MirrorSAR

A Fractionated Space Radar for Bistatic, Multistatic, and High-Resolution Wide-Swath SAR Imaging

G. Krieger, M. Zonno, M. Rodriguez-Cassola, P. Lopez-Dekker, J. Mittermayer, M. Younis, S. Huber, M. Villano, F. Queiroz de Almeida, P. Prats, A. Moreira

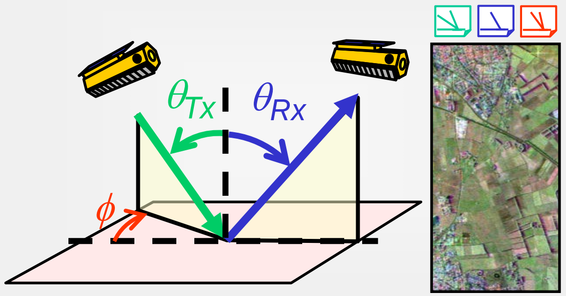
Microwaves and Radar Institute
German Aerospace Center (DLR)

DLR

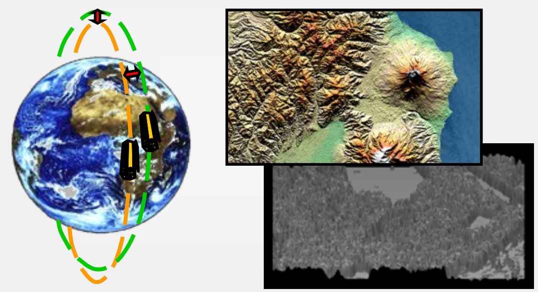
IGARSS
July 24, 2017

Potentials of Bistatic and Multistatic SAR Systems

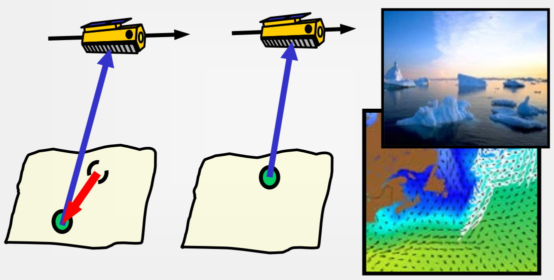
Bistatic Imaging



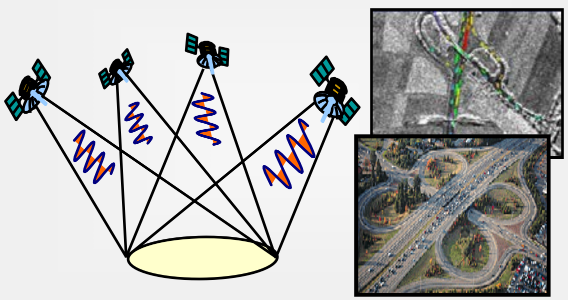
Cross-Track Interferometry



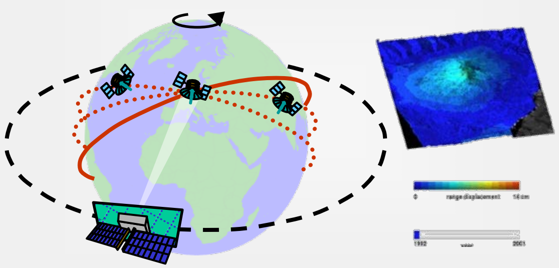
Along-Track Interferometry



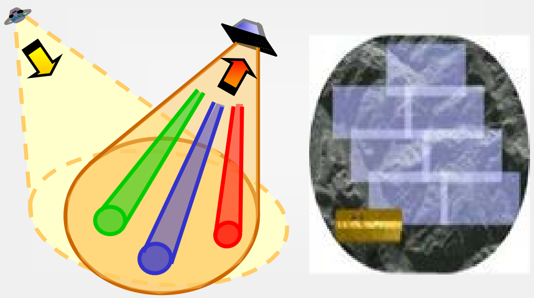
Moving Target Indication



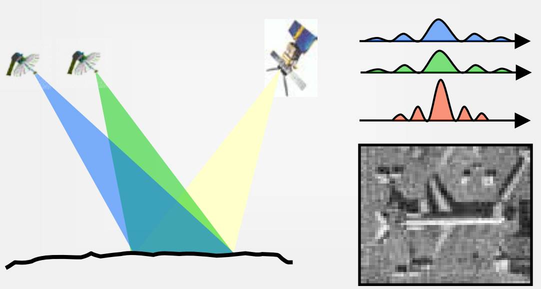
Frequent Monitoring



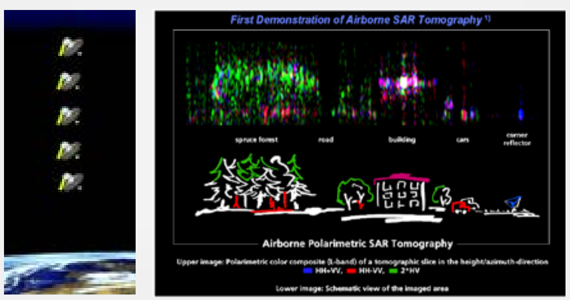
Wide Swath Imaging



Resolution Enhancement



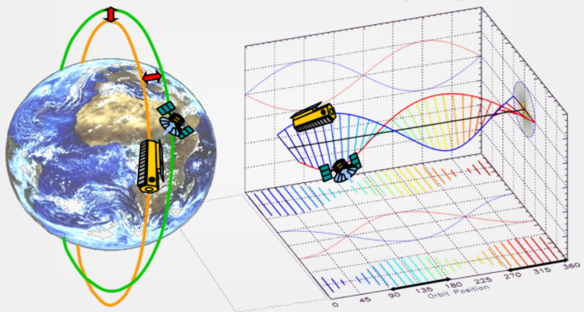
SAR Tomography



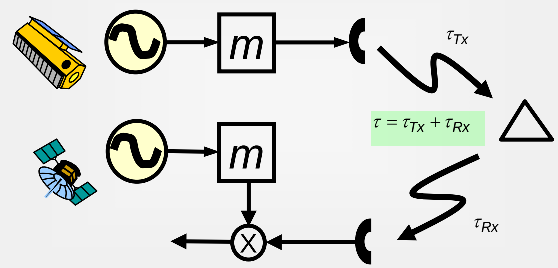
...
4-D Tomography & Holography
MIMO-SAR Tomography
Double Differential InSAR
Increased Radiom. Sensitivity
Adv. Atmospheric Corrections
Interference Suppression
...

Challenges of Companion Satellite Missions

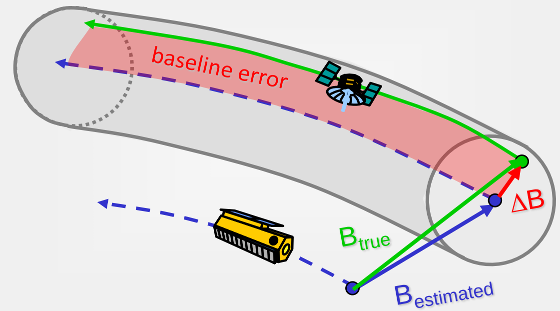
Safe Formation Flying



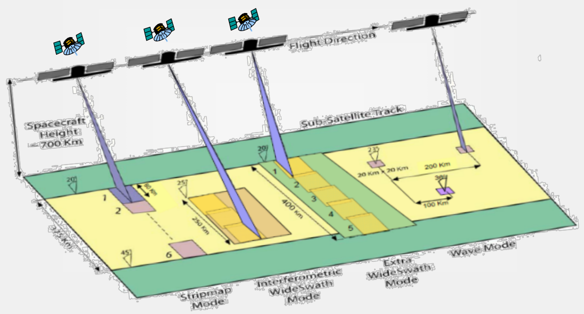
Phase Synchronisation



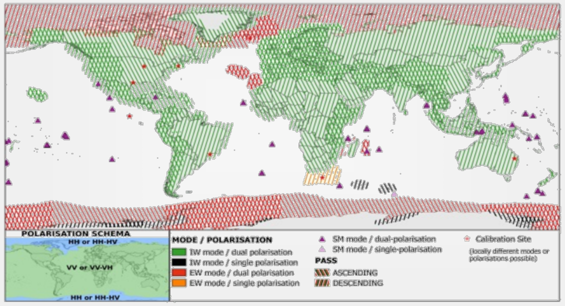
Baseline Estimation



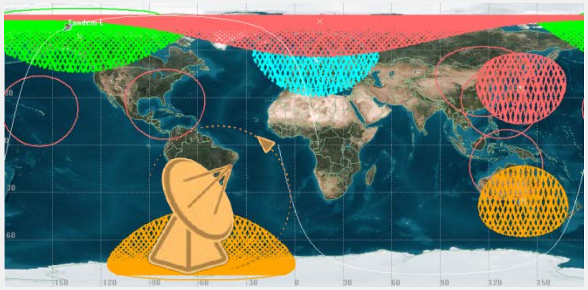
Mode Compatibility & Performance



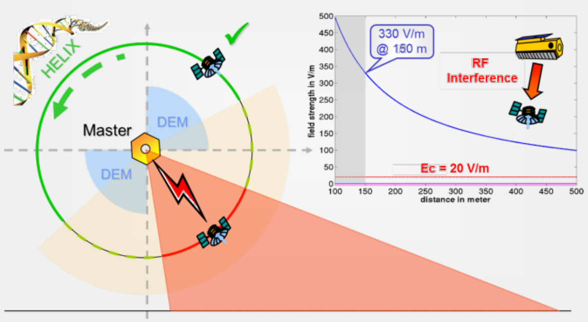
Master/Slave Acquisition Conflicts



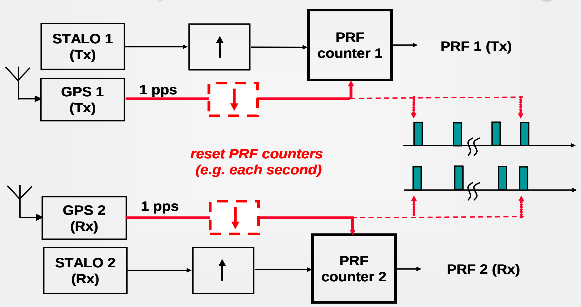
Data Downlink Conflicts



Mutual Illumination Risk



Joint Operation & Commanding



...
Master/Slave Calibration
Development&Operation Schedule
Launch in Master Orbit
Ionospheric Jumps (Scan/TOPS)
Programmatic Aspects
Master Availability / Redundancy
...

