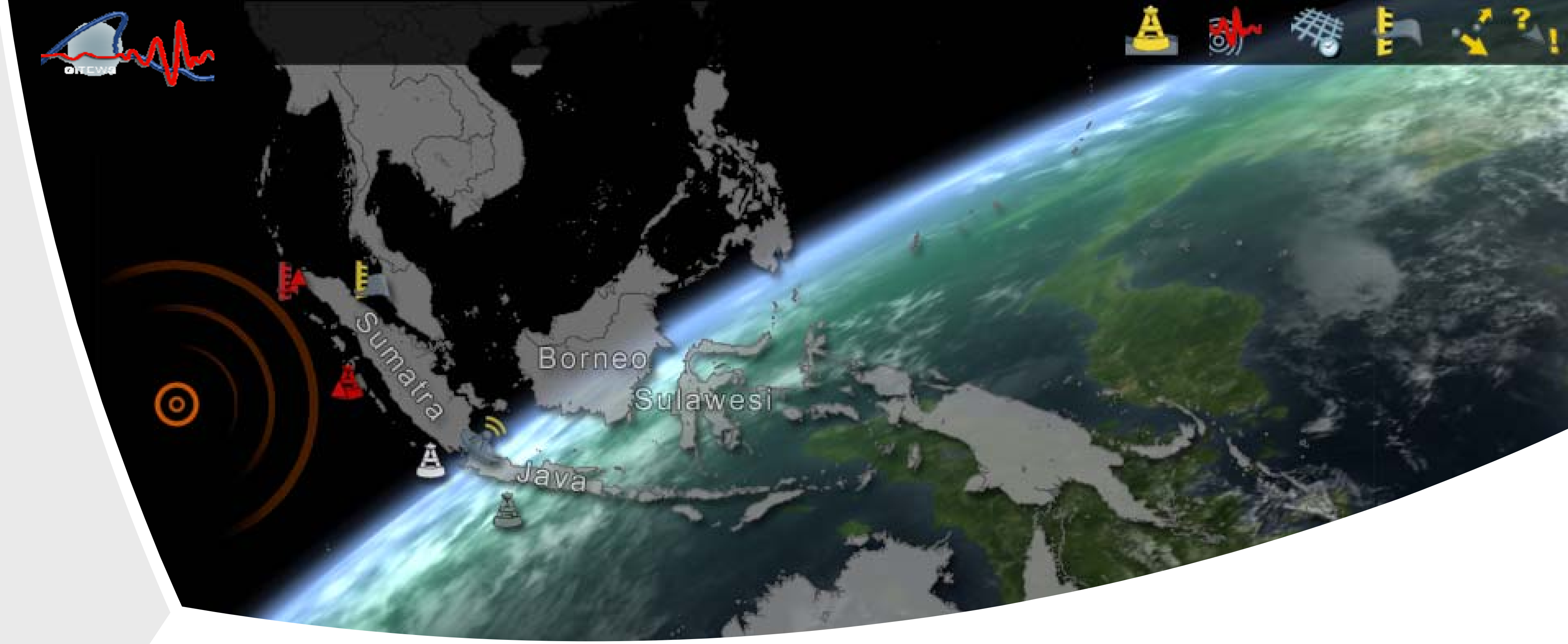


GITEWS

New concepts for space-borne Tsunami early warning using microwave sensors

Dr. Thomas Börner
Microwaves and Radar Institute (IHR)
German Aerospace Center (DLR)

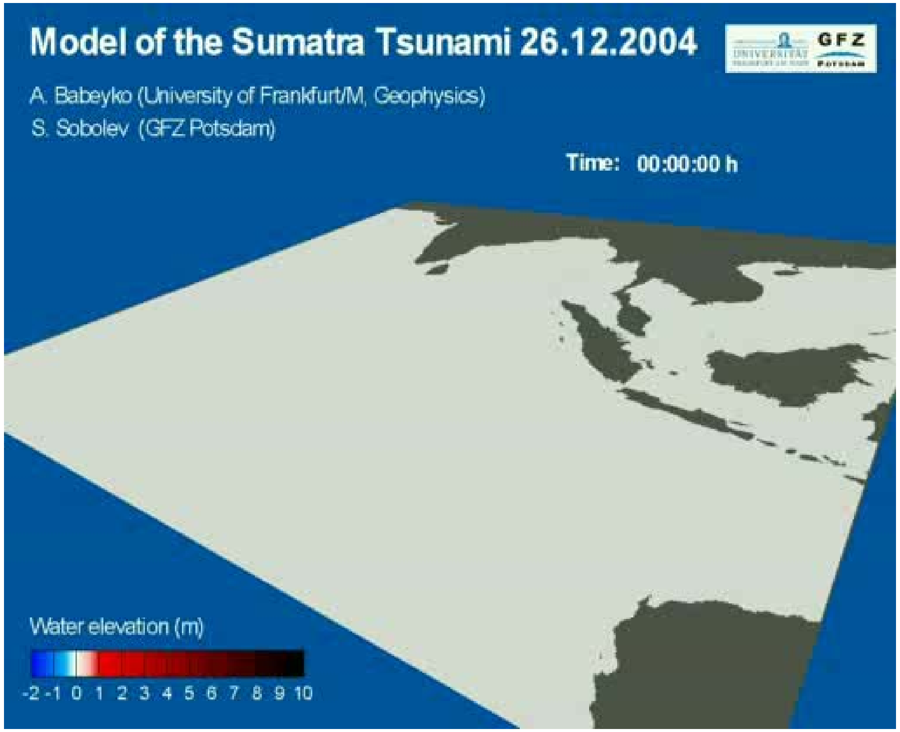
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

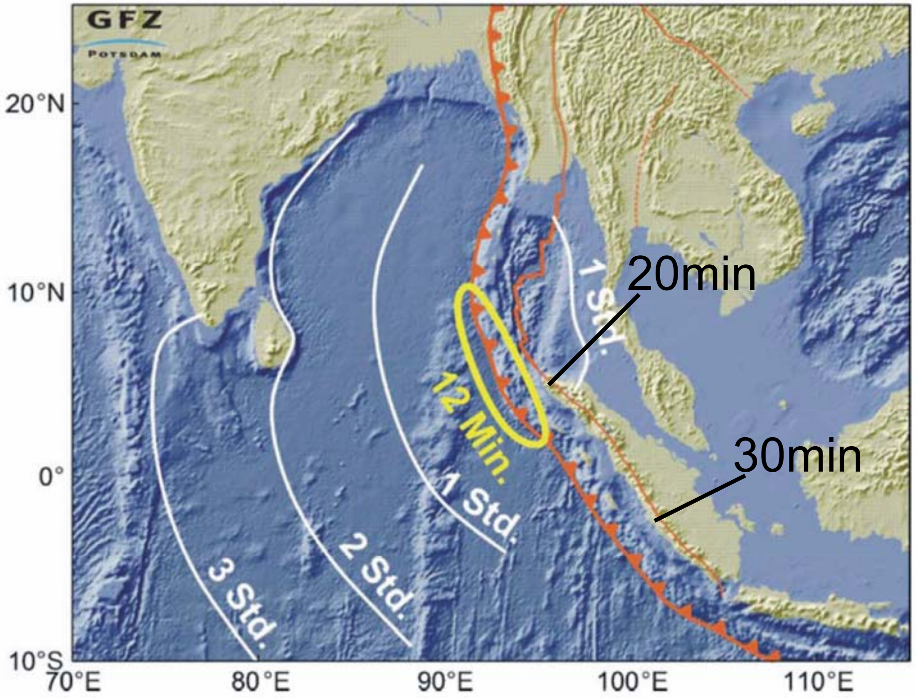
Overview

- Conceiving and designing Radars: Performance Analysis
- Principles of Tsunami Detection for Space-Borne Radars
- Tsunami Early-Warning Systems: Req. on spatial and temporal coverage
- NESTRAD: Near-Space Radar for Tsunami Detection
- G-SAR: Geosynchronous SAR for Tsunami Detection
- Passive Radar: GPS-Reflectometry
- Conclusions

Project Motivation: Boxing Day Tsunami (26.12.2004)

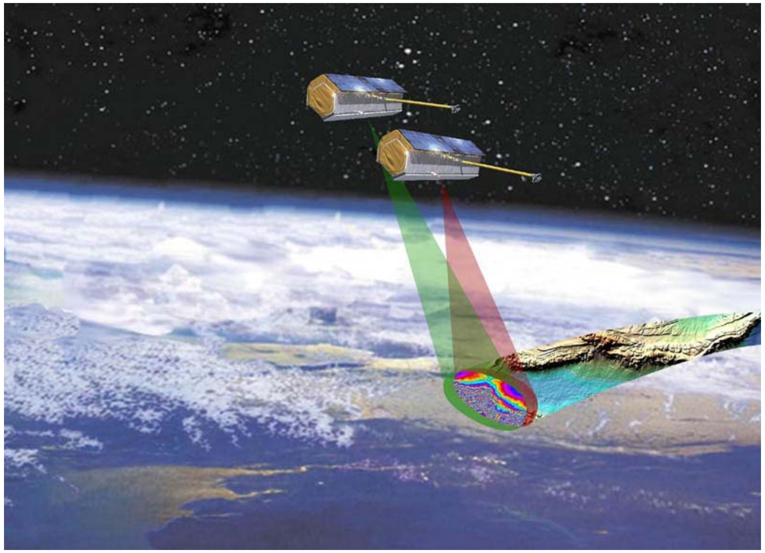
Body count: 228.000 whereas 165.000 in Indonesia (72%)



