ALTIMETRY USING KU-BAND SIGNALS OF OPPORTUNITY (SOOP) SIGNAL

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ABSTRACT

Remote sensing of ocean surface using signals of opportunity (SoOp) has been done using Global Navigation Satellite Signals (GNSS) for last two decades. Recently, techniques that have been developed for GNSS have been expanded to other SoOps like digital communication signals [1]. The work presented here shows results of experiment, which used a Ku-band signal to measure sea surface height (SSH), and L- and S-bands signals to measure Significant Wave Height (SWH).

A reflectometry experiment was conducted at Platform Harvest (Jason-2 calibration and validation site), where a commercial US satellite TV signal located at Ku-band (DirecTV) was recorded from a height of about 27 meters above sea surface. The height was determined from the differences in electromagnetic path delay between the reflected and direct signal, found by cross-correlating the two signals and computing the lag of the peak. It was then compared with the mean sea level value from the tide gauge located at Platform Harvest. The correlation between the two measurements was found to be high with correlation coefficient of 0.9.

The precision of the estimation of height was found to be 13 cm from using 55 seconds of data. A theoretical error analysis was performed to compute the instrumental expected error based on the integration time of the cross-correlation, signal-to-noise ratio of the received signal, and data rate of the transmitting signal; and it was found the experimental error matched theoretical expected error, which was also found to be 13 cm.

This reflectometry experiment also recorded signals from a commercial US radio signal located at S-band (XM radio) and a navigation signal located at L-band (GPS). These signals were used to retrieve SWH using Interferometric Complex Field (ICF) coherence time method [2]. The Light Detection And Ranging (LIDAR) system located at Platform Harvest [3] was used as a reference, and the error was found to be in the order of 0.4 meters.

