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CONCEPT DESIGN OF A NEAR-SPACE RADAR FOR MARITIME SURVEILLANCE AND NEAR-FIELD TSUNAMI EARLY-WARNING

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ABSTRACT: Off-shore detection of Tsunami waves is a critical component of an effective Tsunami early warning system (TEWS). Even more critical is the off-shore detection of local Tsunamis, namely Tsunamis that strike coastal areas within minutes from the triggering quake. In this paper we propose a new concept for near-field Tsunami early warning. NESTRAD (Near-Space Tsunami Radar) consists of a real aperture radar accommodated inside a stationary stratospheric airship providing continuous monitoring of tsunamigenic oceanic trenches.

1. INTRODUCTION

The German Aerospace Center (DLR) is involved in the GITEWS project (German-Indonesian Tsunami Early-Warning System) and the Microwaves and Radar Institute (DLR-HR) is committed to the development of new radar-based concepts for Tsunami detection.

Conventional Tsunami warning systems rely on estimates of an earthquake's magnitude to determine whether a large Tsunami will be generated. Earthquake magnitude is not always a reliable indicator of Tsunami potential, however. The 2004 Indian Ocean quake generated a huge Tsunami, while the 2005 Nias (Indonesia) quake did not, even though both had almost the same magnitude from initial estimates.

When dealing with local Tsunamis, in order to bring useful information to existing warning systems, space-based sensors must provide responses within approx. 5 minutes from the initial quake. Late information is of little value to early-warning, since cheaper, ground-based technologies (tide gauges) have most probably already provided a direct and precise measurement. To match these constraints, a careful analysis of the limitations in terms of time-responsiveness of LEO (low earth orbit) satellites and the opportunities offered by different space platforms is necessary.

Stratospheric airships are an interesting solution for services demanding continuous temporal coverage and continuous data downlink. Stratospheric airships are unmanned, autonomous solar-powered vehicles designed to operate above the jet-stream at approximately 20 km and to carry payloads of approximately 1000 kg. The airships, measuring 150 m long and about 50 m in diameter can be used for both military and civilian applications. Besides early-warning and post-disaster damage assessment, they offer reliable and continuous downlink transmission and might also serve the purpose of mobile data communication.

The NESTRAD (NEar-Space Tsunami RADar) concept (Galletti et al., 2007) presented in this paper consists of a C-band phased-array radar accommodated inside a stratospheric airship, providing all-weather, 24/7 coverage and consequently a response time less than 5 minutes. It is meant to detect Tsunami-induced RCS modulations (Tsunami shadows) (Godin, 2004; Troitskaya et al., 2006), Tsunami wave height as well as Tsunami orbital velocities. Depending whether the platform is stationary or slow-moving, it can operate as a real aperture radar or as a SAR.

The Performance analysis shown in the following tries to give an account on the system capabilities to resolve Tsunami-related geophysical features. In particular, the detection of radar cross section modulations (Godin, 2004) is expected to provide wide area coverage. In this case modulations of a few dB should be present for Tsunamis of virtually any size.

The whole remote sensing community (SAR, Satellite Altimetry, Scatterometry) and the responsible agencies (ESA, NASA, JAXA) (Paganini, 2007) are therefore invited to devote attention to the problem in order to organize data-takes and gain experimental insight about Tsunami geophysical features, in terms of orbital velocities, radar cross section modulations, and Tsunami wave height, in order to validate new concepts for Tsunami early warning (providing continuous temporal coverage) of which NESTRAD is just but one example.

2. TSUNAMI SIGNATURES

In this section we review, from a remote sensing viewpoint, all known Tsunami related signatures. For each detectable geophysical feature, every sensor with either proven or potential detection capability is listed and briefly discussed. Each sensor relies on at least one principle of detection but, obviously, one sensor can combine more principles of detection.