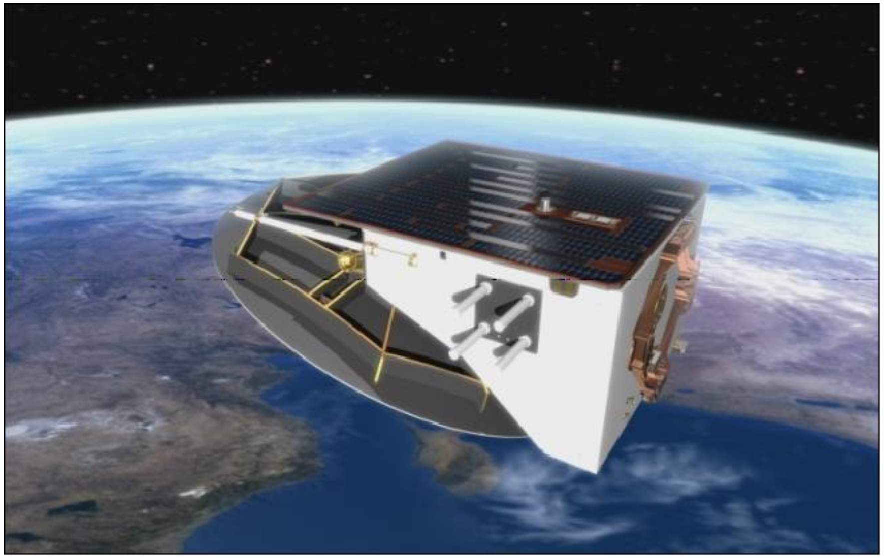


www.gfz-potsdam.de

Microwaves and Radar Institute (Director: Prof. Alberto Moreira)
Current satellite missions



TerraSAR-X TanDEM-X
2 civilian SAR satellites flying in formation



SarLUPE
Constellation of 5 SAR satellites managed by the Ministry of Defense

Conceiving and designing Radars:

Performance Analysis

Heart of radar design – the performance analysis

$$\overline{P}(R) = \left(\frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4}\right)\left(\frac{1}{L}\right)\sigma^0\left(\frac{c\tau}{2\sin(\eta)}\right)\left(\frac{\lambda R}{L_a}\right)$$

Power received by the radar

$$P_N = kNTB$$

Noise power

$$SNR = \overline{P}(R) / P_N$$

Signal-to-**N**oise-**R**atio

→ should be bigger than 10 dB for the desired target!

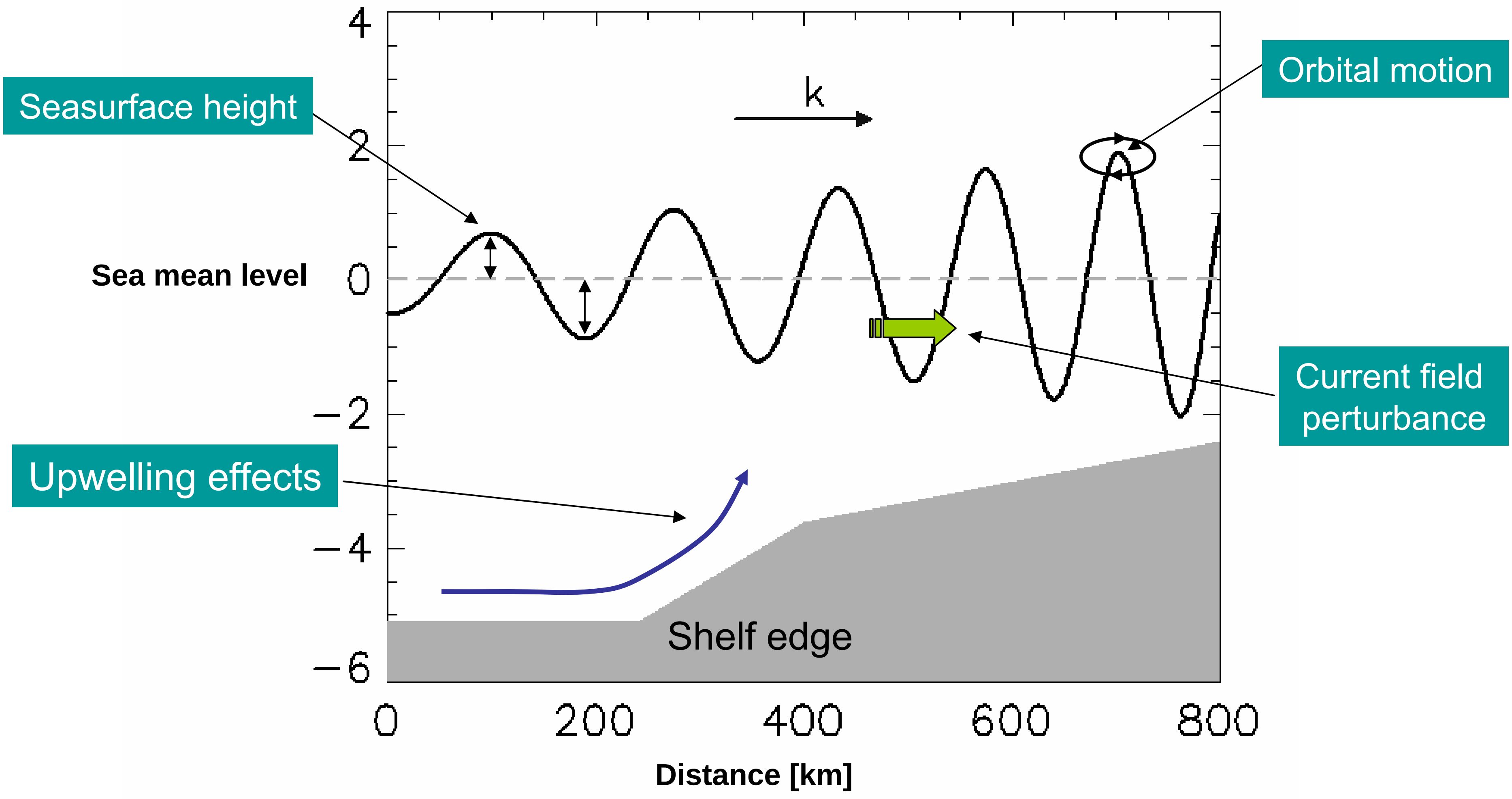
P_t = transmit peak power
L_a = antenna length (azimuth direction)
G = antenna gain
λ = radar wavelength
τ = pulse length
R = range distance to target
η = incidence angle

k = Boltzmann constant
B = receiver bandwidth
T = system temperature
c = speed of light
σ_0 = backscatter cross section
L = loss factor due to attenuation
N = noise figure

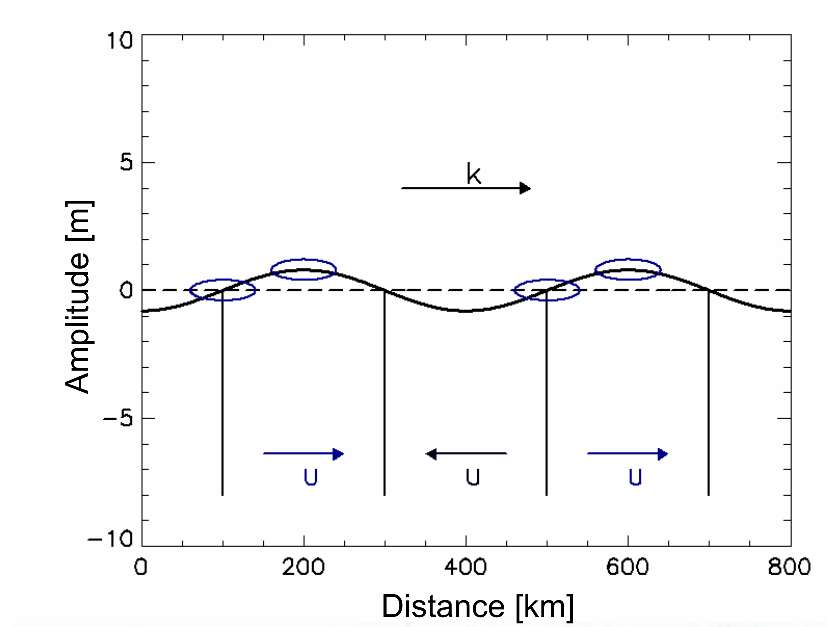
Principles of Detection for Space-borne Radars:

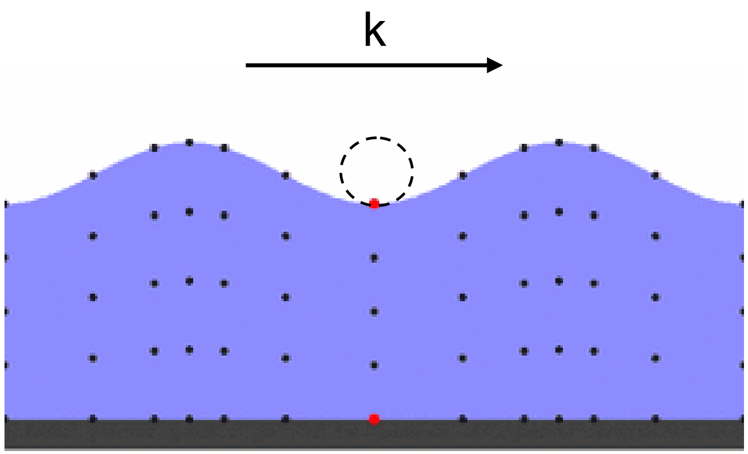
What can we see?

