Concept Design of Space-Borne Radars for Tsunami Detection

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GITEWS: German-Indonesian Tsunami Early-Warning System

GOAL: Development of new, radar-based concepts for future Tsunami Warning Systems

- Seismic component
- GPS technologies
- Tsunami models
- Ocean Instrumentation
- WP 4400
  New earth-observing technologies

www.gitews.org
Overview

- Principles of Tsunami Detection for Space-Borne Radars (4)
- Tsunami Early-Warning Systems:
  Requirements on spatial and temporal coverage (3)
- NESTRAD: Near-Space Radar for Tsunami Detection (1)
- G-SAR: Geosynchronous SAR for Tsunami Detection (6)
- Conclusions (1)
Principles of Detection for Space-Borne Radars:

What can we ‘see’?
ALTIMETER MODE
(measuring tsunami wave height)

Radar Altimeters measured tsunami wave height!

Cautionary Notes:

Data not immediately available
-Geophysical Noise
-Motion Compensation


DOPPLER MODE
(measuring tsunami orbital velocities)

Tsunami horizontal orbital velocities are in the order of

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

ATI-SAR has the potential to detect a tsunami!
Doppler Precision in the order of cm/s (after multi-looking)

Cautionary Notes:
Flight track must be parallel to the wave-front!!
Recent works give an analytical description of tsunami-induced RCS modulations present in the open ocean as well as in coastal areas: Tsunami Shadows.


**TSUNAMI SHADOWS**

(measuring Radar Cross Section)

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.

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

**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 ?

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

Size of tsunami shadows: Tens × Thousands of km

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!

CAUTIONARY NOTES: 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
Requirements for Tsunami Early-Warning

Tsunamigenic areas

NEAR-FIELD TSUNAMI

- 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:
  we need to cover tsunamigenic areas lying close to densely populated coasts: new problem!!

FAR-FIELD TSUNAMI

- Tsunamis can happen anytime but trans-oceanic propagation can take hours....
- we need to track propagation to assess the tsunami hazard in the far-field.
CONCEPT DESIGN OF
SPACE-BORNE RADARS FOR TSUNAMI DETECTION

• Implementing one or more of the above-mentioned principles of detection from
  a platform capable of providing adequate temporal and spatial coverage
  1. Stratospheric Airships
  2. MEO orbits
  3. GEO orbits

NESTRAD
Concept Design of a Near-Space Radar
for Tsunami Detection

G-SAR
Concept Design of a Geosynchronous SAR
for Tsunami Detection
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 coverage.

More on IGARSS 07 Conference Proceedings !!
G-SAR

Concept Design of a Geosynchronous SAR for Tsunami Detection
**G-SAR: Concept Design of a Geosynchronous SAR for Tsunami Detection**

Detected feature: Tsunami Shadows

Spatial Resolution
\[ \Delta r \sim 10 \text{ km} \quad \Delta \text{az} \sim 10 \text{ km} \]

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....

A Synthetic Aperture Radar in a geosynchronous orbit...

incidence angle range: \[ 20^\circ \leq \eta \leq 50^\circ \]

Max scan angle off nadir: \[ 6.6^\circ \rightarrow \text{Nadir looking antenna} \]

Accessible area: two sectors, right and left of flight track
Ambiguities Constraints

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>antenna length</td>
<td>5 m</td>
</tr>
<tr>
<td>Wa</td>
<td>antenna width</td>
<td>2 m</td>
</tr>
<tr>
<td>λ</td>
<td>wavelength</td>
<td>0.03</td>
</tr>
<tr>
<td>c</td>
<td>speed of light</td>
<td>299792458 m/s</td>
</tr>
<tr>
<td>η</td>
<td>incidence angle</td>
<td>20° - 50° (SAR)</td>
</tr>
<tr>
<td>PRF</td>
<td>pulse repetition frequency</td>
<td>4000 Hz</td>
</tr>
<tr>
<td>R</td>
<td>slant range</td>
<td>dependent on η</td>
</tr>
<tr>
<td>V</td>
<td>platform velocity</td>
<td>15 m/s</td>
</tr>
</tbody>
</table>

Range Ambiguities: $Wa > 2AR \text{(PRF) tan(η)/c}$

Azimuth Ambiguities: $La > 2V/(PRF)$

Antenna Aperture: $(La \times Wa) > 4λRV \text{ tan(η)/c}$

Nadir Interference: okay

Transmit Interference: okay
**SNR** Signal-to-Noise Ratio

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_t$</td>
<td>transmitted power</td>
<td>$100$ W</td>
</tr>
<tr>
<td>$\tau$</td>
<td>pulse width</td>
<td>$50$ $\mu$s (duty cycle 20%)</td>
</tr>
<tr>
<td>$N$</td>
<td>noise figure</td>
<td>$3$ dB</td>
</tr>
<tr>
<td>$T$</td>
<td>noise temperature</td>
<td>$300$ K</td>
</tr>
<tr>
<td>$L$</td>
<td>loss</td>
<td>$3$ dB (dependent on atmosphere state)</td>
</tr>
<tr>
<td>$\sigma^0$</td>
<td>normalized RCS</td>
<td>$-20$ dB (dependent on $\eta$, pol and sea state)</td>
</tr>
</tbody>
</table>