2.1 Tsunami wave height

Wave height is the most intuitive geophysical feature of an ocean wave and can be measured by tide gauges at shore, ocean bottom pressure sensors off shore and, lately, Tsunami wave height measurements were recorded by satellite-borne altimeters. Satellite altimetry relies on nadir-pointing radars carried onboard a number of satellite missions like ESA’s ERS-1, ERS-2, ENVISAT, SENTINEL-3 and the series of US-French satellites Topex/Poseidon, Jason-1 and Jason-2. On Boxing Day 2004, a number of altimeters accidentally overflew the Tsunami wave and provided the scientific community with valuable measurements. Following this accidental data-takes, concepts were put forth for Tsunami early-warning from space. The proposed concepts envision a number of LEO microsatellites carrying altimeters (implemented either with active or passive radar technology). For example, results from the GANDER project put forth a constellation of 24 micro-satellites (4 satellites in each of 6 near-polar orbits at 1682 km altitude, orbit period 2 hours) in order to overfly a Tsunami within 30 minutes from the initial quake. However, the satellite still has to overfly a ground station for the data downlink, which might well take another 30 minutes under rather favorable conditions. If a constellation of satellites is put forth for Tsunami early warning, intra-satellite communication links should be envisioned to match the constraints dictated by near-field Tsunami early warning.

2.2 Tsunami Orbital velocities

As with every ocean wave, Tsunami propagation relies on the elliptical movement of water masses. Even though the group velocity of the wave is generally high (700 km/h in the open ocean, slows down with shallower bathymetry) the orbital velocities of water masses accomplishing Tsunami propagation is extremely small: 3 cm/s in the open ocean for the Great Sumatra-Andaman Tsunami. Again, these orbital velocities are amplified by shallow bathymetric features and might reach tens of cm/s or even m/s in coastal areas. Tsunami orbital velocities might be detected by Along-Track Interferometric SAR systems and HF surface wave radars (Anderson, 2008).

2.3 Tsunami Shadows

Tsunami shadows are spatially extended alterations of the radar cross section of the ocean surface. Observations of “Tsunami shadows”, i.e., extended darker strips on the ocean surface along the front of a Tsunami wave were first reported by the pilot of an aircraft overflying the 1946 Aleutian Tsunami. Later, observations were reported by eye-witnesses located at different points along the shore of the island of Oahu, Hawaii, coinciding with the arrival of a small Tsunami triggered by the 1994 Shikotan earthquake. Besides optical observations, Tsunami shadows were also observed at microwave frequencies by satellite altimeters overflying the Boxing Day Tsunami (Godin, 2004; Troitskaya et al., 2006). This unique data-take confirmed the presence of relevant (a few dB) variations of the ocean surface radar cross section associated with the Tsunami wave front.
These observations suggest that Satellite Altimetry, SAR, Scatterometers and Radiometers might have Tsunami detection capabilities. Of particular significance in application to Tsunami warning is the fact that the Tsunami shadows propagate at a known and very distinct speed, which allows for their unambiguous differentiation from other features on the ocean surface. Further research is however

needed to evaluate the time needed for Tsunami shadows to build up after the Tsunami inception. This feature is critical for the near-field problem.

2.4 Tsunami-induced internal waves

Tsunamis are long gravity waves and, like tides, have the capability of triggering internal waves under given oceanographic conditions. Internal waves generated by the Boxing-day Tsunami were recorded by MODIS. Even though internal waves appear as radar cross section variations of the ocean surface, it is worth reminding that the generating mechanism and the spatial scale of these features are completely different from Tsunami Shadows.

2.5 Ionospheric Tsunami signatures

Tsunami ionospheric signals have been detected for recent Tsunamis (Peru 2001, Sumatra 2004, Kourils 2007). Atmospheric coupling is responsible for the generation of acoustic and gravity waves that, after upward propagation, can be detected as TEC perturbations in the ionosphere. This approach has a great potential to improve far-field Tsunami early-warning since it might allow wide area imaging of Tsunami-generated ionospheric signatures by means of HF sky-wave radars (Anderson, 2008). On the other hand, it has a drawback for near-field early-warning: due to upward propagation, the signal reaches the ionosphere with a delay of 15-20 minutes.