Geophysical Parameters

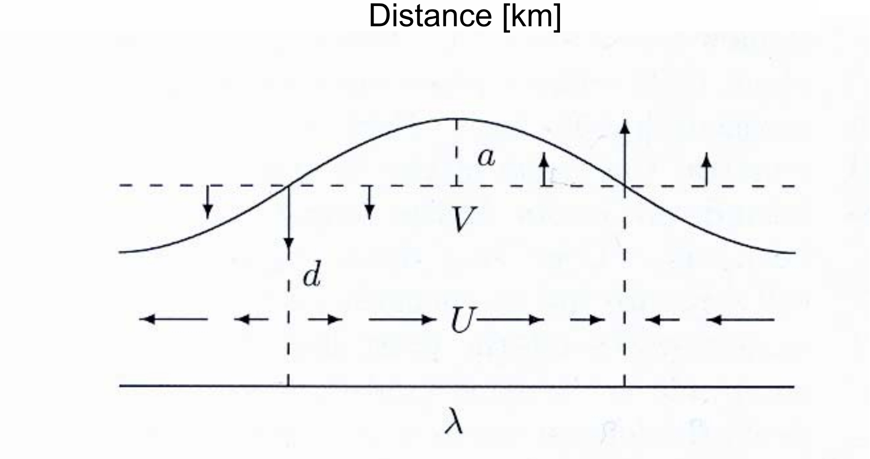


Tsunami parameters





http://de.wikipedia.org/wiki/Tsunami



a	amplitude
d	water depth
U	horizontal velocity
V	vertical velocity
λ	wave length

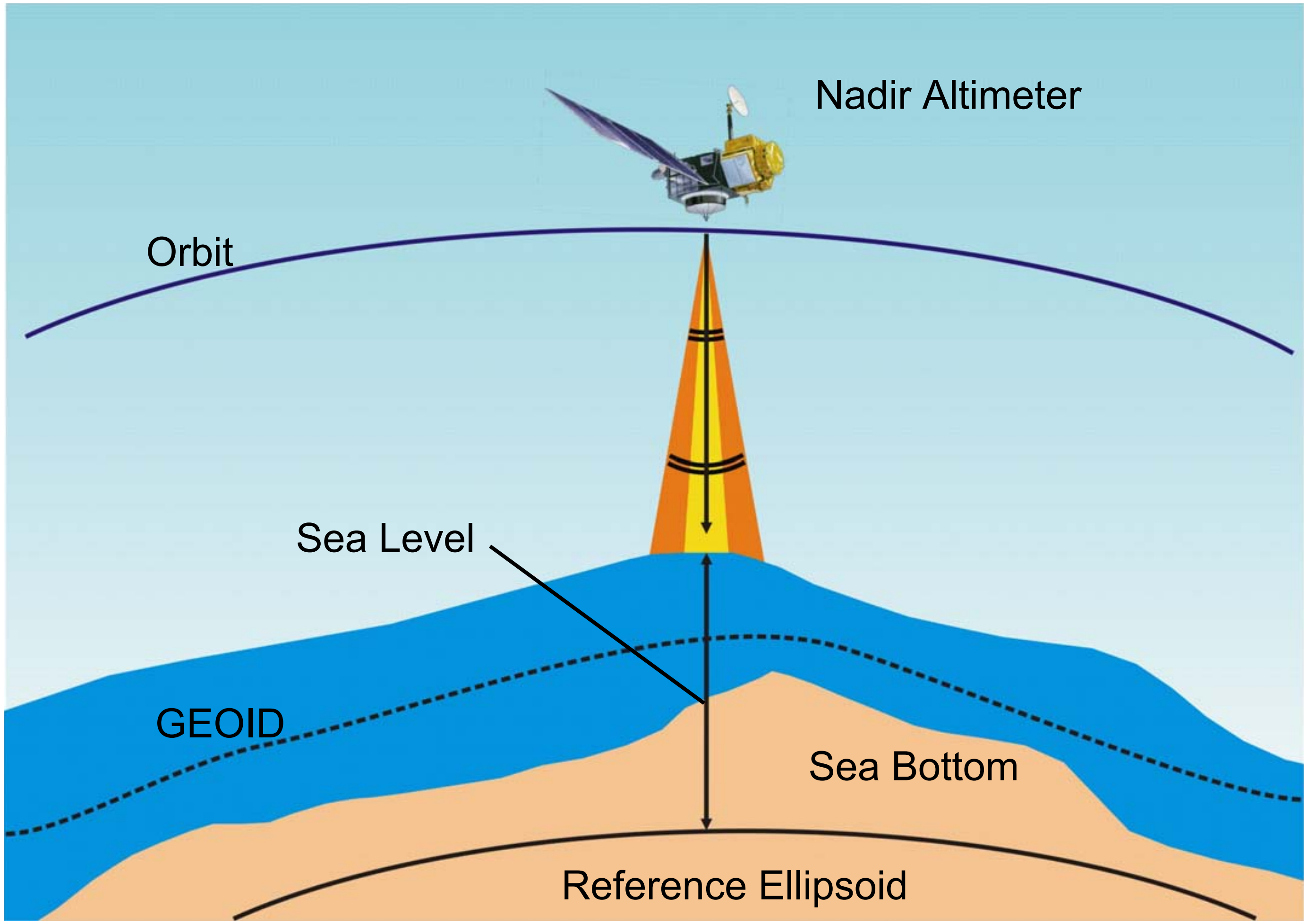
Tsunami Scale

Benny Lautrup, *Tsunami Physics*
Kvant, Jan 2005

Deep Ocean	d = 4000 m	λ = 150 km	a = 0.7 m	U = 0.08 m/s
Coastal Area	d = 40 m	λ = 15 km	a = 5 m	U = 2.5 m/s

Tsunamis are easier to detect in coastal areas

Sea Surface Height (SSH)



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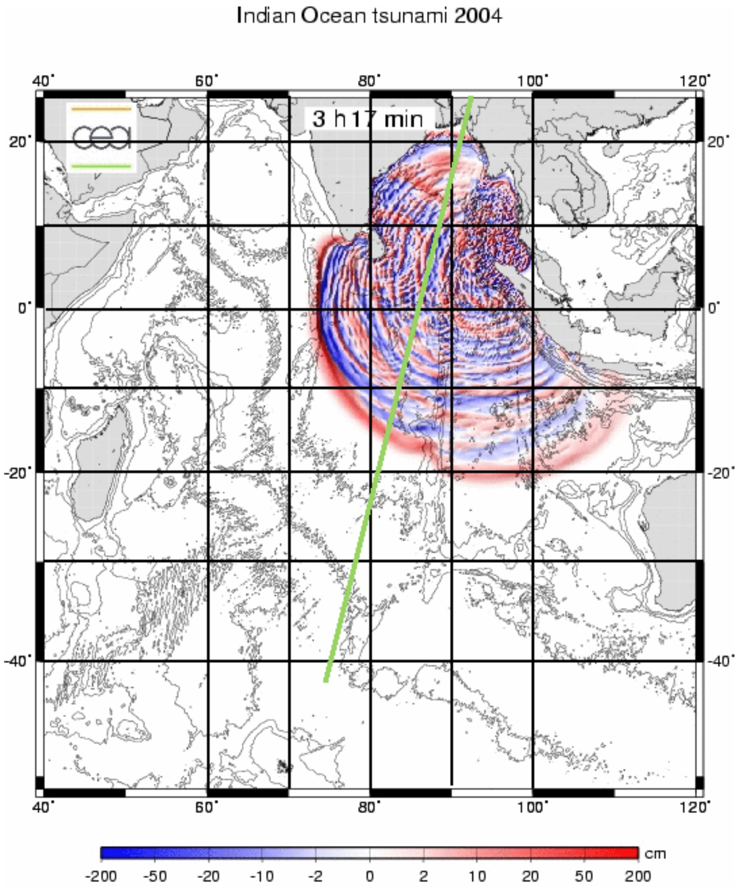
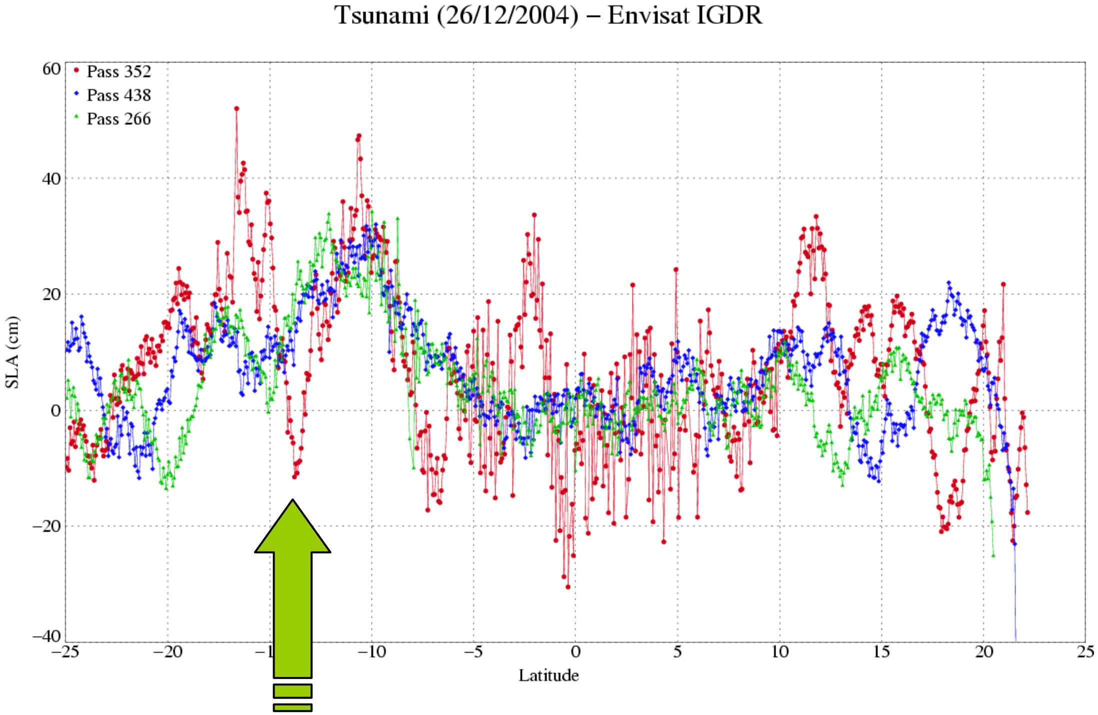
Example SSH: Boxing Day Tsunami





Stacked Data!

In principle a good vertical resolution (< 3 cm), but not sufficient temporal and spatial coverage for an **early** warning system.