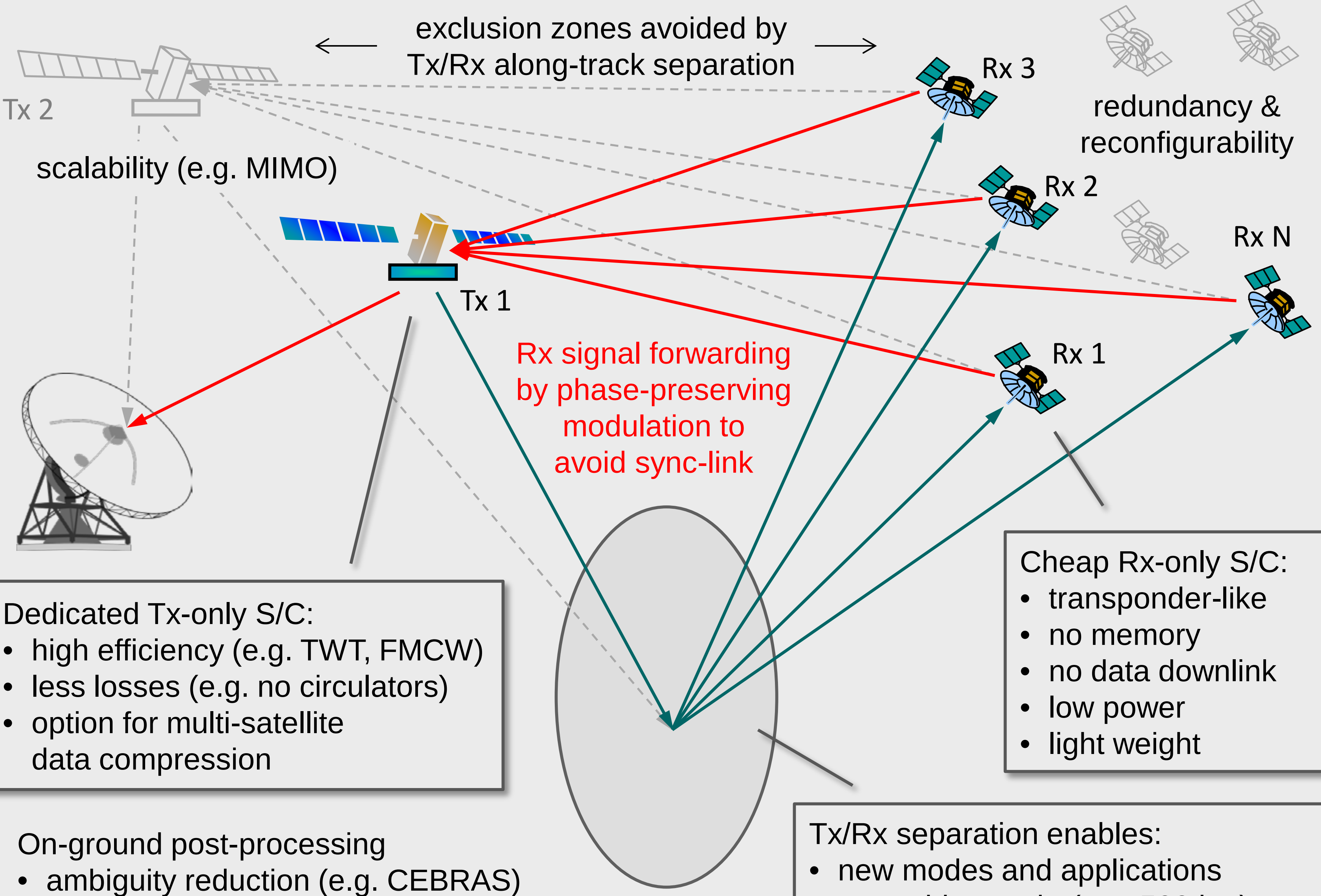
MirrorSAR Concept

MirrorSAR: A New Concept for Multistatic SAR Systems

Pave the way for powerful and affordable multistatic SAR missions by

- Reducing weight, size and cost for each receiver satellite
  - no wide-band communication system for downlink of payload data
  - no full radar receiver, no on-board memory
  - no dedicated synchronization link
  - minimize overall power demands & simplify thermal design
- Mass and volume reduction enables launch of more receiver satellites
  - new applications: multibaseline interferometry, single-pass tomography, ...
  - opportunity for graceful degradation can further simplify Rx satellite design
- Use dedicated Tx-only satellite (if compared to companion mission)
  - highly efficient illuminatior (no TRMs, no circulators, TWTs, FMCW, ...)
  - continuous multistatic operation, free of operational conflicts
  - optimized Tx/Rx design and performance with dedicated acquisition mode
  - combination of multiple Rx signals provides new opportunity for data reduction

The MirrorSAR System Concept



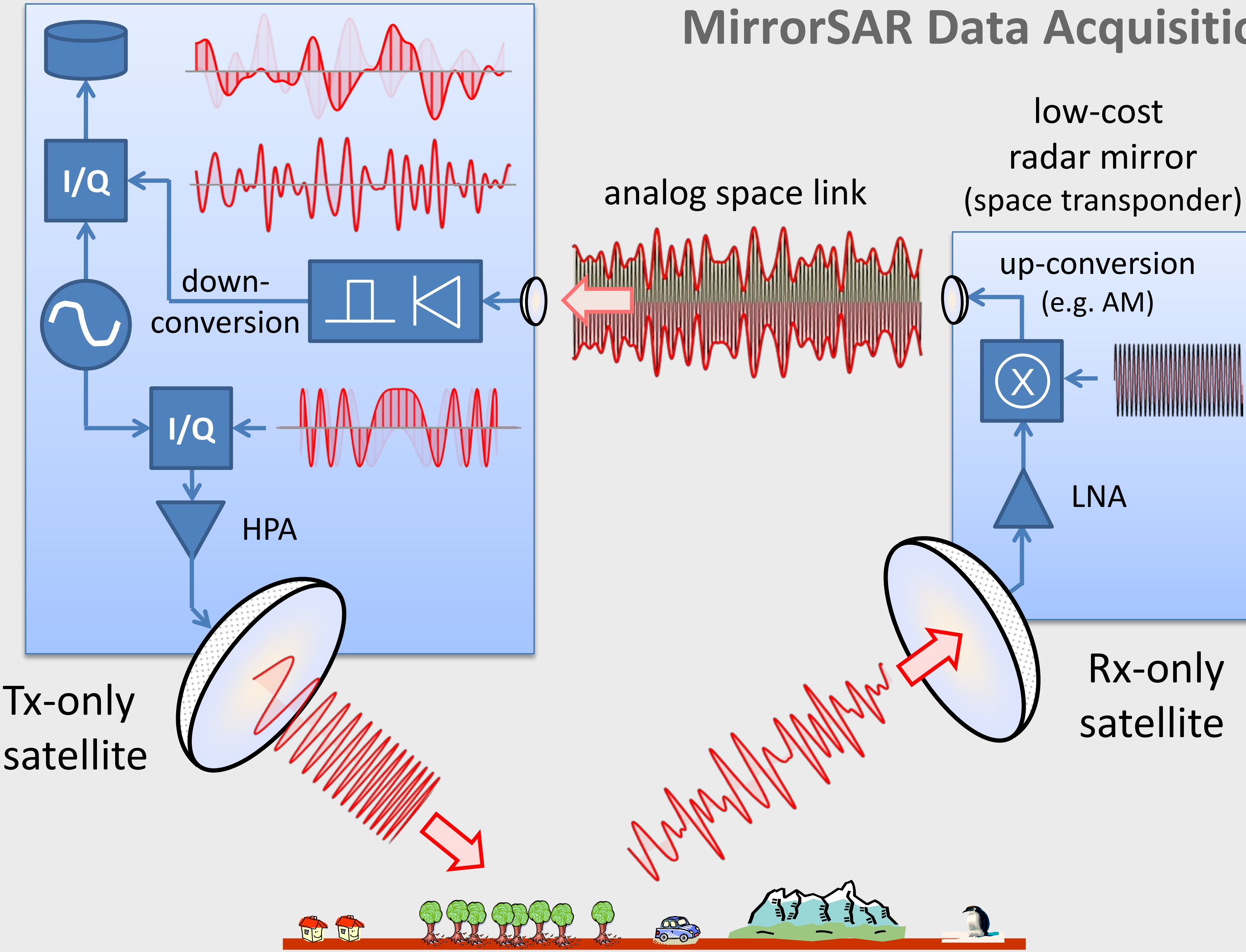
Dedicated Tx-only S/C:
- high efficiency (e.g. TWT, FMCW)
- less losses (e.g. no circulators)
- option for multi-satellite data compression

Cheap Rx-only S/C:
- transponder-like
- no memory
- no data downlink
- low power
- light weight

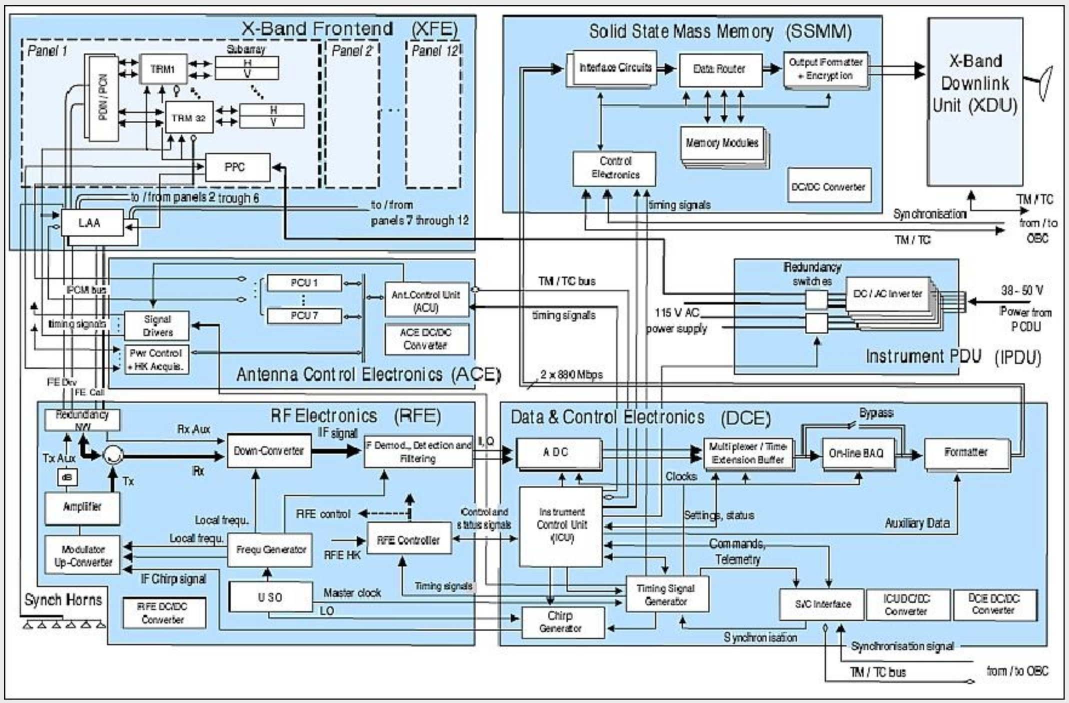
On-ground post-processing
- ambiguity reduction (e.g. CEBRAS)
- direct signal suppression (e.g. Doppler filter)
- nadir suppression (FMCW waveform diversity)