EXPERIMENTAL DESCRIPTION

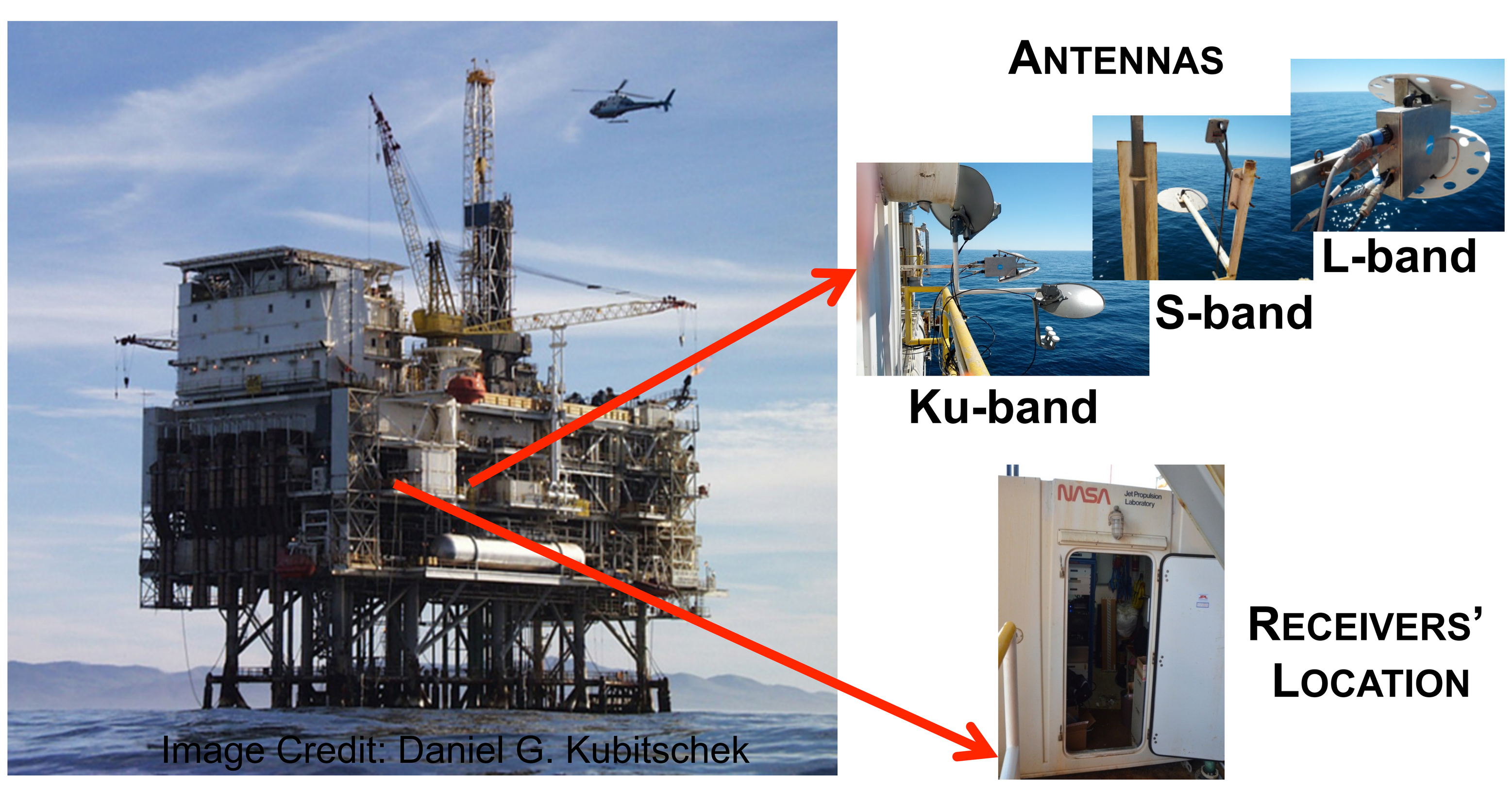

Figure 1: This figure shows the location of antennas and receivers at Platform Harvest. The antennas are located at approximately 27 meters above the ocean surface.

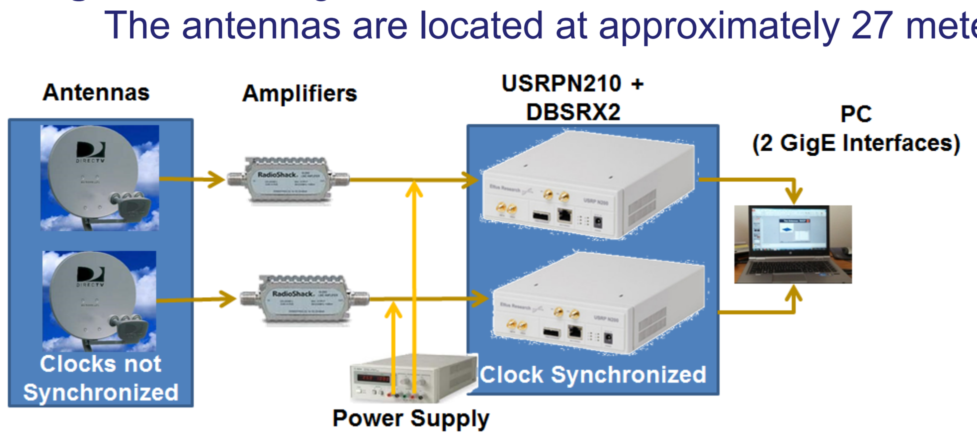

Figure 2: This figure describes Ku-band receivers. The signals captured by the antennas are downconverted, digitized, and sampled by Universal Software Radio Peripherals (USRPs), which then transfers data to a computer to be stored.

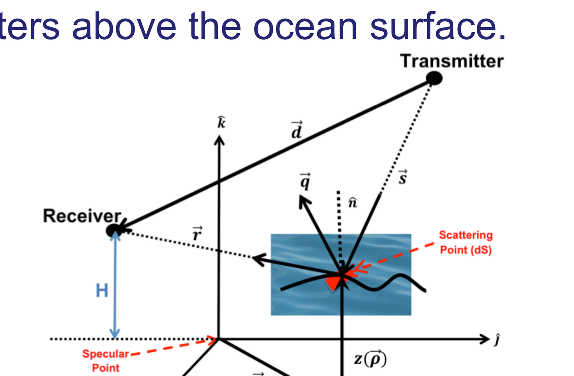

Figure 3: The geometry of the problem is shown in this figure. A direct signal from the satellite and a reflected signal from the ocean surface is recorded by the receiver.

Table 1: Recording parameters for each frequencies is described.

Parameter	Ku-Band	S-Band	L-Band
Center frequency, f_c	12.239 GHz	2.343 GHz	1.575 GHz
Sampling frequency, f_s	50 MHz	8 MHz	16.366 MHz
Sampling quantization	8 bits complex	8 bits complex	1 bit complex
Recorded data length	1 minute	1 minute	1 minute
Date recording period	4 hours	2 hours	~ Every 20 min.

ALTIMETRY USING KU-BAND SOOP

A code altimetry approach is used to retrieve SSH. The direct and reflected signals are cross-correlated to form reflected waveform and the maximum delay is computed (Eq. 1 and Figure 4).