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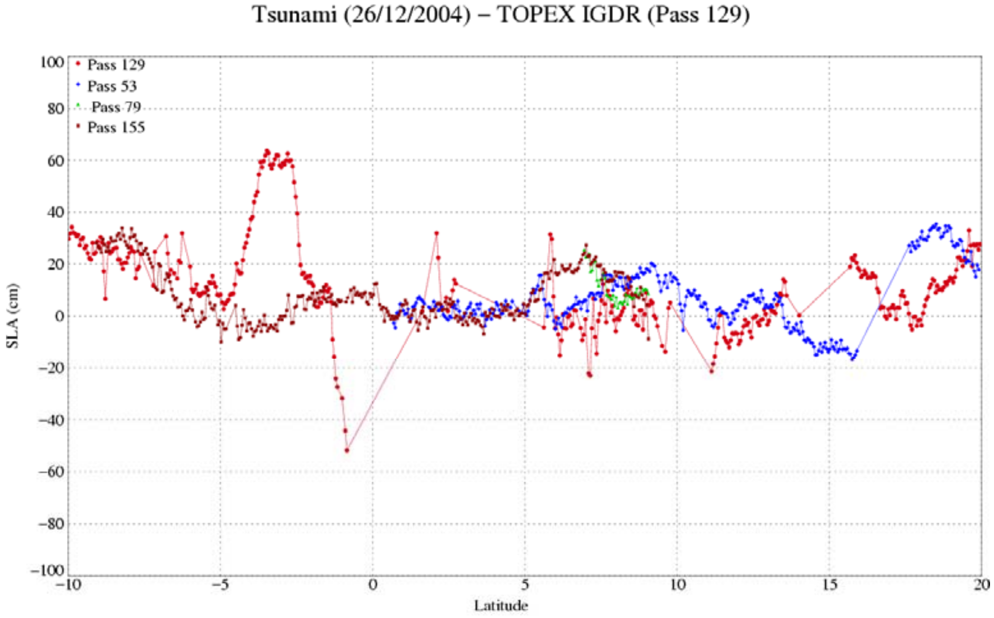
1st Principle: ALTIMETER MODE (measuring tsunami wave height)

Radar Altimeters measured tsunami wave height !



Cautionary Notes:

Data not immediately available!
→ Geophysical Noise
→ Motion Compensation

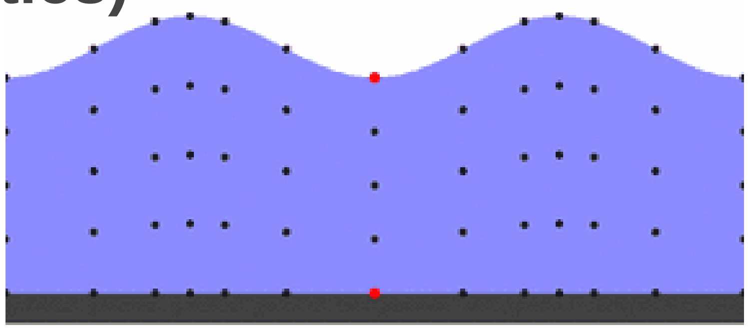
Okal, E. A., A. Piatanesi, and P. Heinrich, Tsunami detection by satellite altimetry, J. Geophys. Res., 104, 599-615, 1999.

Smith, W.H.F., R. Scharroo, V.V. Titov, D. Arcas, and B.K. Arbic, Satellite altimeters measure tsunami. *Oceanography, 18(2)*, 11-13, 2005.

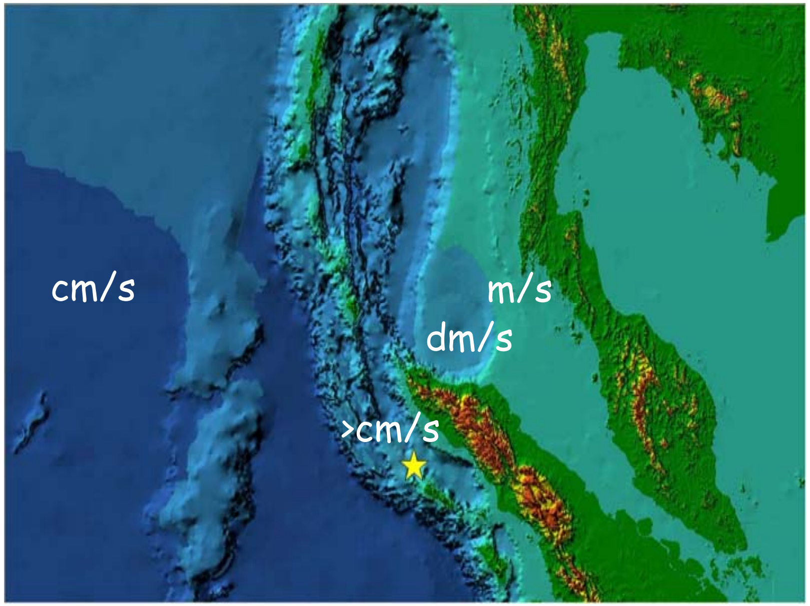
2nd Principle: DOPPLER MODE (measuring tsunami orbital velocities)

Tsunami horizontal orbital velocities depend on bathymetry and tsunami magnitude

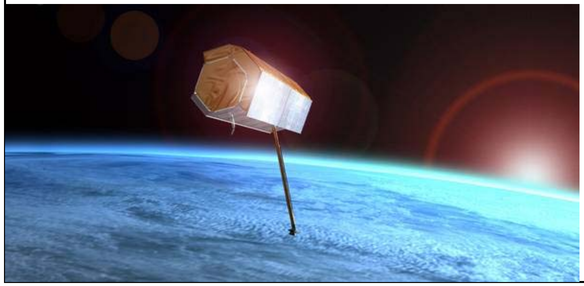
Units of cm/s (high seas)
Tens of cm/s (continental shelf)

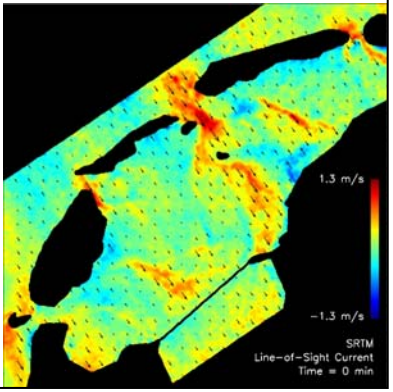


Wikipedia

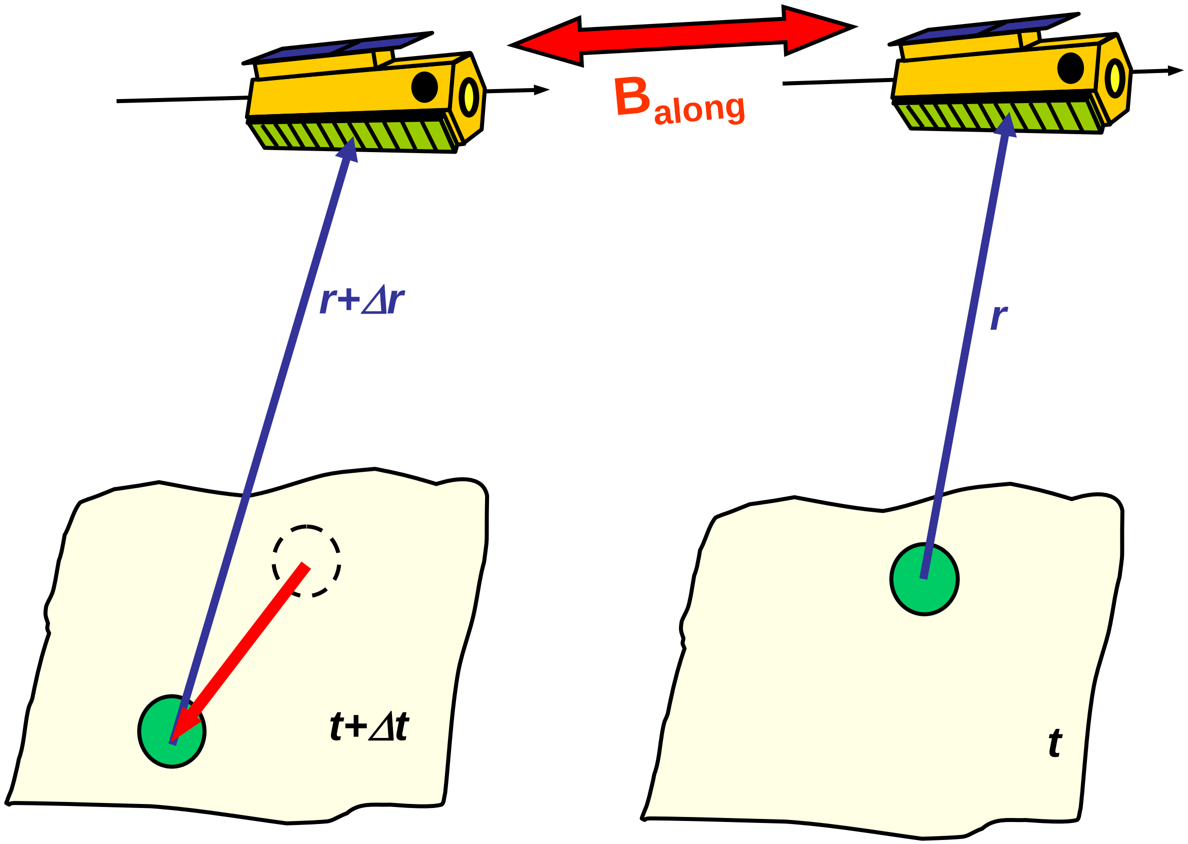


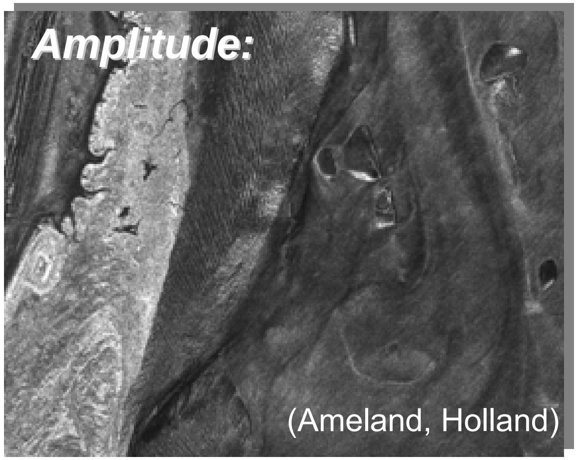
Along Track SAR Interferometry has the potential to detect tsunami! ATI-SAR