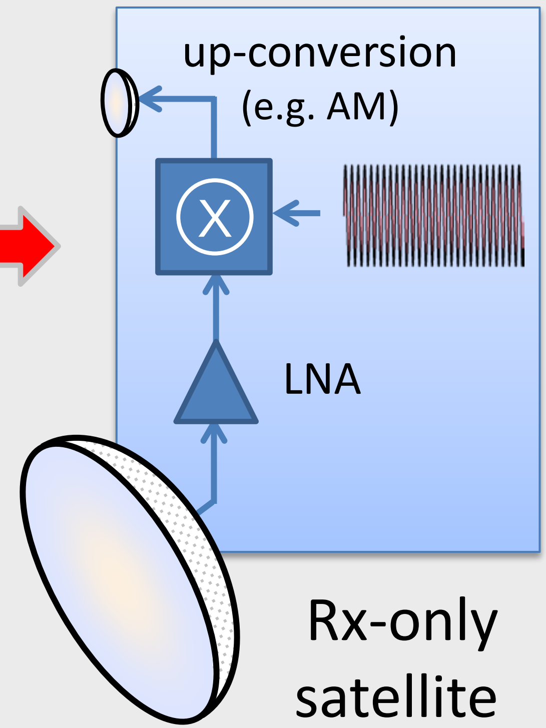
Tx/Rx separation enables:
- new modes and applications
- very wide swath (e.g. 500 km)
- high resolution (e.g. 1-2 m)

MirrorSAR Data Acquisition



low-cost
radar mirror
(space transponder)



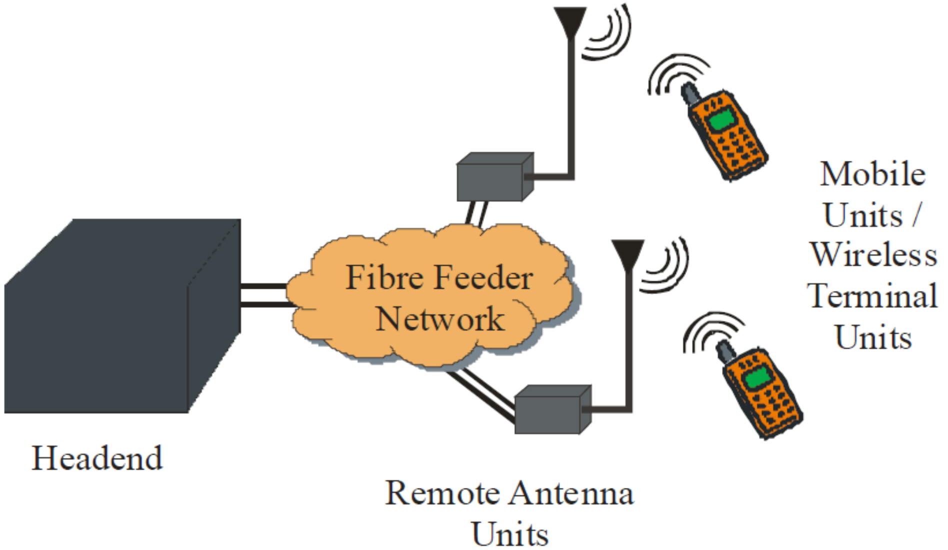


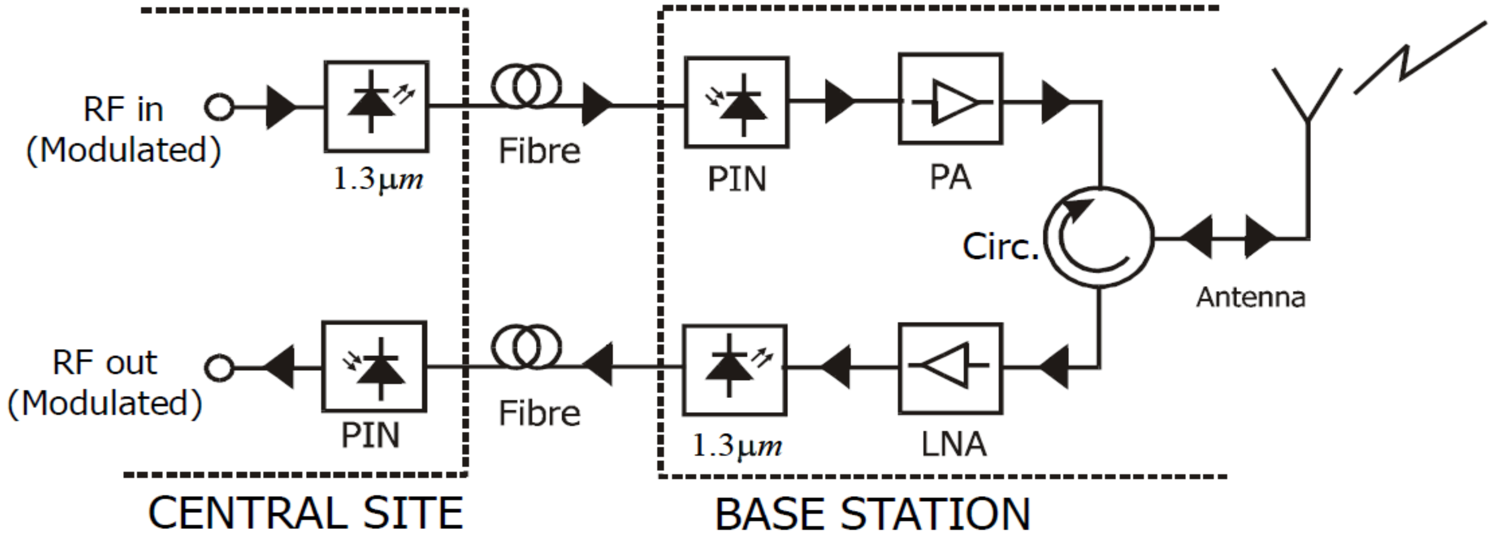
Rx-only
satellite

(from D. Miller, M. Stangl, R. Metzig, "On-Ground Testing of TerraSAR-X Instrument," EUSAR 2006, Dresden, Germany, May 16-18, 2006)

Commonalities with Trends in Mobile Communication

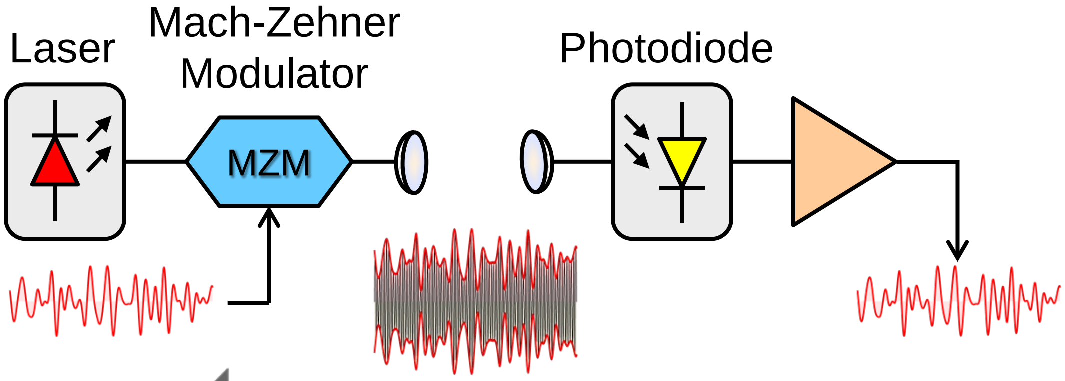
- Centralized RF signal generation and processing (headend)
- Multiple remote antenna units with minimum hardware effort
- RF signal distribution by Radio-over-Fibre (RoF)





Optical Space Link for MirrorSAR

- Wide bandwidth, no ITU restrictions
- Direct intensity modulation also for very high RF frequencies (up to Ka band)
- High SNR already for low laser power and very small telescope
- Less complex than space-to-ground link (relaxed pointing, no atmosphere)
- Will become very light, compact and low power (cf. CubeSat developments)



OsirisV3

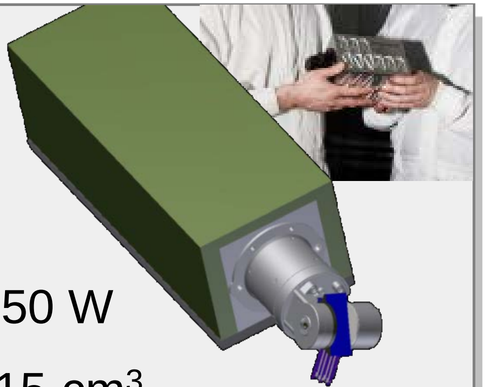
(DLR/Tesat)

Mass: ~ 5 kg

DC power: < 50 W

Size: 30x30x15 cm^3

Rate: 10-100 Gbit/s (to ground!)