2.6 Infrasonic Tsunami signatures

Ultimately, infrasonic Tsunami signatures were detected with ground-based sensors for the Boxing-day Tsunami. It appears that the generation of such signatures is related to the impact of the Tsunami wave on the continental shelf (Le Pichon et al., 2005).

The first 4 geophysical features are ocean surface geophysical features, and can be detected by satellite borne sensors (SAR, satellite altimeters, scatterometers and radiometers). Indeed, a number of mechanisms (either known or unknown) might contribute to Tsunami-induced radar cross section modulations and chances are that these effects are strong enough to be used as principles of detection by future Tsunami warning systems. This involves not only detection but also an estimate of the Tsunami magnitude. Ultimately, a stationary sensor (e.g. NESTRAD) has the possibility to learn normal patterns and detection and/or magnitude estimation can be achieved by comparing pre- and post-quake patterns.

3. THE NESTRAD CONCEPT

NESTRAD consists of a phased array real aperture radar operating at microwave frequencies (C-band for example) accommodated inside a stratospheric airship. Contrary to a satellite, no stowing and deployment of the antenna is required, prompting the use of low power density active electronically scanned array technology (LPD-AESA). In the following, a planar phased array is considered, but other solutions (conformal arrays for example) could be envisioned to achieve full 360° azimuth coverage. NESTRAD offers three principles of detection. The first is the detection of Tsunami-induced radar cross section modulations (RCS mode). The second is the Doppler retrieval of Tsunami orbital velocities (Doppler mode), and the third is the retrieval of Tsunami wave amplitudes obtained by pointing the beam downwards and detecting relative displacements in sea-surface height (altimeter mode). In the following the first two principles will be analyzed for a stationary system and a performance prediction of the proposed design will be provided. However, before performance prediction, we start with spatial coverage considerations.

3.1 Spatial coverage

According to the illumination geometry depicted in figure 1, the off-nadir angle θ can be written as

$$\tan(\theta) = \left[\frac{R\sin(\varphi)}{H - R\cos(\varphi)}\right] \quad \rightarrow \quad \theta = \arctan\left[\frac{R\sin(\varphi)}{H - R\cos(\varphi)}\right] \tag{1}$$

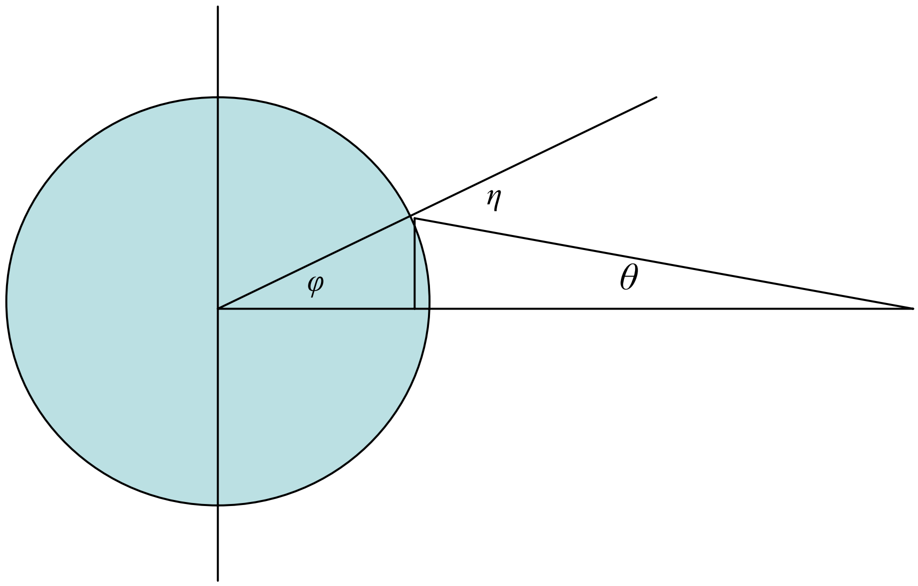

Figure 1. Sketch of illumination geometry and spatial coverage.