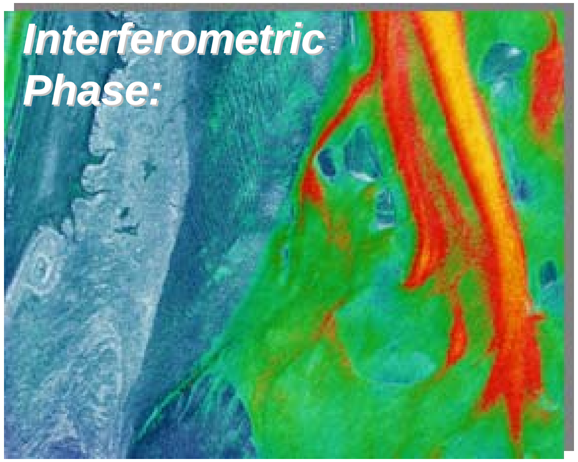




Along-Track Interferometry







accurate measurements of radial displacement between two radar observations separated by a short time lag

3rd Principle: TSUNAMI SHADOWS (measuring Radar Cross Section)

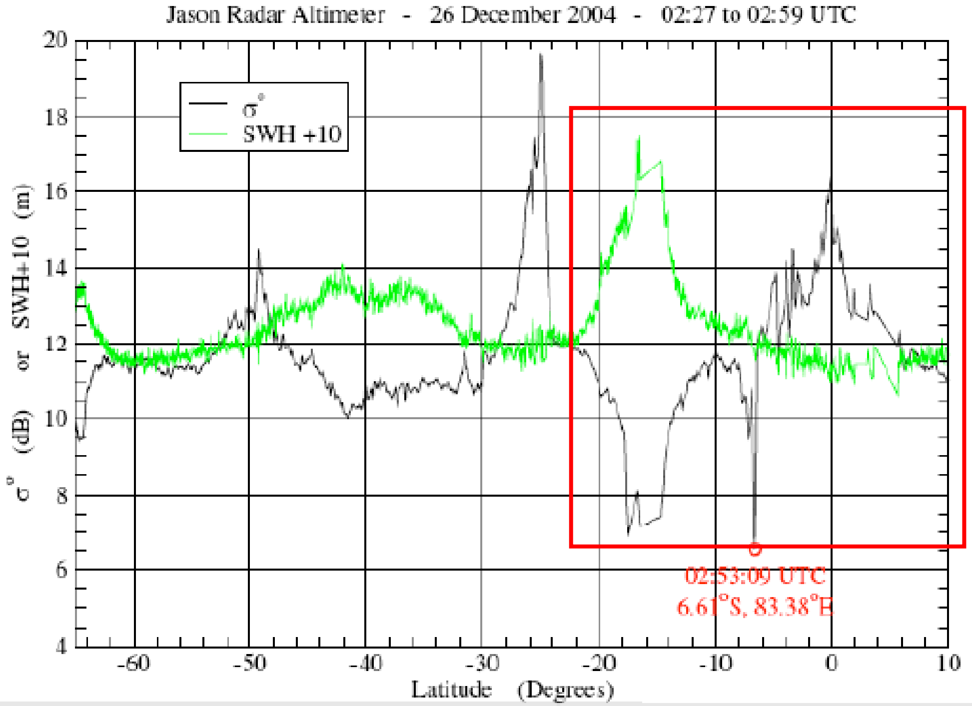
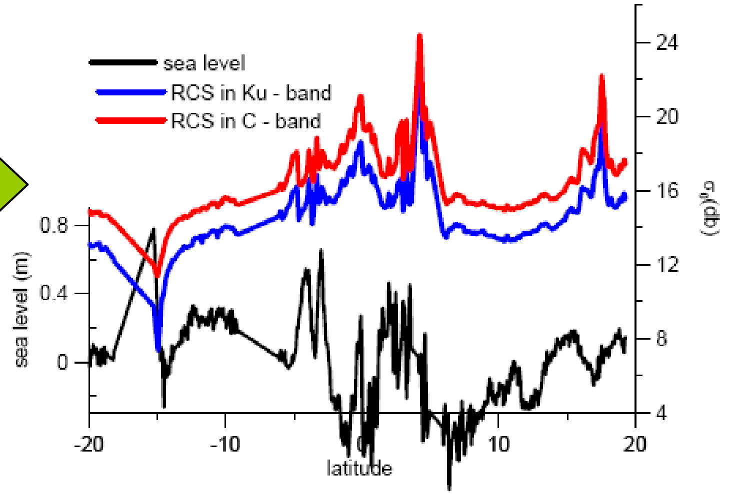


Figure 12. Along-track Jason significant save height and radar back scatter σ0.



Troitskaya, Yuliya I.; Ermakov, Stanislav A., Manifestations of the Indian Ocean tsunami of 2004 in satellite nadir-viewing radar backscatter variations, Geophys. Res. Lett., Vol. 33, No. 4, 24 February 2006

Tsunami Shadows were observed in the Geophysical Data Record of Jason-1 !

Size of tsunami shadows: Tens × Thousands of km

Tsunami Shadows: research under way

Recent works give an analytical description of tsunami-induced RCS modulations present in the open ocean as well as in coastal areas:

Godin, O. A. (2004), Air-sea interaction and feasibility of tsunami detection in the open ocean, J. Geophys. Res., 109.

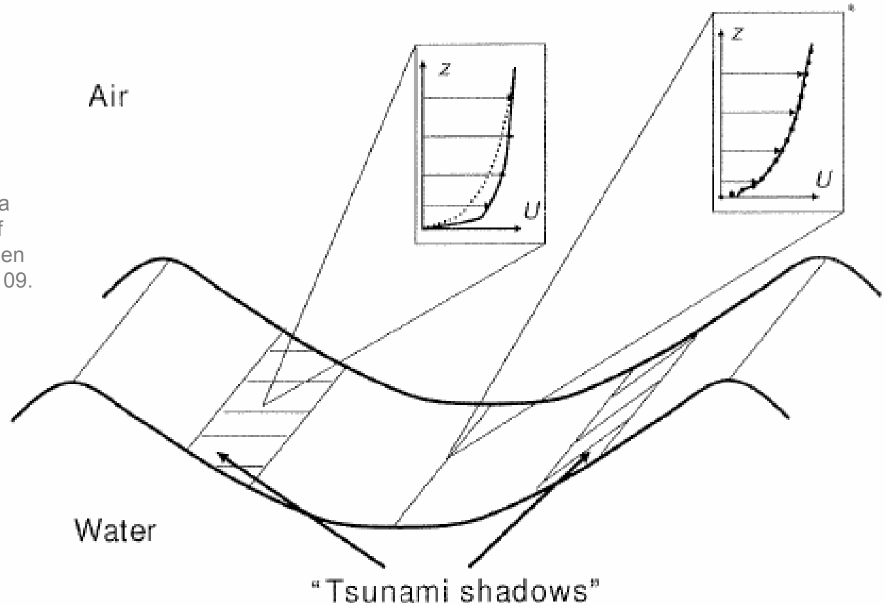


Figure 1. A conceptual representation of "tsunami shadows" and their theoretically predicted relation to the tsunami-induced wind velocity perturbations. "Tsunami shadows" (hatched) are parallel to the tsunami wave front and occur in between the tsunami troughs and crests where the wind perturbation is maximal. Perturbed (solid lines) and unperturbed (dotted lines) wind velocity is shown as a function of height above the ocean surface.

Cautionary Notes about Tsunami Shadows:

- → Robust against sea-state?
- → Robust against atmosphere state?
- → Robust against Tsunami magnitude?
- → Can we timely filter geophysical noise?
- → Can we use the effect for early-warning?

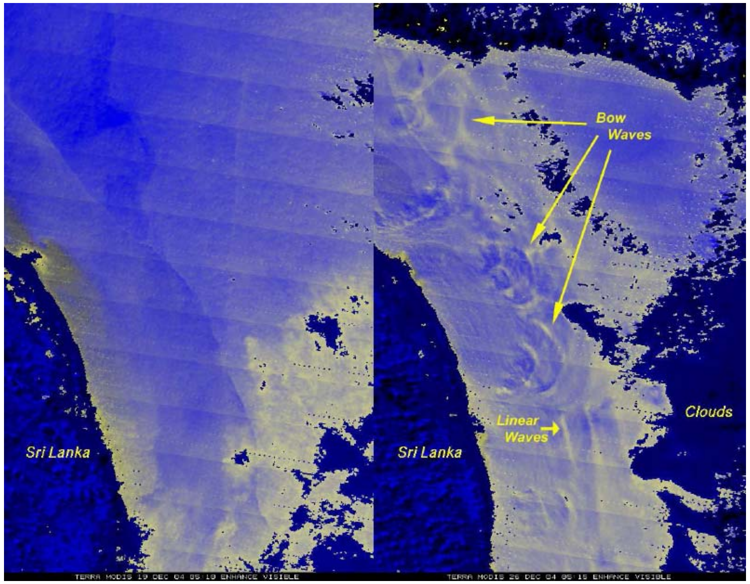
3½ Principle: TSUNAMI-INDUCED INTERNAL WAVES (measuring Radar Cross Section)

Tsunamis are long gravity waves.
As well as tides, tsunamis can trigger internal waves.

Tsunami-induced internal waves were observed by MODIS for the 2004 Boxing Day tsunami.

Single channel SAR systems and Optical passive sensors can image tsunami-related features!

MODIS



D. A. Santek; Winguth A.,
A satellite view of internal waves induced by the Indian Ocean tsunami,
International Journal of Remote sensing,

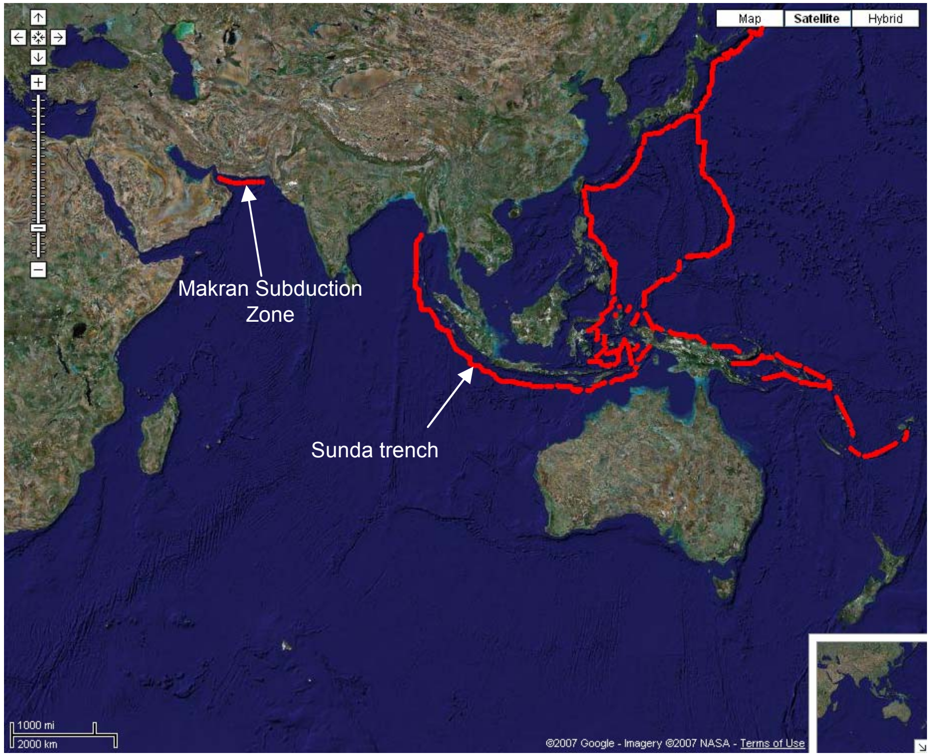
Cautionary Note:
Even though they both appear as radar cross section modulations, Tsunami Shadows and Tsunami-induced internal waves are generated by different physical mechanisms.