Eq. 1: $$|R_{RD}(\tau_i)| = max_{\tau_i}\left\{\left|\frac{1}{T_I}\int_{(t_i)}^{(t_i+T_I)} E_R(t+\tau_i)E_D^*(t)dt\right|\right\}$$

The delay is related to height, *H* (or SSH) by Eq. 2.

Eq. 2: $$\tau_i(t) = \tau_{i,l}(t) + \tau_b = 2\frac{H(t)}{c}\sin\varepsilon + \tau_b$$

The measurement noise, σ_τ, in the estimation of delay is given by Eq. 3.

Eq. 3: $$\sigma_\tau = \frac{T_c}{\sqrt{N_{IN}}}\sqrt{\left(1+\frac{1}{SNR}\right)^2 + \left(\frac{1}{SNR}\right)^2}$$

$R_{RD}(\tau_i)$: Reflected Waveform
$E_D(t)$: Direct Electric Field
$E_R(t)$: Reflected Electric Field
T_I : Integration Time
ε : Elevation Angle
τ_b : System Bias
T_c : Chip Length (Data Rate)
N_{IN} : Incoherent Integration
SNR : Signal to Noise Ratio

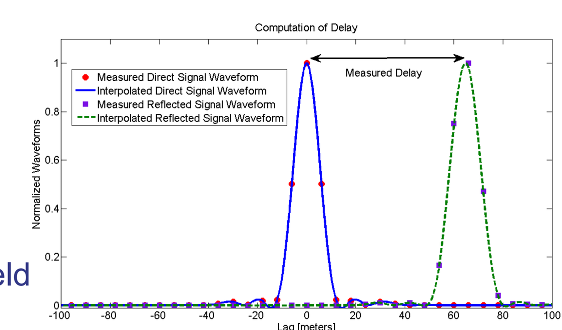

Figure 4: This figure shows an example of the path delay between the direct and reflected waveform.

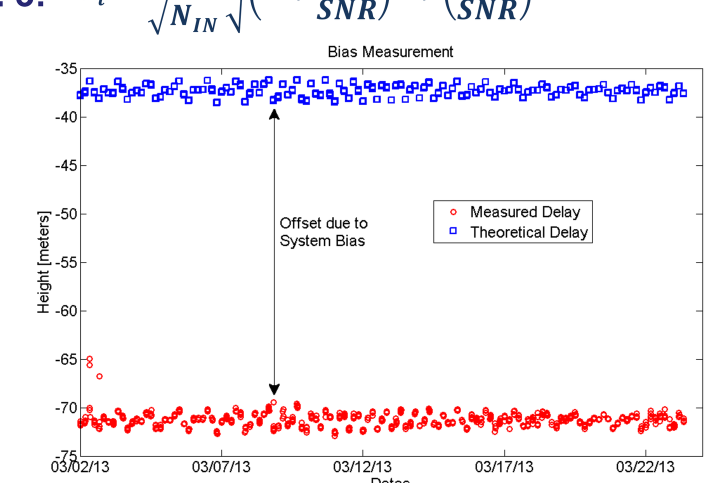

Figure 5: This figure shows the offset between the theoretical delay and experimentally computed delay due to system bias. The mean of the offset was found to be 33.86 meters.

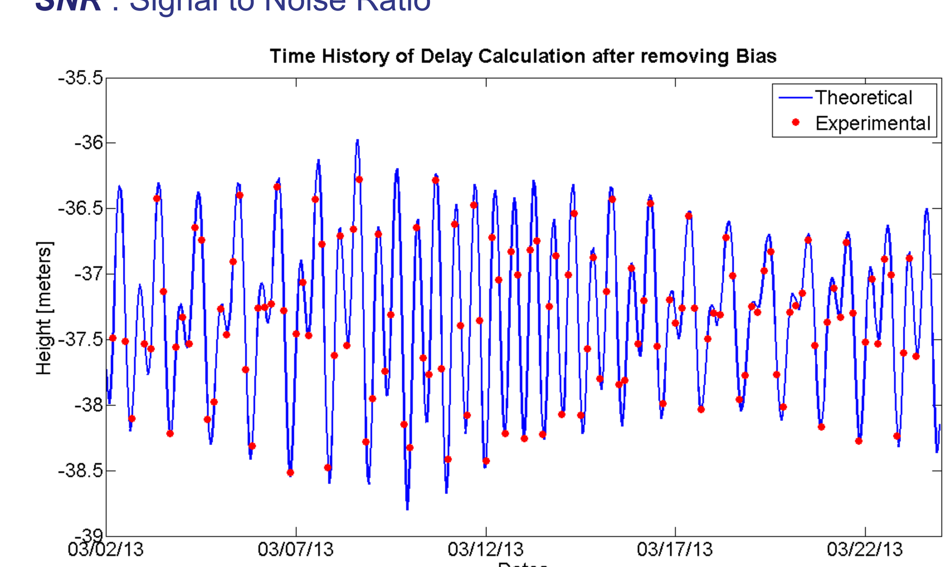

Figure 6: This figure shows time history of experimental delay after removing the mean of the offset. This is plotted along with the expected delay computed from the tide gauge SSH values. It is noted that both the plots follow each other closely. The standard deviation was found to be 0.18 meters.

