Ship-borne Wave Gauge using GNSS Interferometric Reflectometry

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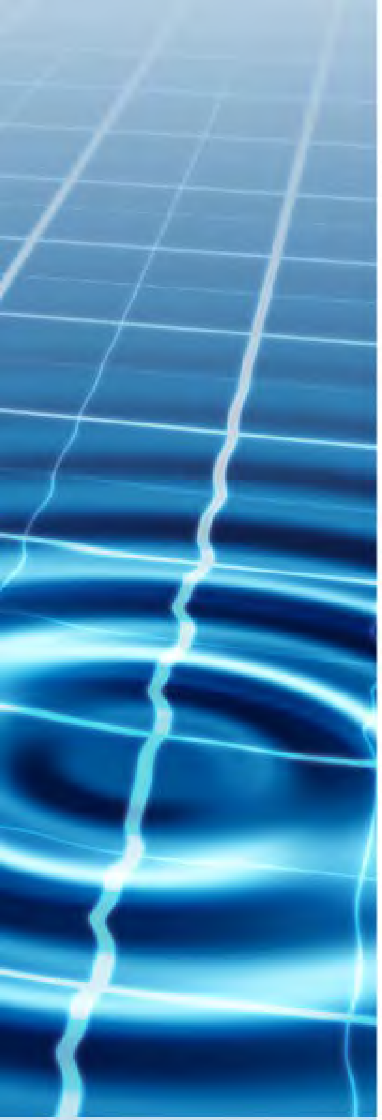

Wave Prediction

- Solve *Energy equations*
  - Energy as the wind stress
  - Wave-wave interactions
  - Energy dissipation
  - ✓ Estimations are possible if wind fields are available
- Various error sources
  - ✓ Wind stress variations within the atmospheric boundary layers
  - ✓ Topographic effects (bottom, side)
- Proper corrections are necessary by **wave field observations**

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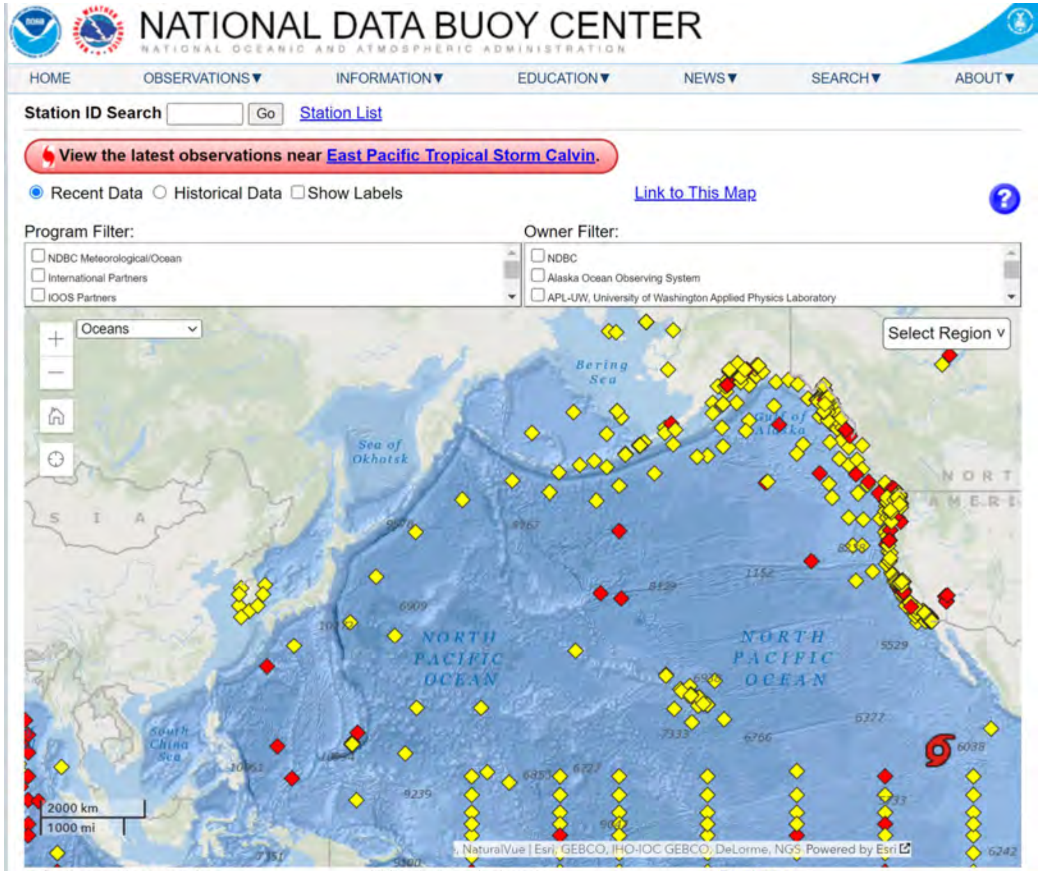
Wave Buoys Distrib.