Tsunami Early-Warning Systems:

Requirements on temporal and spatial coverage

Tsunami Early-Warning: Far-field and Near-field

Tsunamigenic areas of the Indian Ocean



Under near-field tsunami threat in the world ocean: Indonesia, Makran Subduction zone (Iran, Pakistan), Japan, Mediterranean countries, Cascadia, Caribbean, etc.

FAR-FIELD TSUNAMI > 30 min

- Tsunami can happen anytime but trans-oceanic propagation can take hours!
- Far-field Tsunami Early-Warning is operational and effective.

NEAR-FIELD TSUNAMI < 30 min

- Indonesian government requires first warning to be issued within 5 min from the quake!
  → Temporal Coverage: 24/7, for immediate response.
- Spatial Coverage: dictated by plate tectonics.

Near-field tsunami early-warning is challenging. Sometimes the first direct measurements come from tide gauges.

CONCEPT DESIGN OF SPACE-BORNE RADARS

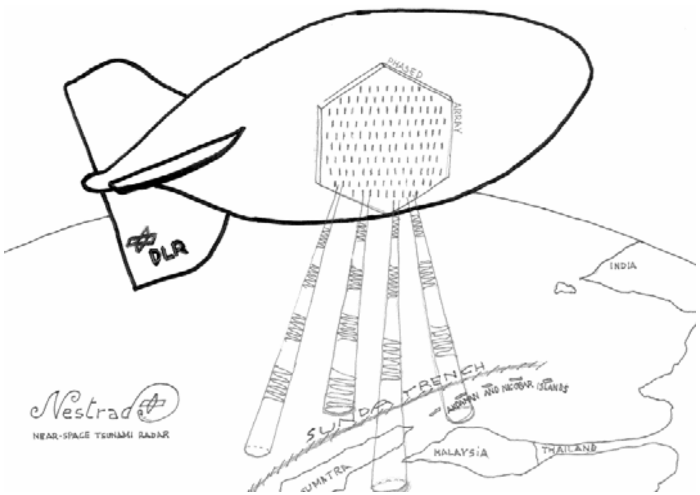
FOR TSUNAMI DETECTION

Two concepts: NESTRAD and G-SAR

Implementing one or more of the above-mentioned principles of detection from a platform capable of providing adequate temporal and spatial coverage:

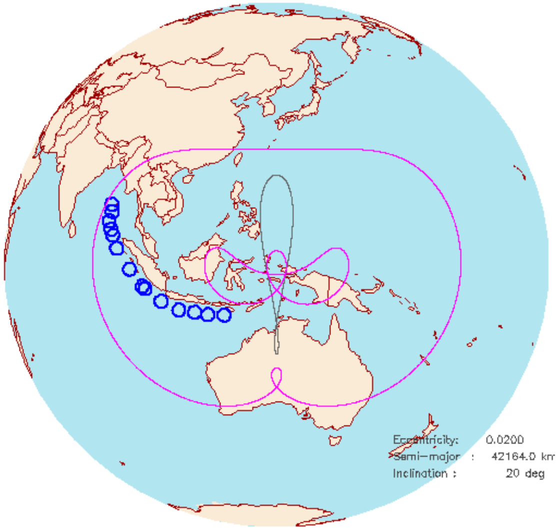
NESTRAD

Concept Design of a Near-Space Radar for Tsunami Detection



G-SAR

Concept Design of a Geosynchronous SAR for Tsunami Detection



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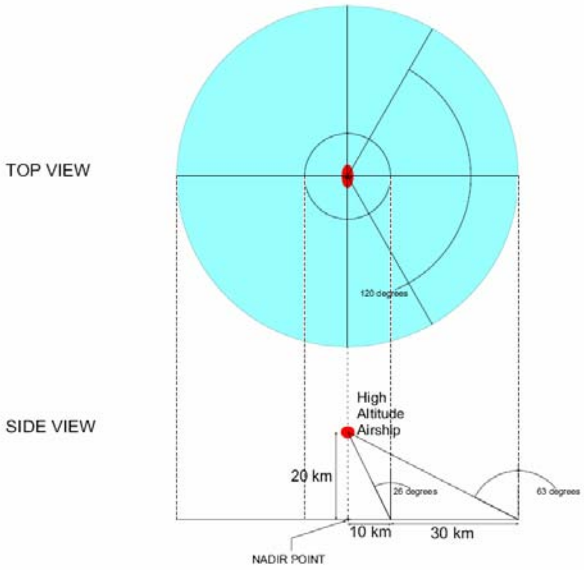
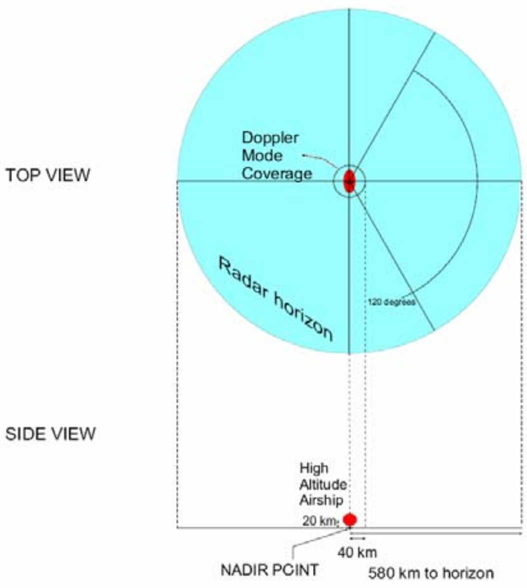
NESTRAD

Concept Design of a Near-Space Tsunami Radar





NESTRAD

DOPPLER MODE
ALTIMETER MODE

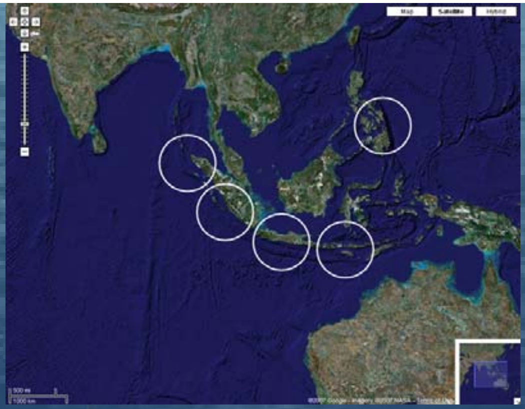
{Wave Height at Nadir
Orbital Velocities}
Tsunami Shadows
Tsunami-induced internal waves}

RADAR CROSS SECTION MODE

NESTRAD coverage (NEAMTWS)

NESTRAD consists of a real aperture phased array radar accommodated inside a stationary stratospheric airship. It provides all-weather, day-and-night coverage.

Stratospheric Airships are unmanned, untethered, lighter-than-air vehicles expected to persist 12 months on station providing continuous, real-time info.



NESTRAD coverage (IOTEWS)

Near Space Platforms:
Stationary Stratospheric Airships for 24/7 coverage

- Geosynchronous satellite at ~20 km (500 km to horizon)
- Unmanned, Untethered
- Persistence: 1 year on station
  - Develop long term clutter maps
  - Learn normal patterns
  - 1 min for attitude change
- Stationary
  - Improved Doppler precision
  - Continuous Coverage

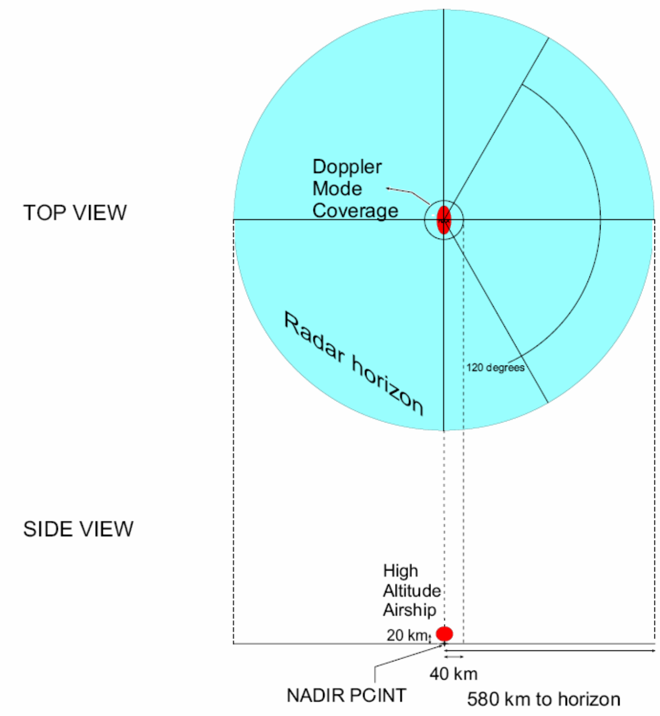
- Platform is good match with LPD
- Airship Size: >50m diameter, 150m length
  - Accommodate large aperture
  - Limited payload prime power and weight
  - No stowing, launch or deployment required

Lockheed-Martin

Zeppelin GmbH

NESTRAD: System Design

System	Antenna	(10×3)m phased array
	Frequency	5 GHz
	Polarization	VV
	Path Loss	3 dB
	Noise Figure	3 dB
Antenna	Antenna Aperture	30 m^2
	Antenna Gain	51 dBi
	Side lobe level	-15 dB
	Max. scan angle from broadside (elevation)	45°
	Max. scan angle from broadside (azimuth)	60°



Response time: 1 min epicenter location
+ 1 min attitude change
+ 1 min detection and data-downlink

~ 3 min

NESTRAD: Waveform Design (RCS Mode)

Far range

Waveform Parameters	
Incidence angle	87°
Backscatter cross section	-30 dB
PRF	800 Hz
Pulse Width	1.25 ms
Peak Power	100 W
Bandwidth	150 MHz
Duty Cycle	100% FMCW
SNR	13 dB
Range resolution	1 m
Azimuth resolution	2000 m

Near range

Waveform Parameters	
Incidence angle	20°
Backscatter cross section	-20 dB
PRF	2 kHz
Pulse Width	0.5 ms
Peak Power	1 W
Bandwidth	150 MHz
Duty Cycle	100 % FMCW
SNR	40 dB
Range resolution	3 m
Azimuth resolution	100 m

Far range resolution: 2 × 0.5 km

Near range resolution: 100 × 100 m

→ We can resolve tsunami shadows: tens × thousands of kms !