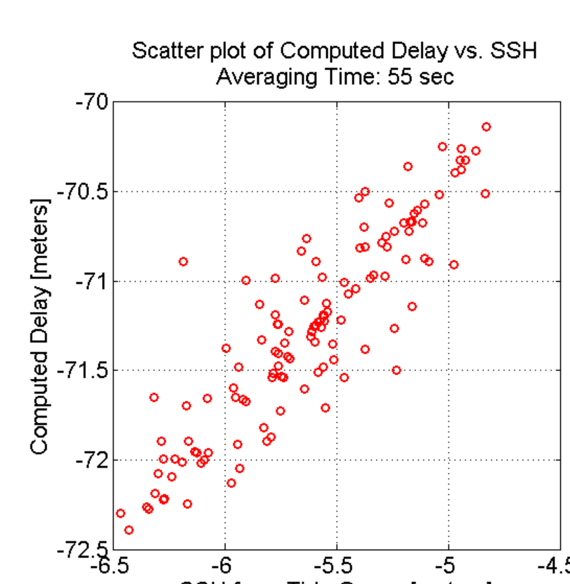

Figure 7: This figure shows a scatter plot of computed delays vs. the SSH measured by the tide gauge located at Platform Harvest. The correlation coefficient was found to be 0.90.

Table 2: Summary of altimetric precision from Ku-band signal is provided here.

Parameter	Avg. Time	Theoretical	Experimental
SNR [dB]	4 ms	25.8	25.11
σ_τ [meters]	55 s	0.1880	0.1882
σ_H [meters]	55 s	0.13	0.13

The standard deviation, σ_H, in the estimation of height is given by Eq. 4.

Eq. 4: $$\sigma_H = \frac{\sigma_\tau}{2\sin\varepsilon}$$

SIGNIFICANT WAVE HEIGHT USING L- AND S-BANDS SOOPS

The model used for SWH retrieval is ICF coherence time model. The fundamental measurement of this model is the ICF coherence time, τ_F, which is the width of the ICF autocorrelation (ICFA) function [2]. Here, ICF is defined at time, t, by: $F_I(t) = F_R(t)/F_D(t)$ where $F_D(t)$ and $F_R(t)$ are the complex values at the amplitude peaks of direct and reflected complex waveforms, respectively. ICFA function is assumed to be Gaussian and the width of this Gaussian function has been shown to be related to SWH as Eq. 5 using the definition of $SWH = 4 * \sigma_H$, where σ_H is the standard deviation of the height of the sea surface [2].

Eq. 5: $$\tau_F = \frac{\lambda}{\pi\sin\varepsilon}\frac{\alpha+\beta\, SWH}{SWH}$$

λ : Wavelength of recorded signal
α, β : Empirical parameters

Table 3: Statistics of SWH retrieval error when SWH from LIDAR was used as a reference

Frequency	Std. Dev.
L-band	0.40 m
S-band	0.44 m
Combined (Ensemble)	0.38 m
Combined (Averaged)	0.27 m

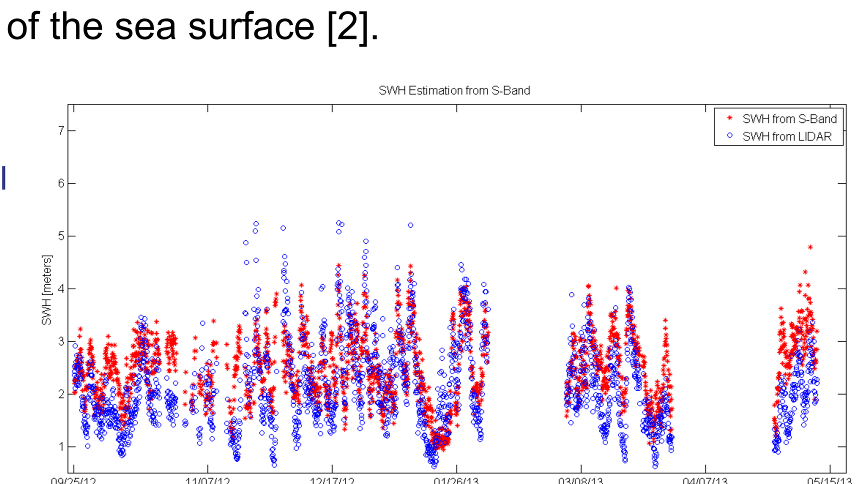

Figure 8: This figure shows a time series of SWH estimation from the S-band. The standard deviation of the error in estimation was 0.44 m.