where R is the earth radius (6370 km), H is the platform height from earth center (i.e. 6370 km + 20 km = 6390 km) and $\varphi = \eta - \theta$, where η is the incidence angle. The distance D_{hor} from nadir to horizon is then derived by

$$D_{hor} = R\varphi \tag{2}$$

The formulae above account for the geometric horizon (also called visual horizon). At microwave frequencies however, electromagnetic energy is bent slightly downwards. This phenomenon is such that the radar horizon is displaced farther away from the visual horizon. This effect can be taken into account by multiplying the earth radius by 1.33 (provided propagation occurs through a standard atmosphere). For a stratospheric airship located 20 km above ground, the radar horizon is thus located 575 km from the nadir point. So, considering the attitude change capabilities of the airship, the radar coverage for target detection is a disk of approximately 1000 km diameter. For the purpose of Tsunami detection however, we must be able to retrieve the RCS of the ocean itself, and not of a target on its surface. In the following section the performance prediction shows acceptable SNR even for -30dB at incidence angles up to 85° (250 km ground range, 500 km diameter disk), but the variability of ocean surface RCS at low grazing angles is such that the real monitoring capabilities of the system can only be ascertained by experimental measurements.

Figure 2. Spatial coverage for Sunda trench and the Philippines.

In the case of the Sunda trench (see figure 2), the length (3000 km) is such that an array of 4-5 airships is necessary to provide early warning to Java and Sumatra. There are however situations where fewer units could cover the whole tsunamigenic areas of concern, providing near-field early warning to densely populated areas like Japan, the Cascadia Subduction Zone (CSZ) off Oregon and British Columbia or the Philippines.

3.2 RCS mode

For the RCS mode we present a performance prediction based on the single pulse radar equation, known in the literature as the SLAR radar equation. In remote sensing applications, in which the target is extended, it is appropriate to define σ_0 (normalized radar cross section) as the radar cross section per unit area of the scene as a random variable, with a mean σ_0 which in general varies from one resolution element to another. The following equation expresses the average SNR (signal-to-noise ratio) of a single radar pulse viewing an extended target with homogeneous mean specific backscatter coefficient σ_0.

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

where P_t is the transmitted power, G the antenna gain, R the range distance, L_a the antenna aperture, τ the pulse width, λ the radar signal wavelength, c the speed of light, N the noise figure, T the noise temperature, L the loss, and B is the Boltzmann constant.
For oceanographic applications, the normalized radar cross-section is strongly dependent on polarization (vertical *VV* or horizontal *HH*), angle of incidence, local wind speed and sea-state. For our performance prediction we will use indicative values. NESTRAD is meant to detect Tsunami-induced radar cross section modulations in the largest possible area. We will therefore consider incidence angles ranging from 0° (nadir) to 80°- 85° (low grazing). For ocean observations, vertical polarization yields higher RCS than horizontal, thus driving the choice for a single pol *VV* system. For low grazing angles, the RCS can be taken approximately equal to -30 dB. For airship-borne real aperture radars, PRF (pulse repetition frequency) constraints come from

- Nadir-Transmit interference
- Range Ambiguities $W_a > 2\lambda R\left(PRF\right)\tan(\eta)/c$

Further, if Doppler measurements are considered, the PRT (pulse repetition time) must also be reasonably shorter than the target decorrelation time.
Considering a continuous waveform (FMCW), follows an indicative system design for NESTRAD:

Table 1. NESTRAD design parameters.