NESTRAD: Spatial Coverage for Indonesia

NESTRAD: A Multi-Purpose Platform

- **Seldom do Tsunami happen!**

→ NESTRAD must be conceived as a multi-purpose sensor:

- Sea state monitoring
- Maritime (and coastal) traffic monitoring
- Ship Tracking
- Reconnaissance and Surveillance (submarine periscopes)
- Piracy prevention
- Weather monitoring
- Monitoring of volcanic activities
- Relay station for communication/navigation
- etc.

G-SAR

Concept Design of a Geosynchronous SAR for Tsunami Detection

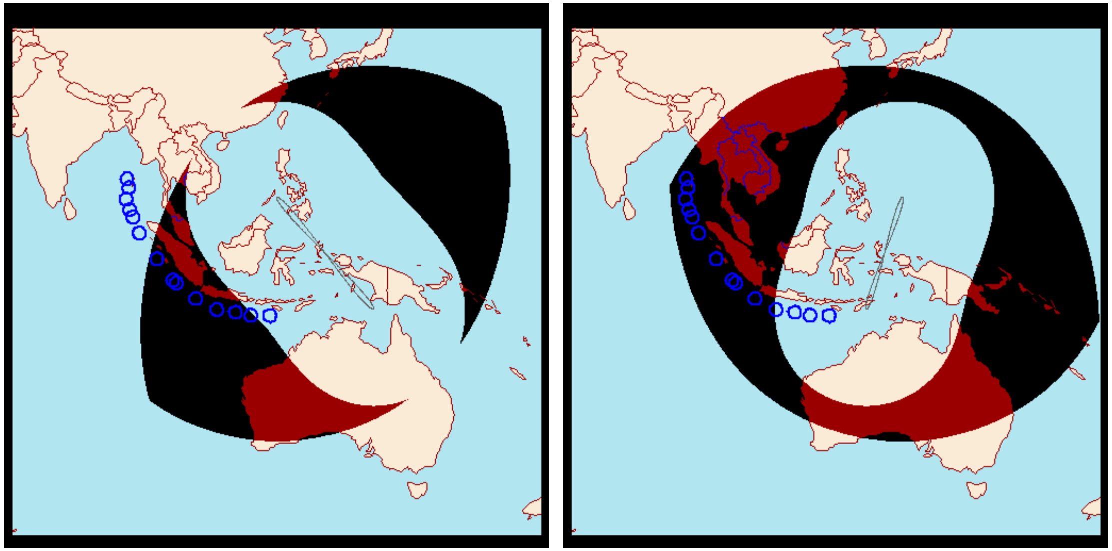
G-SAR: Synthetic Aperture Radar in a Geosynch. Orbit

Detected feature:
Tsunami Shadows

Spatial Resolution:
$\Delta rg \sim 10$ km and $\Delta az \sim 10$ km

Temporal Coverage:
24/7 for Near-field tsunami

Spatial Coverage:
As large as possible



We can choose eccentricity, inclination and argument of perigee to optimize the coverage.

incidence angle range:	$20° \leq \eta \leq 50°$
Max scan angle off nadir:	6.6° → Nadir looking antenna
Accessible area:	two sectors, right and left of flight track

G-SAR: System Design

System Parameters

L_a	antenna length	= 7 m
W_a	antenna width	= 2 m
A	antenna aperture	= 14 m^2
λ	wavelength	= 0.03 m (X-band)
c	speed of light	= 299792458 m/s
η	incidence angle	= 20° - 50°
PRF	pulse repetition frequency	= 200 Hz
R	slant range	= dependent on η
V	platform velocity	= 500 m/s

Incidence angle η	20°	50°
Range Ambiguities: $W_a > 2\lambda R \cdot PRF \cdot \tan(\eta)/c$	2 > 0.526 [m]	2 > 1.8 [m]
Azimuth Ambiguities: $L_a > 2V/PRF$	7 > 5 [m]	7 > 5 [m]
Antenna Aperture: $L_a \cdot W_a) > 4\lambda RV \cdot \tan(\eta)/c$	14 > 2.6 [m^2]	14 > 9 [m^2]

G-SAR: Signal-to-Noise Ratio

P_t	transmitted power	= 2 kW	
τ	pulse width	= 1 ms	(duty cycle 20%%, minimum Bn = 1 kHz)
N	noise figure	= 3 dB	
T	noise temperature	= 300 K	
L	loss	= 3 dB	(dependent on atmosphere state)
σ^0	normalized RCS	= - 20 dB	(dependent on η, pol. and sea state)
Pol	polarisation	= VV	

Signal Power (radar equation) Noise Power

$$SNR = \underbrace{\left(\frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4}\right)\left(\frac{1}{L}\right)\sigma^0\left(\frac{c\tau}{2\sin(\eta)}\right)\left(\frac{\lambda R}{L_a}\right)}_{\text{Signal Power (radar equation)}}\underbrace{\left(\frac{1}{kNTB}\right)}_{\text{Noise Power}}$$

→ SNR > 10 dB ⇕ Bn < ~ 40 kHz

Incidence angles	20° (σ^0 = -10 dB)	50° (σ^0 = -15 dB)
SNR (B = 40 kHz)	20.18 dB	11.07 dB

G-SAR: Spatial Resolution

B	bandwidth	= 40 kHz
L_a	antenna length	= 7 m
R	slant range	= dependent on η
R_e	Earth radius	= 6.400 km
h	platform height	= 35.600 km
L_s	synthetic aperture length	
T_s	integration time	

	20°	50°
$\Delta r = \dfrac{c}{2B\sin(\eta)}$	11 km	4.9 km
$\Delta az = \left(\dfrac{L_a}{2}\right)\left(\dfrac{R_e}{R_e+h}\right)$	0.53 m	0.53 m
$T_S = \dfrac{L_S}{v}$	2031 s	2128 s
$L_S = \left(\dfrac{\lambda R}{L_a}\right)\left(\dfrac{R_e+h}{R_e}\right)$	1.02e6 m	1.06e6 m

Not needed, and further, requires very long integration times.

→ not suitable for tsunami early-warning!

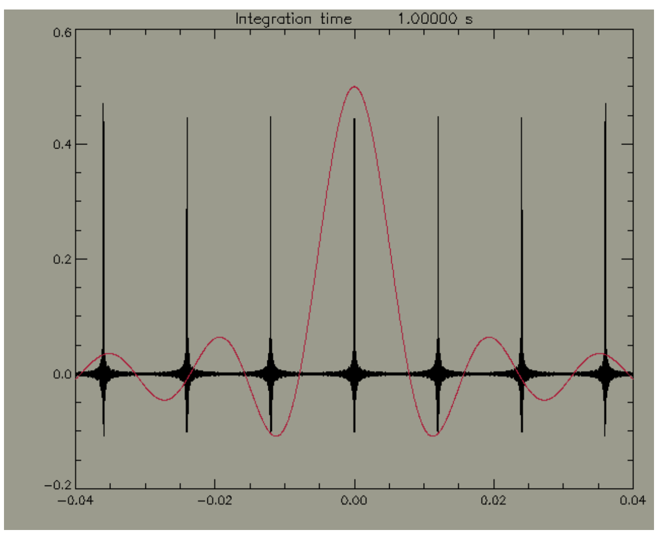
~ 35 min

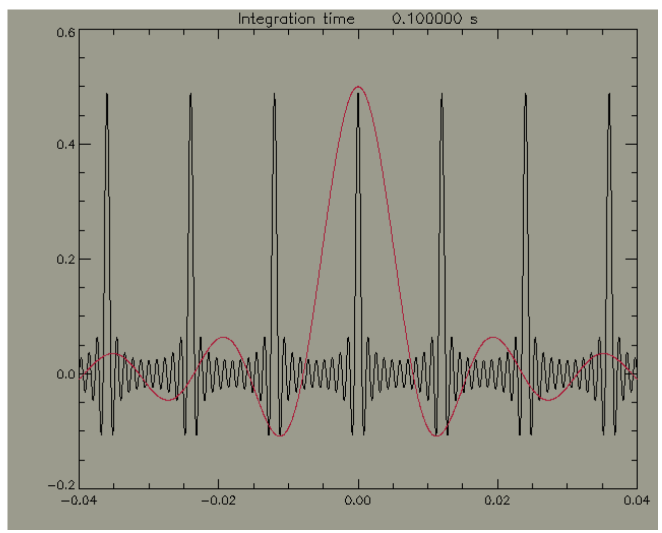
Then go for sublooks

G-SAR: Sublook Azimuth Resolution

L_a antenna length	7 m	}	SAR antenna radiation pattern
λ wavelength	0.03 m		
PRF	200 Hz	}	Ambiguity positions
V	500 m/s		
T_s integration time		}	main lobe 3dB beam width

Inc. angles / Int. times (s)	20°	50°
0.1	10.8 km	11.4 km
0.2	5.4 km	5.7 km
0.5	2.2 km	2.3 km
1	1.1 km	1.1 km



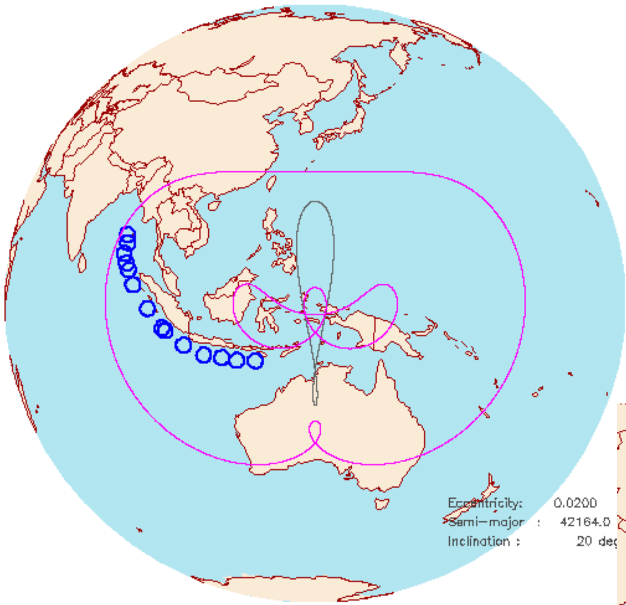


Minimum integration times to match the (10×10) km resolution constraint.