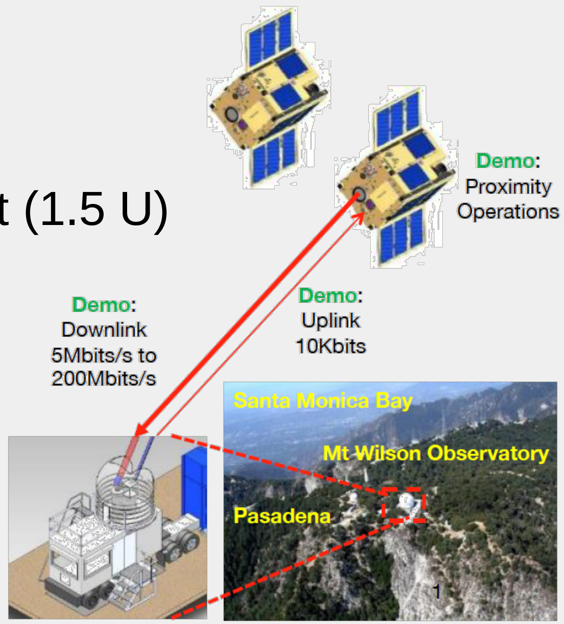
OCSD

(NASA)

CubeSat (1.5 U)

Demo

(2017)

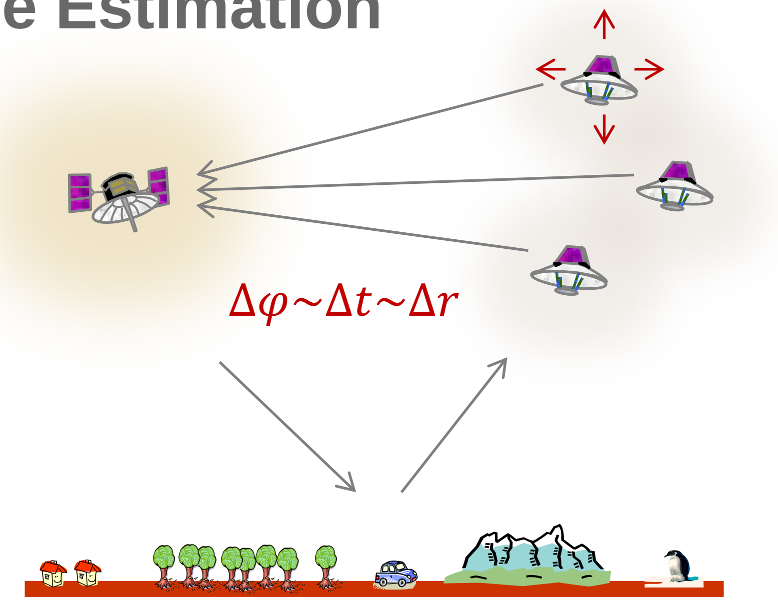


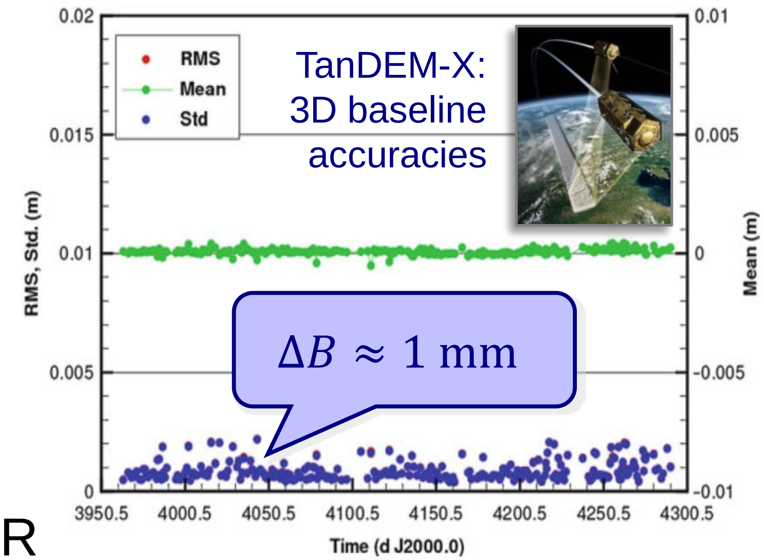
Future

Data Rate: 2.5 Gbit/s (to ground!)

MirrorSAR Synchronization / Baseline Estimation

- Radar echo forwarding causes time delay that depends on relative satellite position
- Relative satellite position varies smoothly
  - no high-frequency phase errors (in contrast to companion sat with separate Rx oscillator)
  - low-frequency phase errors can be corrected by knowledge of relative satellite position
- Relative satellite position can be estimated with high accuracy by double differential GPS measurements (TanDEM-X: ~ 1 mm)
- Dual-frequency GPS is anyway needed for accurate baseline determination
- Remaining phase errors are comparable to the effect of residual baseline errors in InSAR





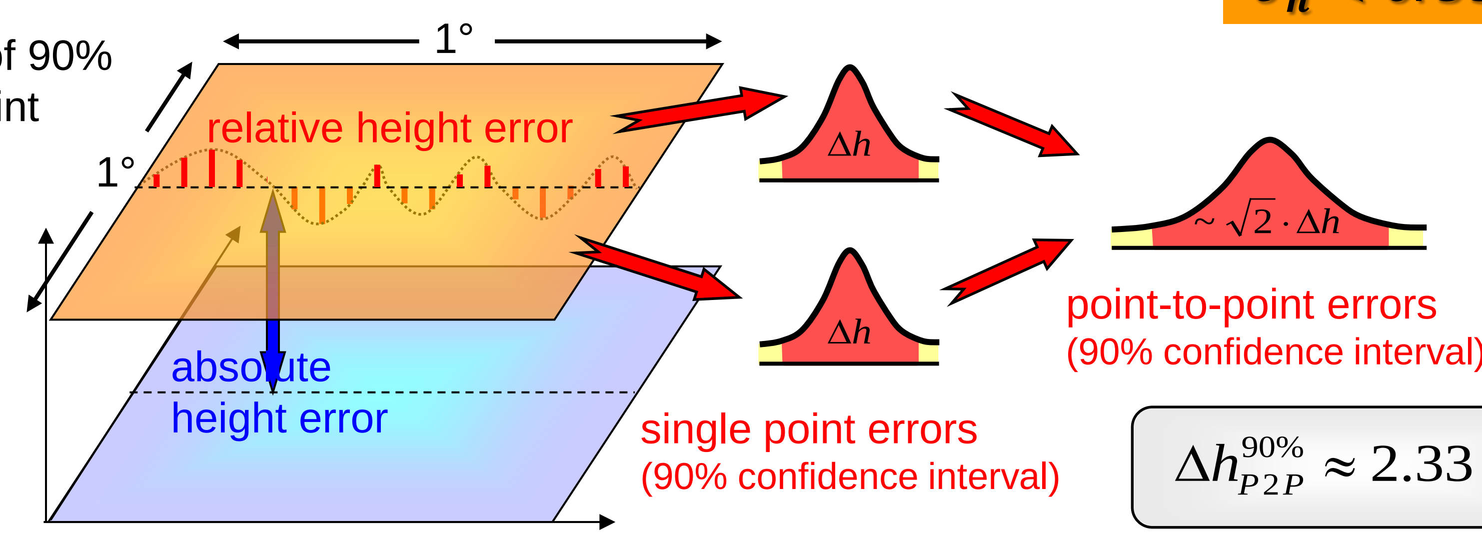
MirrorSAR Example: Cost-Efficient Acquisition of DEMs with Unprecedented Accuracy

Digital Elevation Models

	Spatial Resolution	Absolute Vertical Accuracy (90%, max. global offset)	Relative Vertical Accuracy (point-to-point in 1° cell, 90%)
DTED-1	90 m x 90 m	< 30 m	< 20 m
DTED-2	30 m x 30 m	< 18 m	< 12 m
TanDEM-X	12 m x 12 m	< 10 m	< 2 m
Level 4	**6 m x 6 m**	**< 5 m**	**< 0.8 m**

$\sigma_h < 0.35\ \mathrm{m}$!

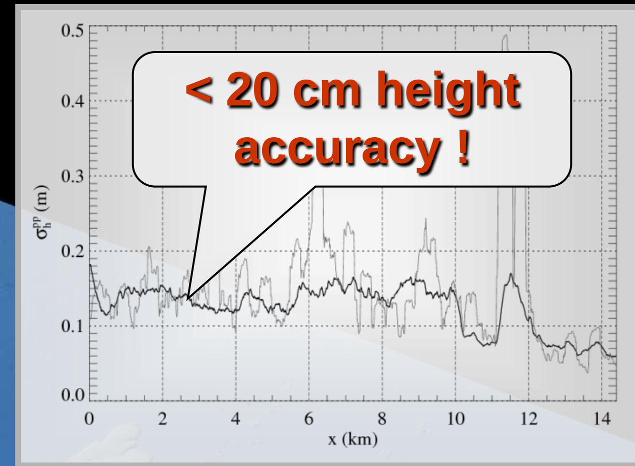
Definition of 90% point-to-point errors:

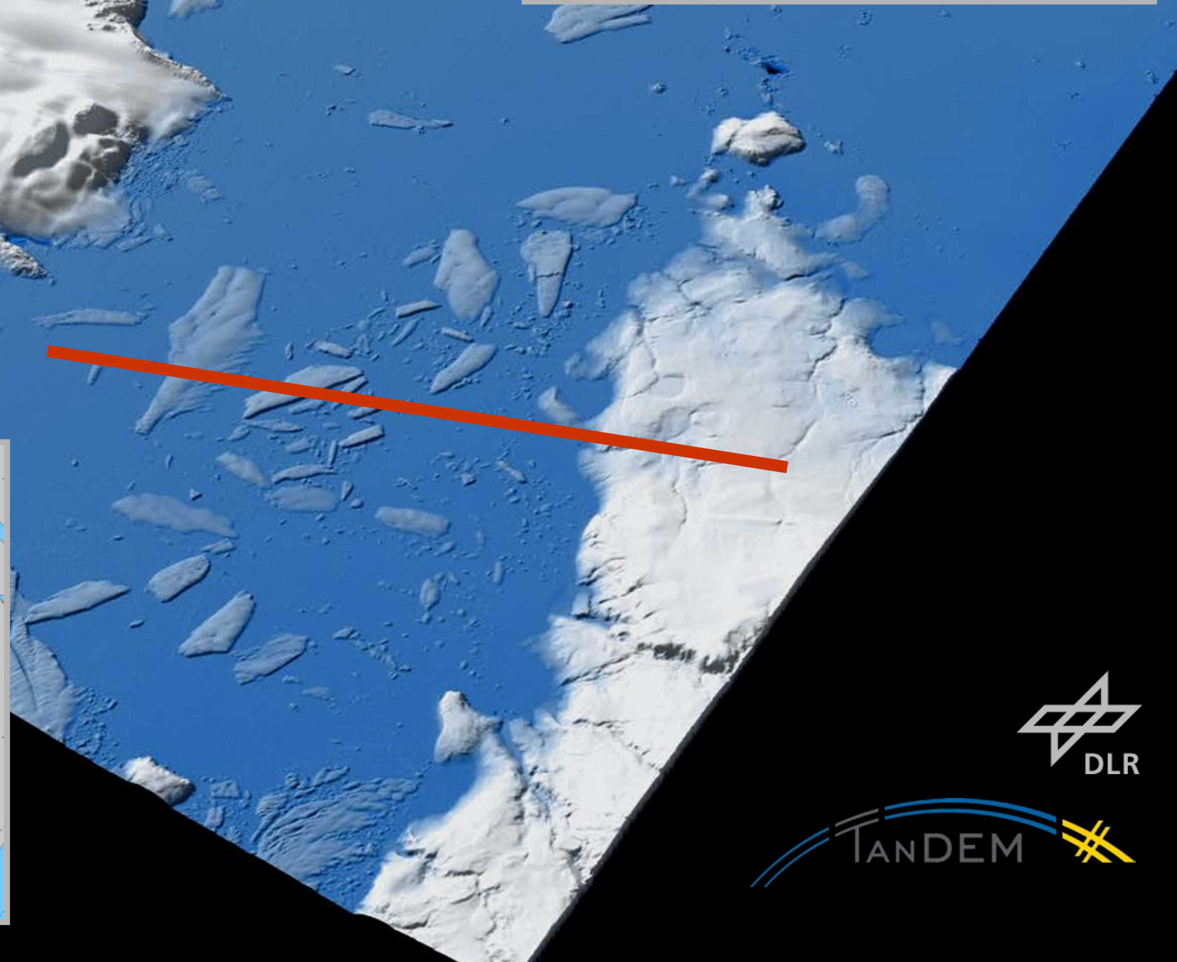


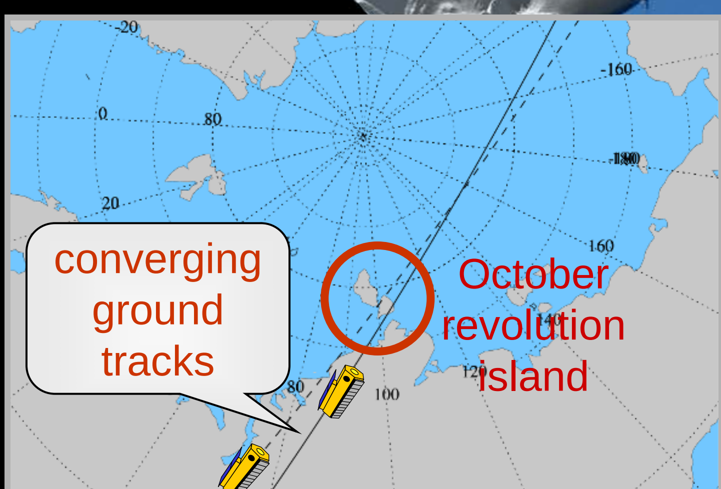
$$\Delta h_{P2P}^{90\%} \approx 2.33 \cdot \sigma_h$$

Large Baseline DEM with TanDEM-X

- First TanDEM-X DEM (acquired before reaching 20 km formation)
- Large effective baseline (~ 2 km) from Earth rotation
- $h_{amb} \approx 3.8$ m !



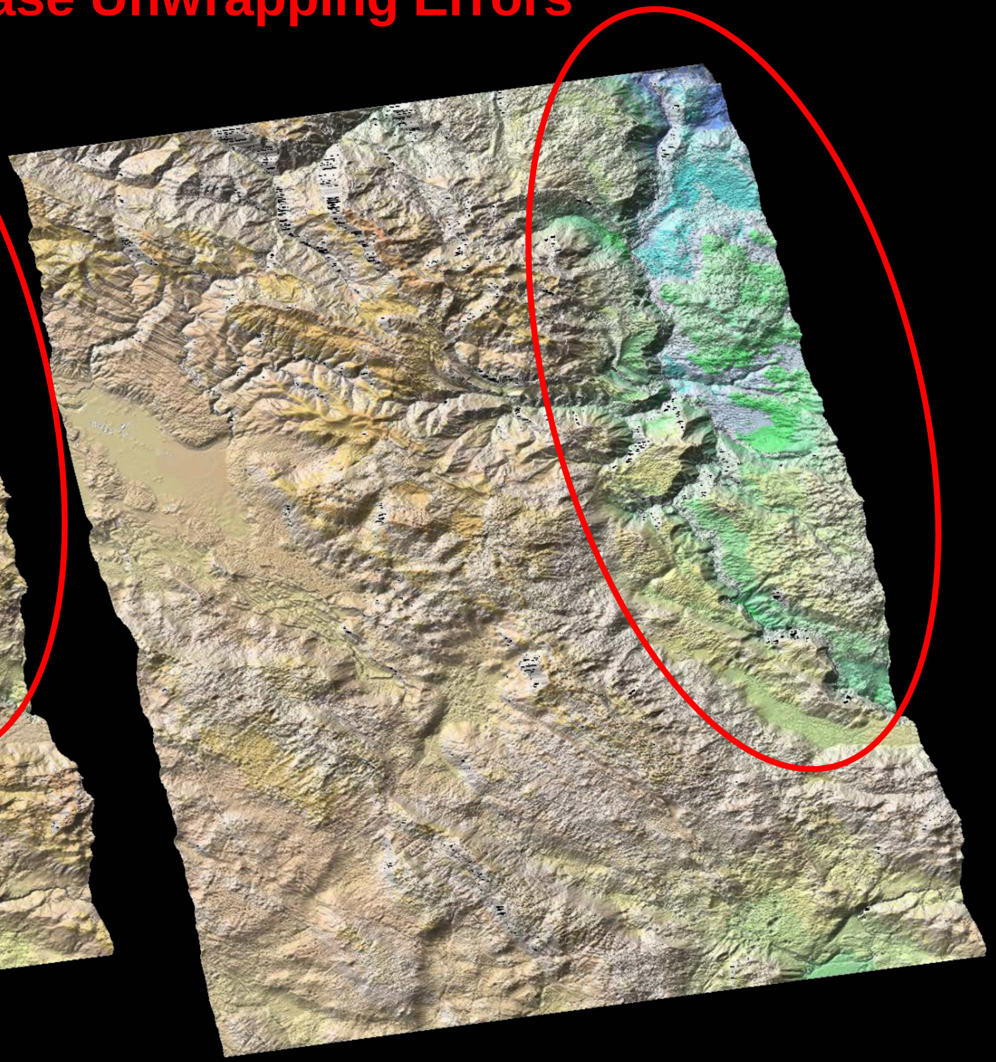




DLR
TANDEM

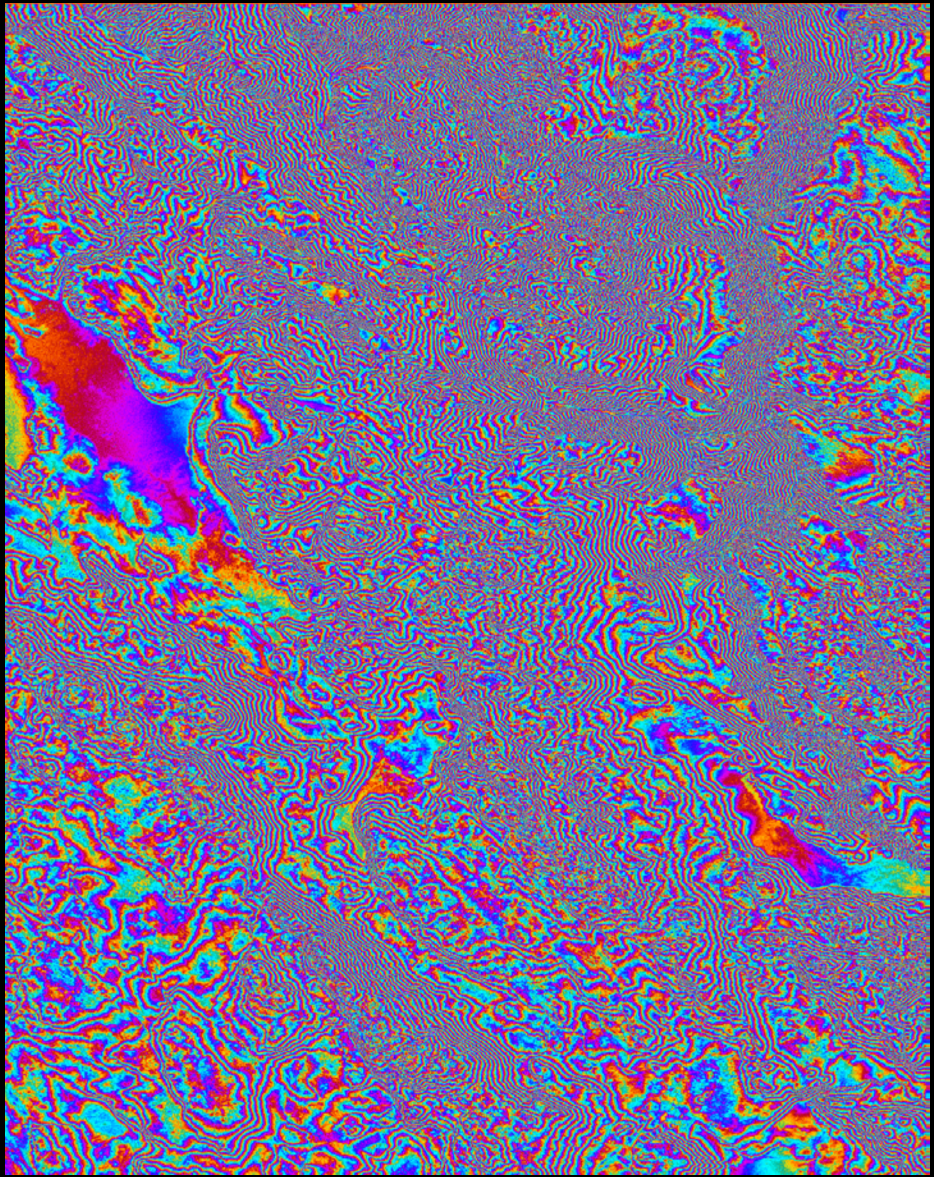
TanDEM-X DEMs with Different Baseline Lengths