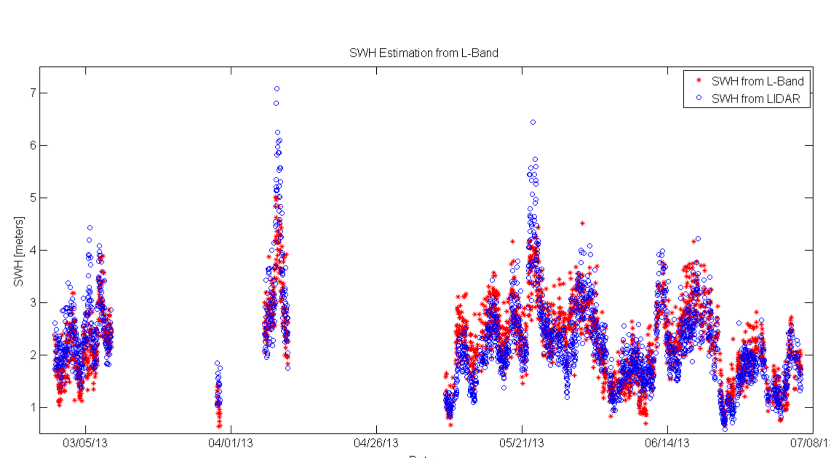

Figure 9: This figure shows a time series of SWH estimation from the L-band. The standard deviation of the error in estimation was 0.40 m.

JASON- 2 OVERFLIGHTS

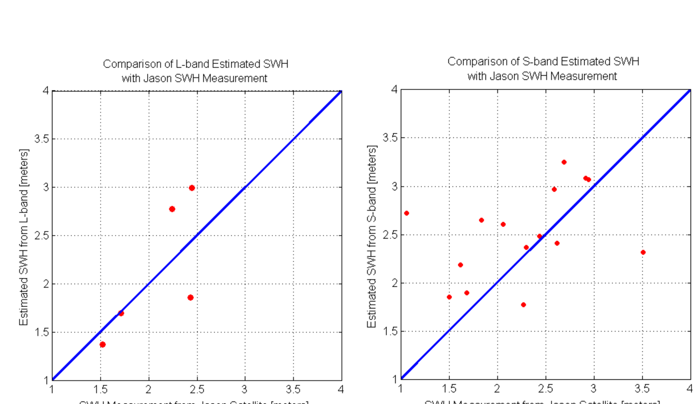

Figure 10: These plots compare estimated SWH from L- and S-bands with Jason-2 overflights data.

Table 4: Comparison summary of SWH retrieved from L- and S-bands and SWH from Jason-2 satellite

Parameter	S-band	L-band	Units
Number of data points	15	6	
Mean temporal difference between data	70	4	min
Error standard deviation	0.42	0.33	m
Correlation coefficient	0.72	0.94	

SUMMARY

This poster showed preliminary results of an estimation of SSH using Ku-band data. The precision of estimation of height was found to be 13 cm after using 55 seconds of data. In order to optimize the precision of the measurement, the coherent integration should be as low as possible since the incoherent integration significantly improves precision (by reducing speckle noise) as observed in Eq. 3. In this experiment, a coherent integration time of 4 milliseconds was used as an initial value. As an example, if we lower the coherent integration time to 1 millisecond and keep the incoherent averaging to 55 sec, then the expected σ_τ would be 0.095 m (almost half of 0.18 m, the value at a 4 milliseconds coherent integration time). Another way to improve the precision would be to increase the incoherent averaging time. For example, if the coherent integration time is kept at 4 milliseconds and the incoherent averaging is increased to 2.5 min, then the expected σ_τ would be reduced to 0.11 m.

Finally, L-band and S-band signals were used to retrieve SWH using ICF coherence time method [2]. The LIDAR system located at Platform Harvest was used as a reference, and the error was found to be in the order of 0.4 meters. However, when the retrievals were combined from multiple frequencies, the error reduced to 0.27 m with 1-minute averaging time.

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