**SNR** = Signal Power (radar equation)

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

$SNR \approx 30$ dB
## Spatial Resolution

<table>
<thead>
<tr>
<th></th>
<th>20°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta r = \frac{c}{2B \sin(\eta)}$</td>
<td>11 km</td>
<td>4.9 km</td>
</tr>
<tr>
<td>$\Delta z = \left( \frac{L_a}{2} \right) \left( \frac{R_e}{R_e + h} \right)$</td>
<td>0.53 m</td>
<td>0.53 m</td>
</tr>
<tr>
<td>$T_s = \frac{L_s}{v}$</td>
<td>2031 s</td>
<td>2128 s</td>
</tr>
<tr>
<td>$L_s = \left( \frac{\lambda R}{L_a} \right) \left( \frac{R_e + h}{R_e} \right)$</td>
<td>1.02e6 m</td>
<td>1.06e6 m</td>
</tr>
</tbody>
</table>

Bandwidth $B = 200$ MHz

Antenna Length $L_a = 5$ m

Slant range $R$ dependent on $\eta$

Earth radius $R_e = 6400$ km

Platform height $h = 20$ km

Synthetic aperture length not needed, and further, requires very long integration times, not suitable for tsunami early-warning!!

Integration time $T_s \approx 35$ min

Then go for sublooks
Sublook Azimuth Resolution

La      Antenna Length     7 m
\lambda  wavelength       0.03 m
PRF      200 Hz
v         500 m/s
Ts       integration time

SAR antenna radiation pattern
Ambiguity positions
main lobe 3dB beamwidth

<table>
<thead>
<tr>
<th>Inc. angles</th>
<th>20°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. times (s)</td>
<td>0.1</td>
<td>10.8 km</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>5.4 km</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.2 km</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.1 km</td>
</tr>
</tbody>
</table>

Minimum integration times to match the (10x10) km resolution constraint:

- 500 m/s → 0.1 s
- 50 m/s → 1 s
- 5 m/s → 10 s

range of allowed platform velocities !!

50 m/s < V < 500 m/s
G-SAR: 2 SAR satellites in geosynchronous orbit

System Parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna</strong></td>
<td>(7×2)m phased array</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>10 GHz</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>VV</td>
</tr>
<tr>
<td><strong>Path Loss</strong></td>
<td>3 dB</td>
</tr>
<tr>
<td><strong>Noise Figure</strong></td>
<td>3 dB</td>
</tr>
</tbody>
</table>

Antenna Parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna Aperture</strong></td>
<td>14 m²</td>
</tr>
<tr>
<td><strong>Antenna Gain</strong></td>
<td>53 dBi</td>
</tr>
<tr>
<td><strong>Side lobe level</strong></td>
<td>-13 dB</td>
</tr>
<tr>
<td><strong>Max. scan angle</strong></td>
<td>7°</td>
</tr>
</tbody>
</table>

Waveform Parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range resolution</strong></td>
<td>~ 10 km</td>
</tr>
<tr>
<td><strong>Azimuth resolution</strong></td>
<td>&lt;10 km (depending on V)</td>
</tr>
<tr>
<td><strong>Peak Power</strong></td>
<td>2 kW</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>40 kHz</td>
</tr>
<tr>
<td><strong>Pulse width</strong></td>
<td>1 ms</td>
</tr>
<tr>
<td><strong>PRF</strong></td>
<td>200 Hz</td>
</tr>
<tr>
<td><strong>Power Duty cycle</strong></td>
<td>20 %</td>
</tr>
</tbody>
</table>

v_min: 50.7 m/s
v_max: 115.2 m/s
Inclination: 1.0°
Semi major: 42164.0 km
Eccentricity: 0.0165
Ascend. Node: 132.3°
Arg. of Perigee: 0.0°
CONCLUSIONS

- A number of sensors (passive and active) can provide valuable information about tsunami
  - 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)
  - RADIOMETERS

- It is mandatory to know more about tsunami-related features (especially tsunami shadows !)
  - Airborne SAR campaigns
  - Theoretical modeling

- A Geosynchronous SAR is proposed as a concept for tsunami early-warning.

- NESTRAD, another concept for tsunami early-warning is illustrated in the proceedings

- BOTH CONCEPTS ARE DESIGNED AS MULTI-PURPOSE SENSORS

- Always consider the possibility of implementing the same concepts with parasitic signals from communication and navigation !! (GPS signals or TV signals)
THANKS, and go to high ground!!