500 m/s → 0.1 s
50 m/s → 1 s
5 m/s → 10 s
platform velocities!

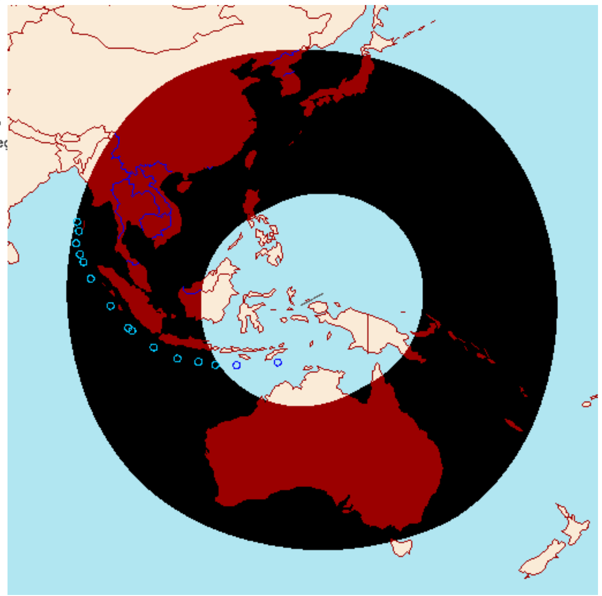
V ~ 500 m/s

G-SAR: 2 SAR Satellites in Geosynchronous Orbit



orbits

spatial coverage



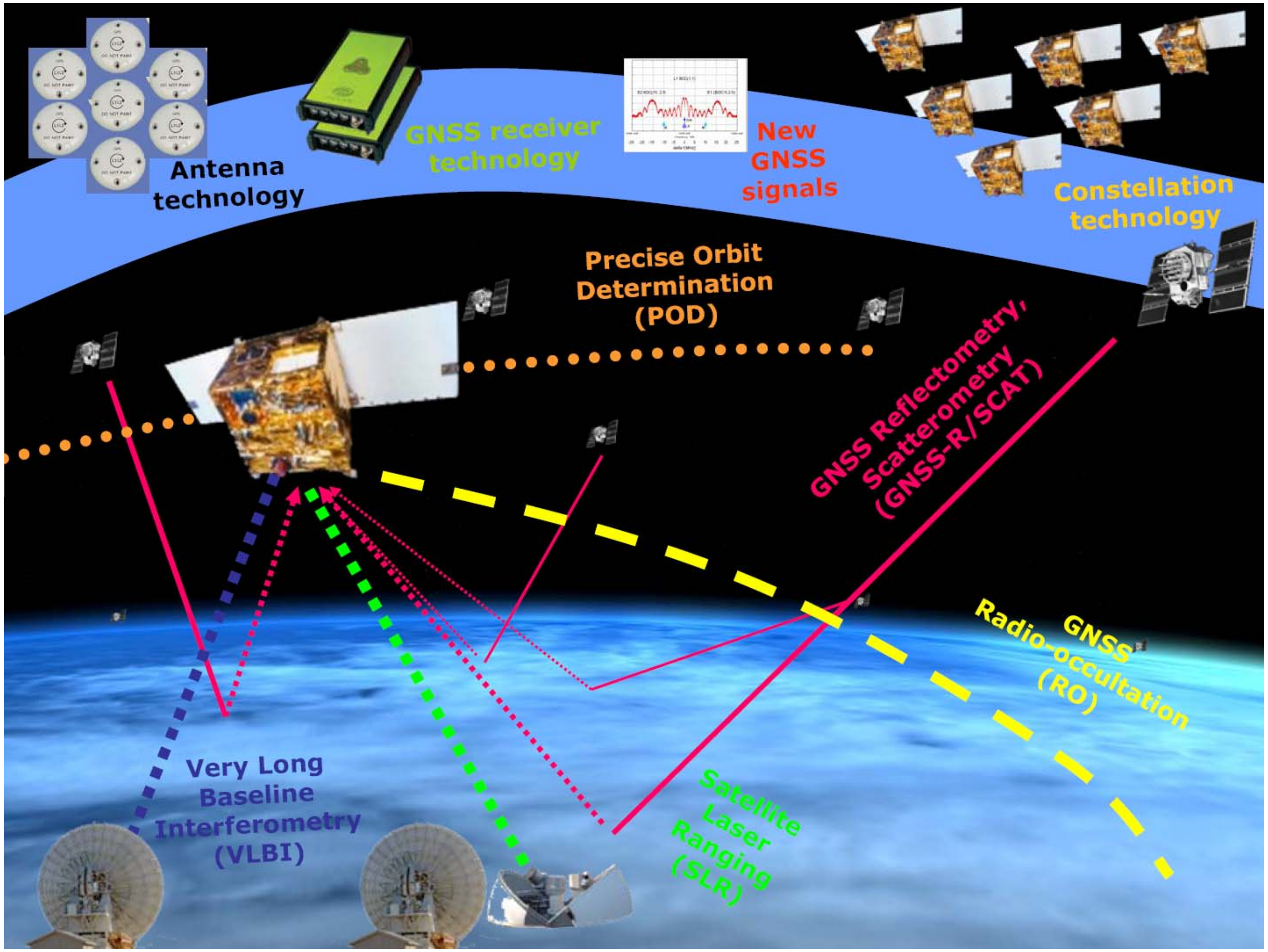
System Parameters	
Antenna	(7×2)m phased array
Frequency	10 GHz
Polarization	VV
Path Loss	3 dB
Noise Figure	3 dB
Antenna Parameters	
Antenna Aperture	14 m^2
Antenna Gain	53 dBi
Side lobe level	-13 dB
Max. scan angle	7°
Waveform Parameters	
Range resolution	~ 10 km
Azimuth resolution	<10 km
Peak Power	2 kW
Bandwidth	40 kHz
Pulse width	1 ms
PRF	200 Hz
Power Duty cycle	20 %

Passive Radar

GPS-Reflectometry

GPS-Reflectometry – another possibility for TEWS
A cooperation between GFZ and DLR

GFZ
POTSDAM



DLR

picture kindly provided by A. Helm, GFZ Potsdam

GPS-Reflectometry: Goals, Innovations and Applications

- GNSS-based remote sensing for atmosphere, ionosphere, oceans, ice, soil (moisture), etc.
- Passive radar for altimetry and scatterometry.
- Precise orbit determination (POD) and co-location of geodetic methods from space (reference systems, gravity field, etc.).
- Development of technologies and know-how for future micro satellite constellations (formation flights) using GNSS.
- Oceanographic applications (sea ice parameters, wave spectra and heights, wind fields, orbital velocities, Tsunami detection, etc.).
- Would be the first demonstration of GPS-reflectometry from space!

GPS-Reflectometry: Reqs. for Tsunami detection

- Tight temporal coverage is essential:
  - Constellation of satellites needed that ensures data takes over the same area every 5-10 minutes.
  - Downlink of acquired data has to be permanently available for processing required results in (near) real time.

- Accuracy of measured ocean heights must be in the order of some cm!

- Assessment of accuracy, stability and robustness of GPS-reflectometry from space has to be carried out → need for demonstrators!

- Sensor constellation must serve various purposes. Tsunami detection capabilities only triggered through seismic events.

Conclusions

- A number of sensors can provide valuable information about Tsunamis:
  - RADAR ALTIMETRY (tsunami shadows and wave height)
  - GPS REFLECTOMETRY (tsunami shadows and maybe wave height)
  - SCATTEROMETERS (tsunami shadows)
  - ATI-SAR (tsunami shadows and orbital velocities)
  - single channel SAR (tsunami shadows)
- NESTRAD would be able to detect Tsunamis within 3 minutes from the quake! It is also a perfect platform to serve numerous purposes.
- G-SAR is probably a feasible concept in about 10-20 years, but for the time being not practicable.
- GPS-Reflectometry and other passive/parasitic systems (e.g. using TV satellite signals) might perhaps be used for Tsunami detection, if a large constellation of such sensors provides appropriate temporal and spatial coverage and permanent downlink capabilities.
- It is mandatory to know more about Tsunami-related features:
  - Airborne SAR campaigns
  - Theoretical modeling

Conclusions

The concepts need validation …

Can we do Tsunami Early Warning with Tsunami Shadows?

Robust against sea-state?
Robust against atmosphere state?
Robust against tsunami magnitude?

Can we filter ‘geophysical noise’?

Effective detection at low grazing angles?

… through modeling

Source Modeling	provide maps of tsunamigenic areas, provide initial waveforms
Tsunami Modeling	provide tsunami waveform in the propagation phase
Sea-Surface roughness	hydrodynamic modulation of long-wave induced sea surface roughness
Radar Signature Modeling	RCS modeling of the sea surface at steep and low grazing angles
Radar System Design	Radar System Design

THANKS, and go to high ground !!