandatory

→ Grounding line detection, vegetation growth, snow/ice accumulation, … ?

TanDEM-X Summary

- TanDEM-X passed a phase A feasibility study with great success
- TanDEM-X has outstanding scientific and commercial potentials
- TanDEM-X will be implemented as a public private partnership
- TanDEM-X key technologies are:
  - bistatic radar operation and phase synchronisation
  - precise baseline determination
  - close formation flying capability
  - new algorithms for interferometric processing
- TanDEM-X plays a key role in the development of next generation SAR missions