B_{eff} = 107.8 m, h_{amb} = 49.2 m

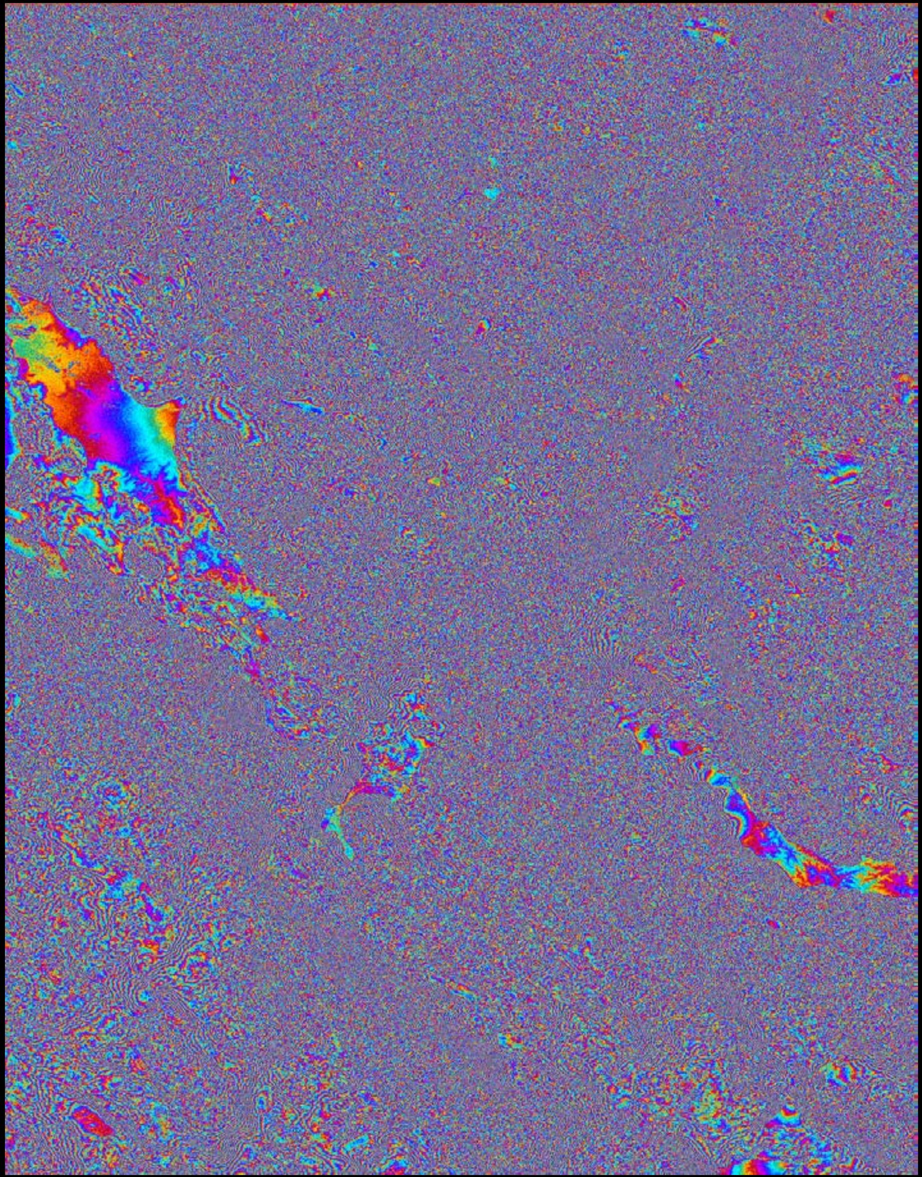


B_{eff} = 267.9 m, h_{amb} = 19.7 m

TanDEM-X Interferograms with Different Baseline Lengths



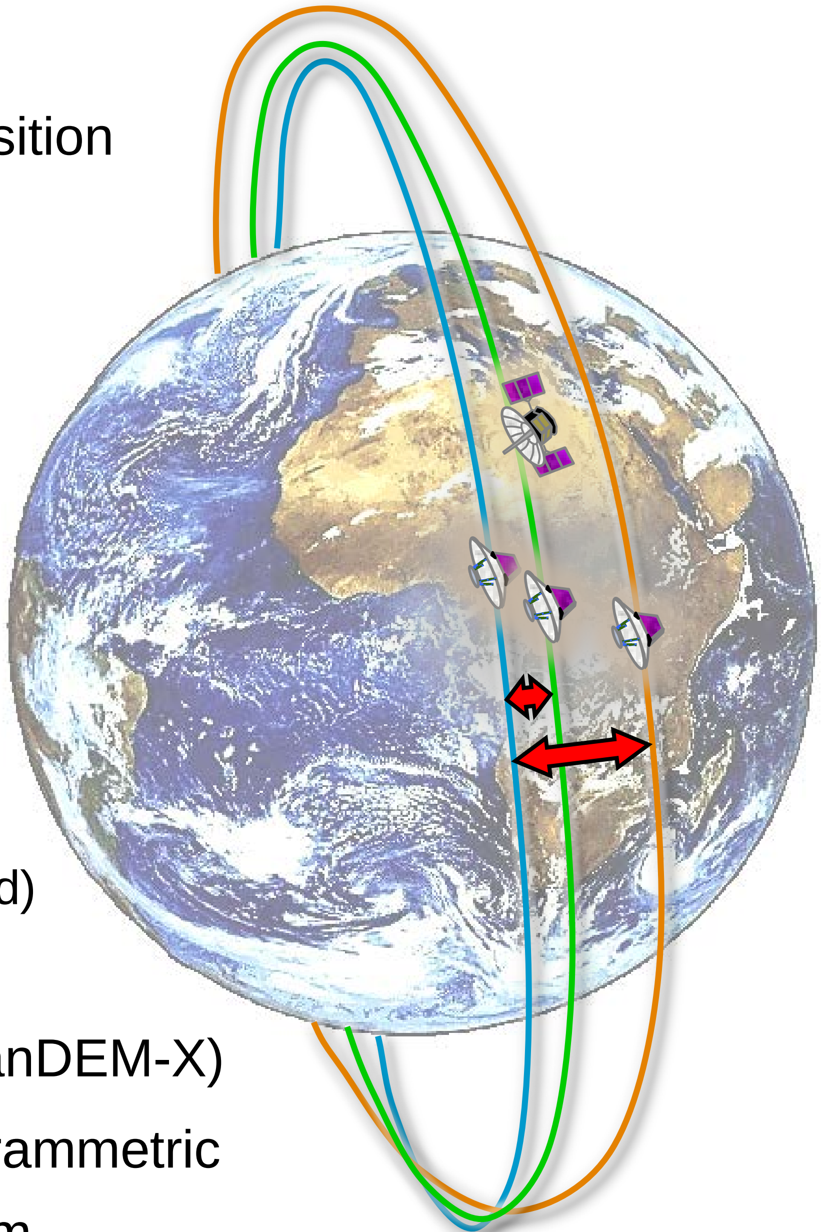
B_{eff} = 107.8 m, h_{amb} = 49.2 m



B_{eff} = 267.9 m, h_{amb} = 19.7 m

Mission Concept

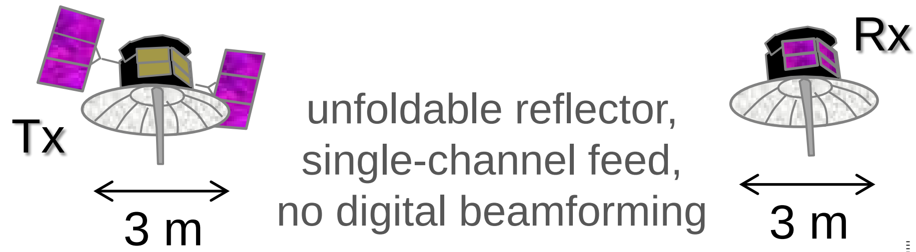
- Simultaneous interferometric data acquisition with two interferometric baselines
- Small baseline (e.g. h_{amb} = 75 m):
  - avoid height ambiguities
  - high coherence for volume scatterers
- Large baseline (e.g. h_{amb} = 15 m):
  - excellent relative height accuracy (e.g. Δh = 0.4 m for $\Delta\varphi$ = 10°)
  - excellent absolute height accuracy (e.g. Δh = 0.5 m for ΔB = 1 mm in X band)
- No decorrelation and height changes between acquisition of two baselines (TanDEM-X)
- Phase unwrapping supported by radargrammetric evaluation of large baseline interferogram

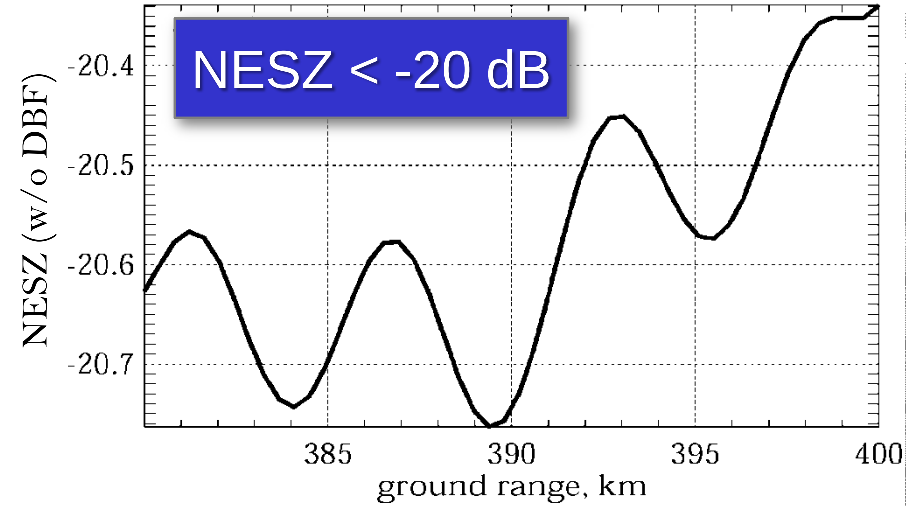


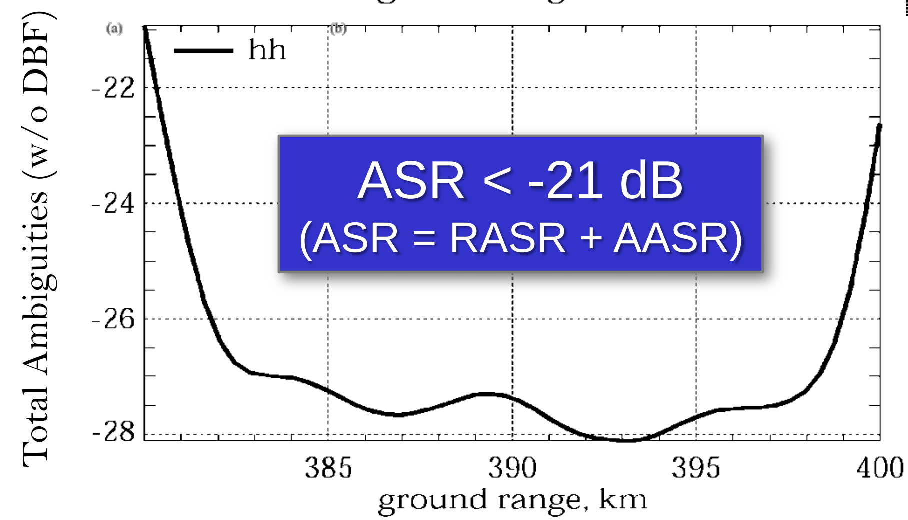
X-Band Performance Example

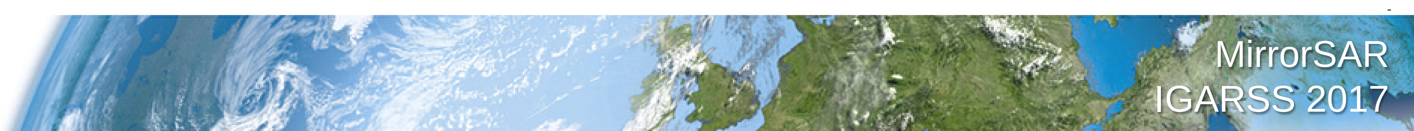
- Design goal: minimize weight, costs, stowed volume and hardware effort
- 20 km swath can provide two global coverages (asc. & desc.) in 4.4 months