System Parameters	
Antenna	(10×3)m phased array
Frequency	5 GHz
Polarization	VV
Path Loss	3 dB
Noise Figure	3 dB
Antenna Parameters	
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°

C-band is chosen for its sensitivity to sea-surface roughness and cloud penetrating capabilities. Vertical polarization is chosen given the higher RCS with respect to horizontal polarization. Beam steering capabilities allow the coverage from nadir to low grazing in elevation and from -60° to +60° from broadside in the azimuth direction, thus covering a circular sector approximately 120° wide. From table 2 we can see that in the far range a SNR of 13 dB can be achieved at broadside, corresponding to an acceptable 10 dB SNR at 60° off broadside. Even though azimuth resolution in the far range appears to be poor (2000 m), it is still acceptable to resolve Tsunami shadows, the latter having spatial extensions of thousands times tens of kilometers.

Table 2. NESTRAD performance at near and far range.

Waveform Parameters	far range	near range
Incidence angle	70°- 80°	20°
σ_0	-30 dB	-20 dB
PRT	800 Hz	2 kHz
Pulse width	1.25 ms	0.5 ms
Peak power	100 W	1 W
Bandwidth	150 MHz	150 MHz
Duty cycle	100% FMCW	100% FMCW
SNR	13 dB	40 dB
Range resolution	1 m	3 m
Azimuth resolution	2000 m	100 m

3.3 Doppler mode

Being stationary, the system can be used as a pulse Doppler radar to estimate sea surface radial velocities. Tsunami orbital velocities appear as anomalous surface currents whose value is crucially dependent on Tsunami magnitude and bathymetry. In this section, we consider the problem of Tsunami orbital velocity detection with a real aperture radar at microwave frequencies.
The accuracy of the velocity measurement yielded by a stationary Doppler radar system is given by the square root of the variance of the velocity estimator (Doviak et al., 1993; Rodriguez et al., 1992):

$$\mathrm{var}(\hat{v}) = \left(\frac{\lambda}{4\pi PRT}\right)^2 \frac{1}{2N^2} \left(\frac{1-|\rho[1]|^2}{|\rho[1]|^2}\right) \sum_{n=-(N-1)}^{(N-1)} |\rho[n]|^2 \left(N-|n|\right) \quad (4)$$

where $\hat{v}$ is the line-of-sight velocity estimator, N is the number of samples, $\rho[n]$ is the correlation coefficient at $PRT \cdot n$ time lag, and λ is the radar wavelength. Substituting the design values given in tables 1 and 2 into the formula we obtain a velocity accuracy of approx. 1 cm/s. This value should in principle allow the retrieval the Tsunami induced surface current signature also in the open ocean without requiring the wave to propagate in shallow bathymetry.
Note that the correlation coefficient is not only dependent on the time lag, but also on the spatial extension of the radar resolution cell. Being a real aperture radar the quality of the Doppler measurement might be degraded in the far range with a consequent constraint on the coverage area for this operating mode.

4. CONCLUSIONS

In this paper, a concept for near-field Tsunami early warning is presented. NESTRAD (Near-Space Tsunami Radar) consists of a phased array antenna accommodated inside a stationary or slowly moving airship meant to provide continuous monitoring of the ocean surface. A preliminary performance prediction is given, and the system appears to be capable of providing off-shore measurements of Tsunami-related features.

The initial review of Tsunami geophysical features has highlighted a plethora of phenomena that have received widespread attention in the remote sensing literature. Research in the field was mainly substantiated by data from LEO satellites. However, unless an inter-linked constellation of a large number (> 50) of satellites is considered, LEO satellites cannot match the challenging requirements posed by near-field Tsunami early warning. All possible space platforms have then been considered and stratospheric airships were found to be able to serve as ideal platforms for continuous monitoring of large ocean areas.

The geophysical characterization of Tsunami waves from a radar remote sensing viewpoint is still in its initial stages, and more information is needed for a robust characterization. Open questions are, among others, related to information on the initial stages of the wave:

- How long does it take for orbital velocities and/or for Tsunami shadows to build up to a maximum after the initial generation?
- Which is the dependence of Tsunami shadows on atmospheric weather?
- Which is the dependence of Tsunami shadows on Tsunami magnitude?

5. ACKNOWLEDGEMENTS

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