Parameter		Value
Resolution		1.5 m x 1.5 m
Incident Angle		40°
Swath Width (no DBF)		20 km
Orbit Height		~ 500 km
Tx Antenna (Reflector)		3 m ∅
Rx Antenna (Reflector)		3 m ∅
Center Frequency		9.65 GHz
Bandwidth		150 MHz
Avg. Tx Power	w/o Rx DBF	500 W
	(with Rx DBF)	(167 W)
Noise Figure / Losses		5 dB





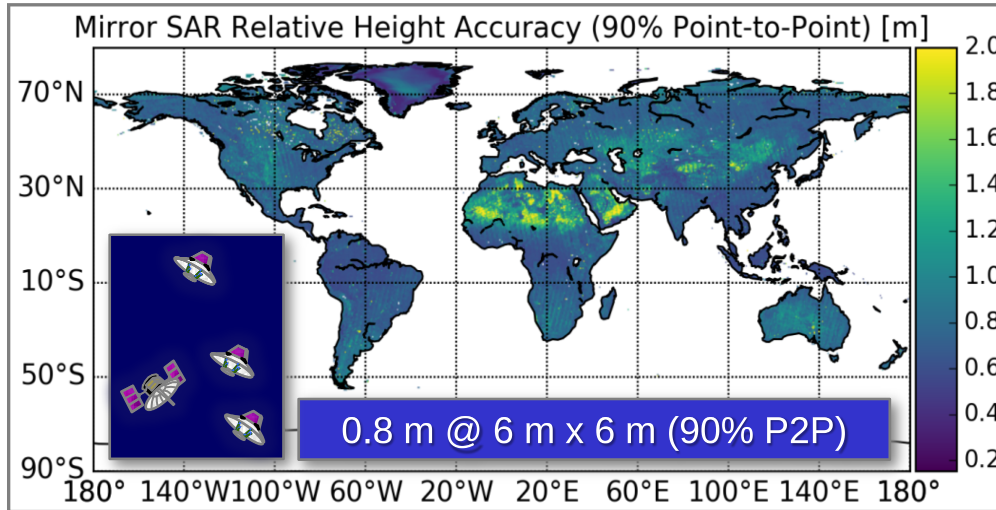




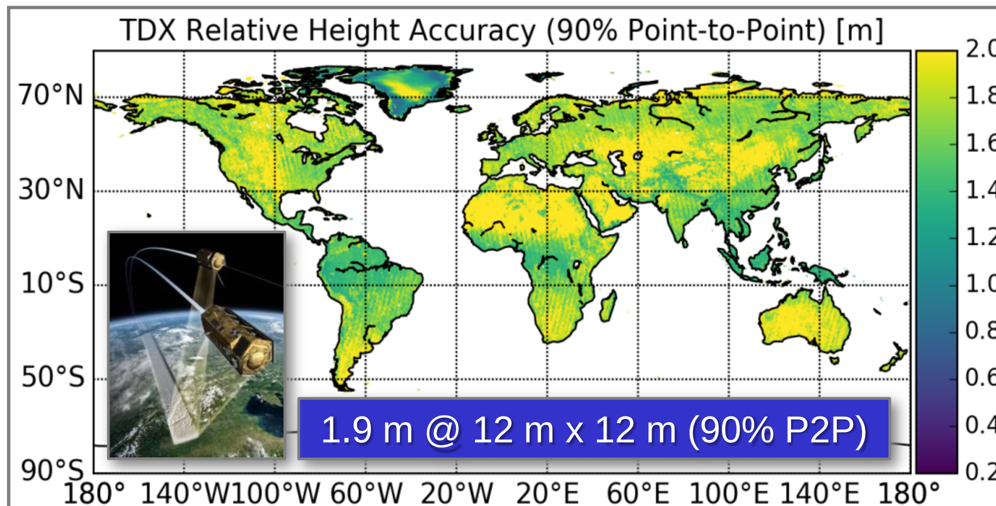
X-Band Performance Example

- Constant incident angle: 40°
  - good compromise between sensitivity, layover & shadow
- Two interferometric baselines:
  - $B_\perp$ = 870 m (h_{amb} = 15 m, 5% of $B_{\perp,crit}$)
  - $B_\perp$ = 174 m (h_{amb} = 75 m, 1% of $B_{\perp,crit}$)
- 20 km swath can provide total global coverage in less than 5 months
  - two coverages (asc. & desc.) possible
  - full coverage for Φ_{lat} > 60° could be achieved already after 2 months
- Frequency selection
  - TanDEM-X: good results with X band
  - Ku/Ka band could be an alternative to reduce penetration for volume scatterers (cf. SIGNAL proposal)
  - MirrorSAR with reflector antennas is well suited for multi-frequency DEMs

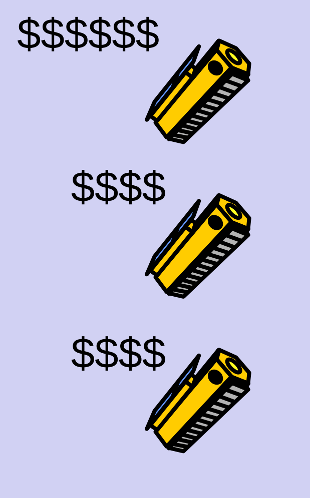
MirrorSAR global DEM (~ 5 months)

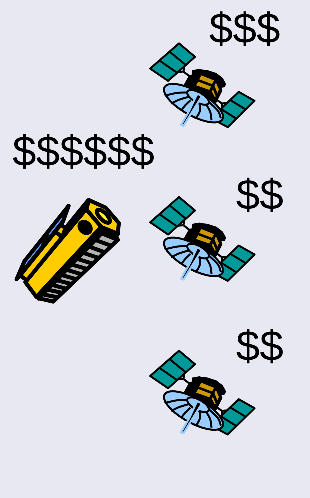


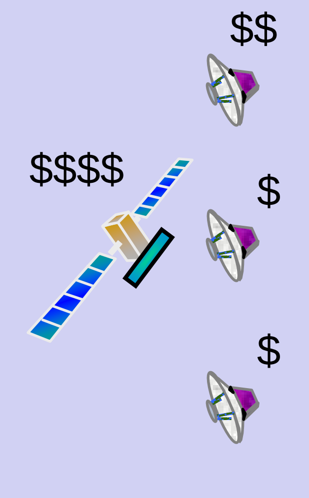
TanDEM-X global DEM (~ 3 years)

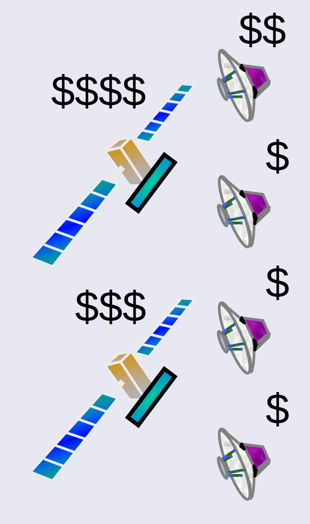


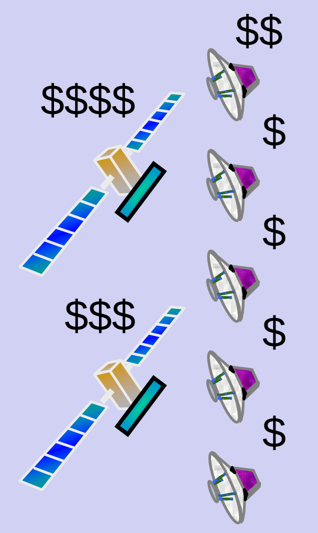
MirrorSAR: Cost and Reliability Considerations











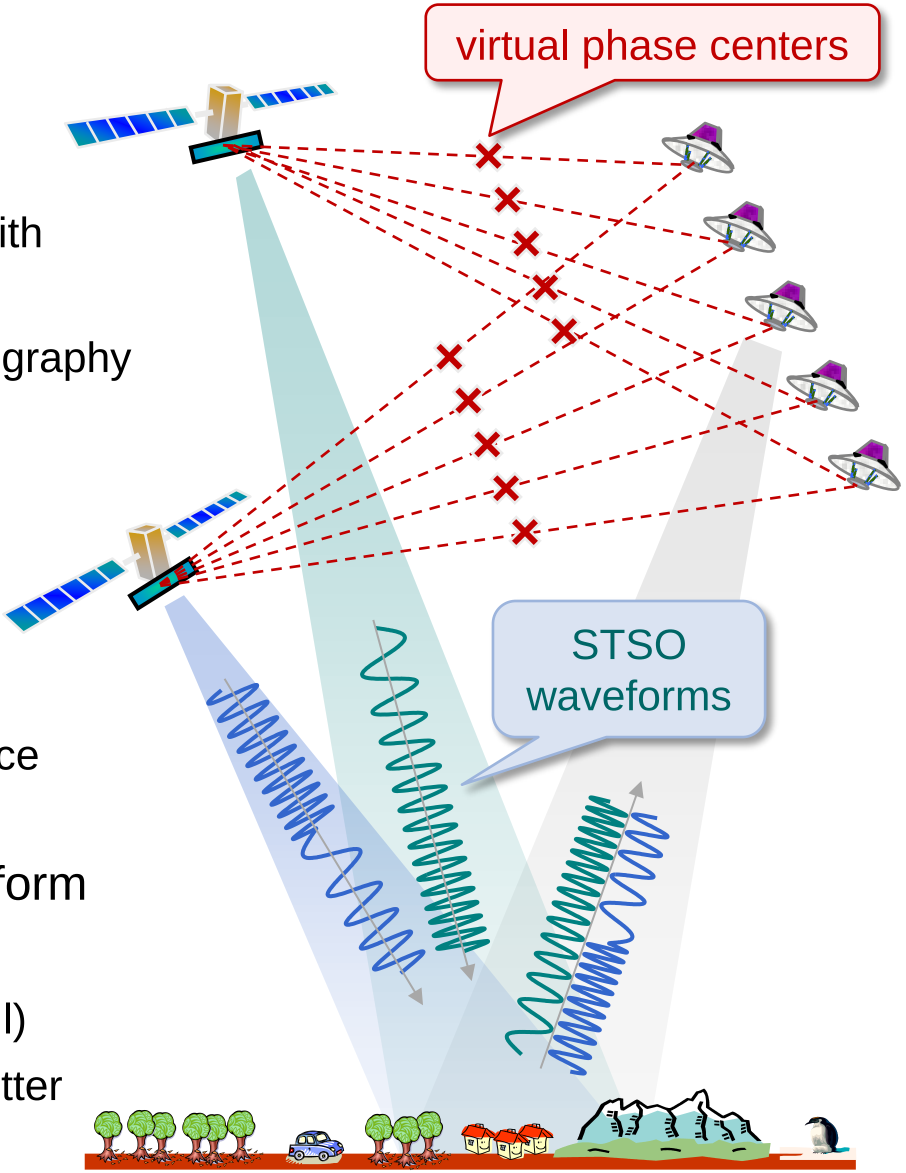
		3 Tx/Rx	1 Tx/Rx + 3 Rx	1 Tx + 3 Rx	2 Tx + 4 Rx	2 Tx + 5 Rx
Costs		14 \$	13 \$	8 \$	12 \$	13 \$
Reliability (2 $B_\perp$)	p=0.95	0.86	0.81	0.81	0.98	0.996
	p=0.90	0.73	0.66	0.66	0.94	0.982
	p=0.85	0.61	0.52	0.52	0.87	0.951
	p=0.80	0.51	0.41	0.41	0.79	0.904

Opportunities with Additional Receivers and Transmitters

- Additional receivers can be used to
  - improve DEM (triple-baseline interferometry with h_{amb} = 4 m enables Δh = 0.2 m @ 6 m)
  - resolve layover (enables DEM generation with steep incident angles in canyons, cities, ...)
  - demonstrate 3-D imaging (single-pass tomography for cities and semi-transparent scatterers)
- Additional transmitters can be used to
  - demonstrate new MIMO-SAR modes
  - increase number of virtual phase centers

$$n = n_{Tx} \cdot n_{Rx}$$

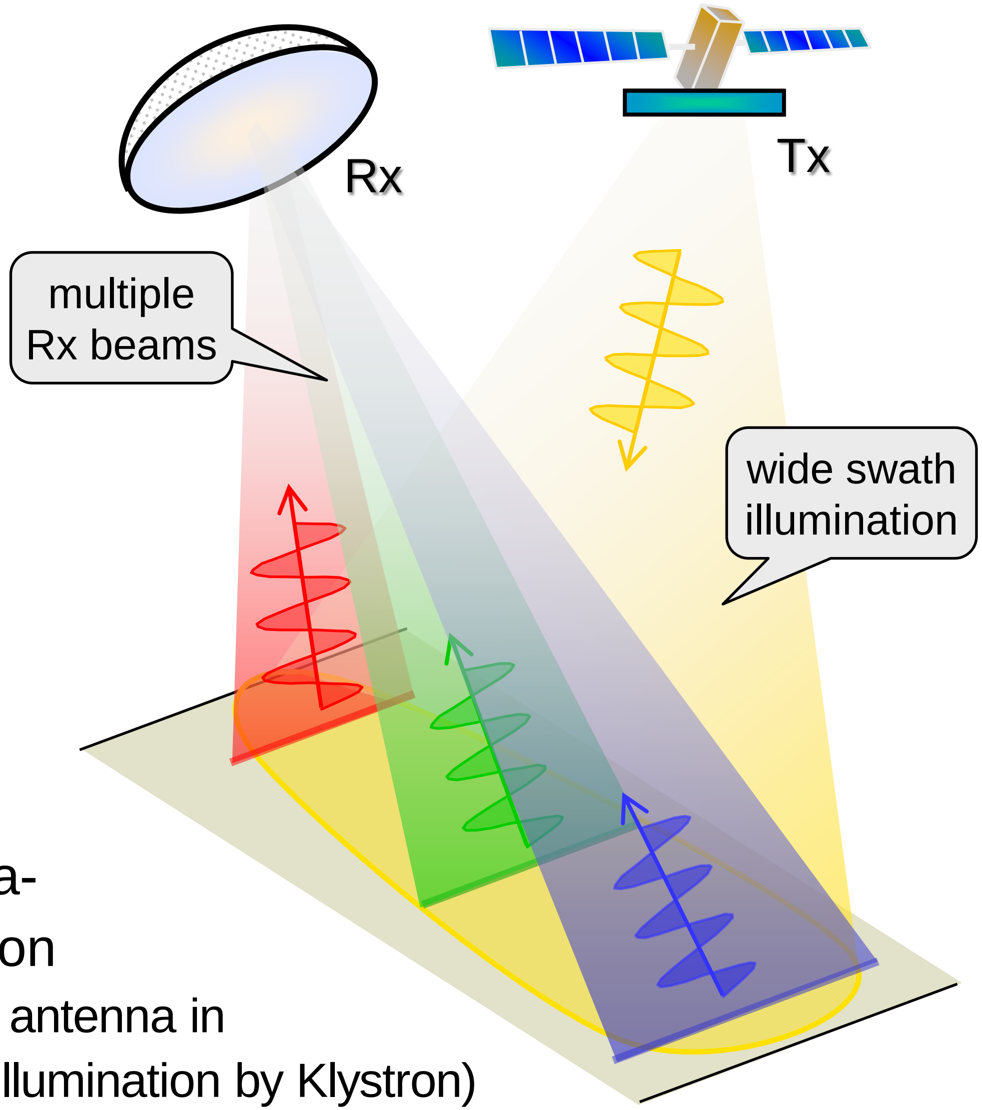
  - separate single-, double- and multiple-bounce scattering by MIMO-SAR tomography
- MIMO-SAR demonstrations require waveform separation that can be achieved by
  - choosing steeper incident angle (satellite roll)
  - adding a switchable feed network in transmitter and/or receiver to narrow beamwidth



MirrorSAR for High-Resolution Ultra-Wide Swath SAR Imaging

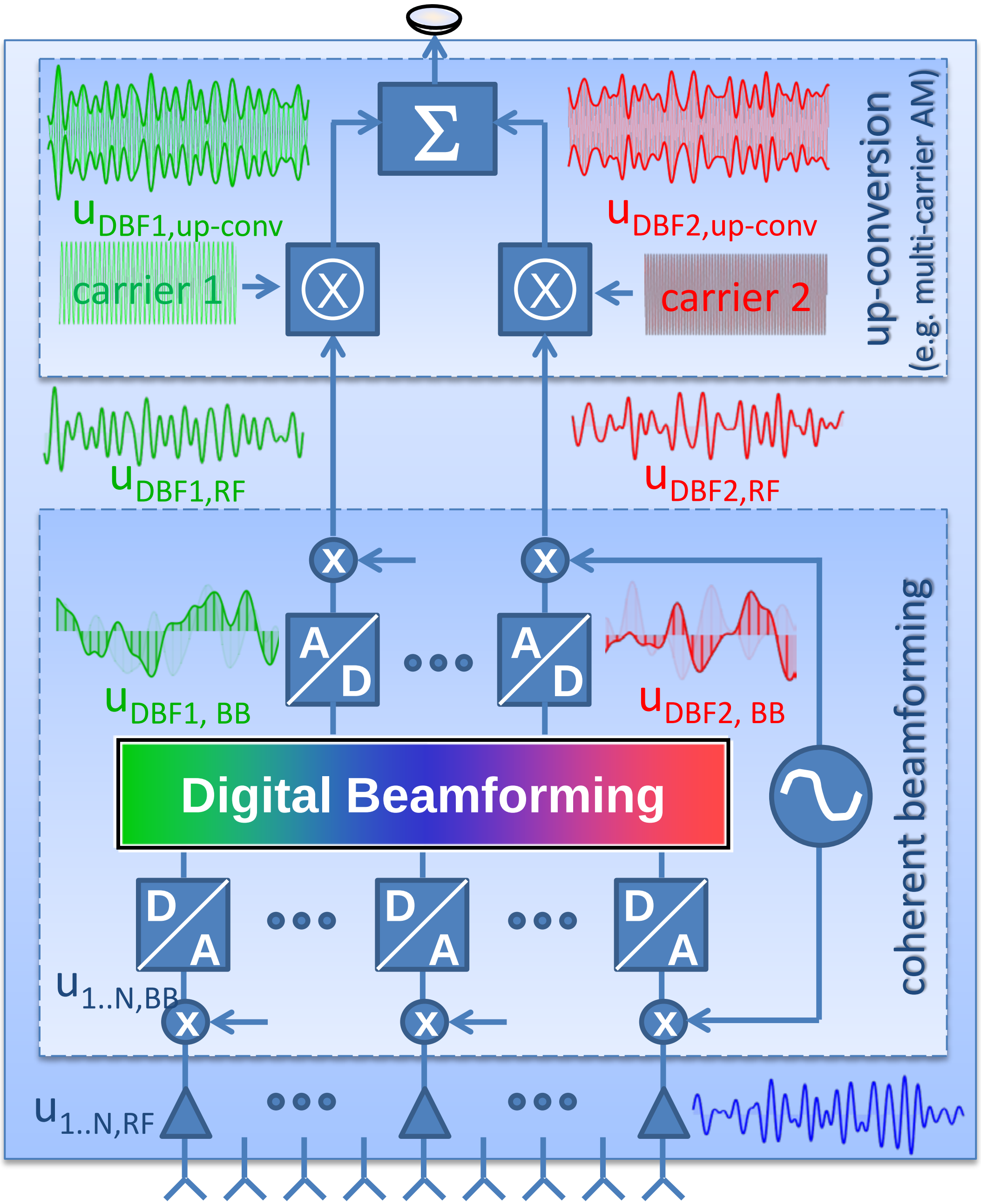
High-Resolution Ultra-Wide-Swath SAR Imaging

- Simultaneous imaging of multiple swaths in stripmap mode
- No blind ranges due to separate Tx and Rx satellites
- Advanced range ambiguity suppression with CEBRAS enables compact Rx antenna (if compared to staggered SAR)
- Advanced suppression of direct signal and nadir echo by Doppler filter and waveform diversity
- Unique potential for imaging of ultra-wide swaths with very high resolution
  (even up to 500 km @ 1 m with 6 m^2 Rx antenna in X band (2 m^2 in Ka band) using FMCW illumination by Klystron)



Multichannel Mirror-SAR Transponder

- wide-swath imaging requires digital beamforming with multiple Rx beams
- phase integrity can, e.g., be preserved by
  - coherent demodulation
  - baseband DBF
  - coherent remodulation
- radar echoes from multiple Rx beams are simultaneously transferred to master satellite
  - use of different carriers
  - multichannel encoding



Conclusions

- MirrorSAR is a new approach for the cost-efficient implementation of future multistatic SAR systems and missions
  - low-cost Rx satellites (no RFE, no DCE, no sync, no memory, no downlink, …)
  - highly efficient Tx satellites (no TRMs, no circulators, TWT, FMCW, …)
  - new opportunities for multistatic on-baord data reduction before downlink
  - distributed redundancy concepts support further simplification of hardware
- MirrorSAR paves the way for new Earth observation products
  - decimeter-level DEMs and DEM time-series by multibaseline interferometry
  - 3-D structure maps by single-pass SIMO and MIMO tomography
  - 4-D structure change maps by differential tomography and holography
  - quasi-continuous Earth monitoring by new high-resolution wide-swath modes
  - multiangular images for better segmentation, classification and identification
  - resolution enhancement, measurement of object movements, …