- The distribution of wave buoys is quite sparse
  - v.s. spatial scales of wave fields



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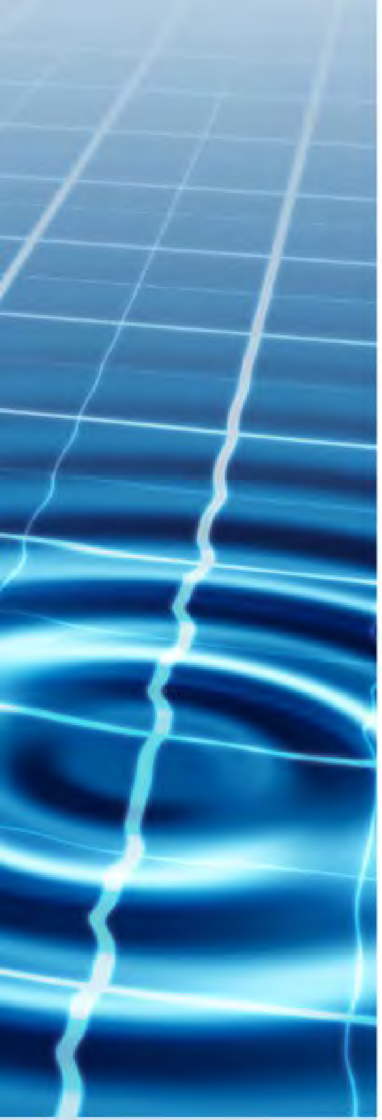

Waves from satellites

Waves = wind waves + swells

- Various sensors detect *wind waves*
  - *For estimations of wind speeds*
- Only satellite altimeters measure *swells*
  - Observe nadir points only
    - Significantly sparse both in time and space
      - » 10 day + 330 km or 35 day + 75 km

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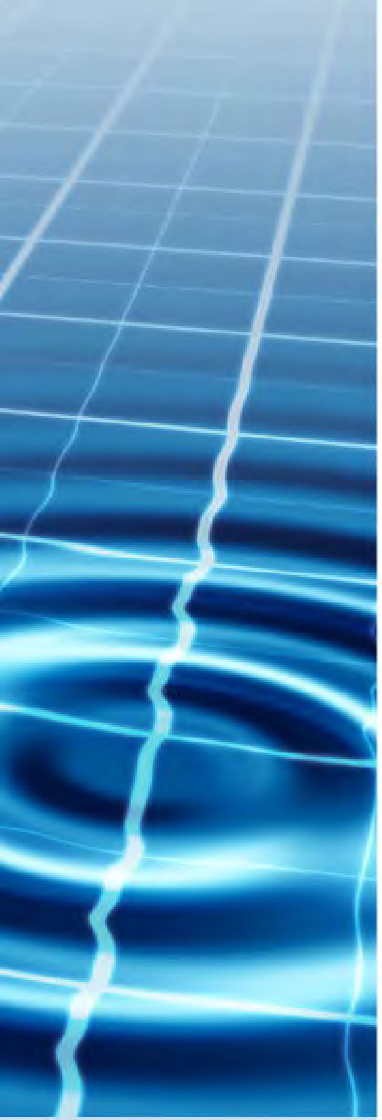

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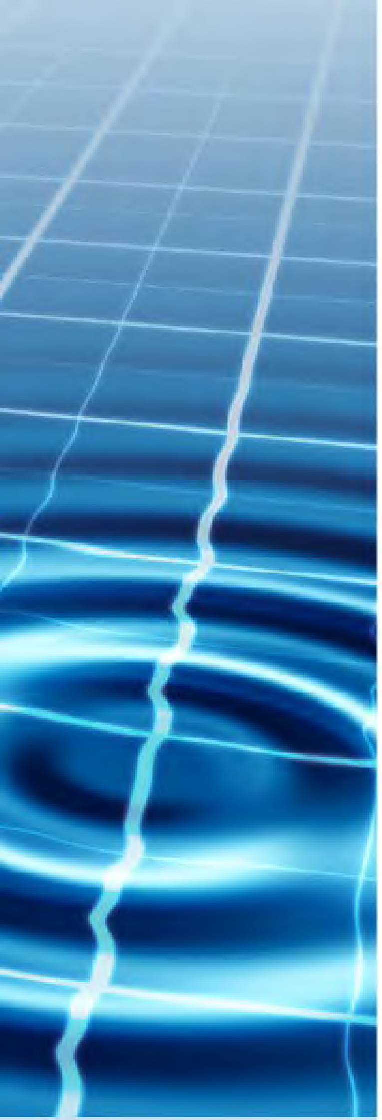
Waves from ships

- Practically useful
  - ✓ Areas of high demands

- Subjective visual observations by experienced crew
  - ☐ Trials for objective obs
    - Machine learning of video recordings
    - Ranging by wires and lasers
  - ✓ Moving vessels generate waves around themselves



Purpose of this study

- <u>Objective wave observations</u> from <u>moving vessels</u>
  - Wave fields slightly away from ships
- <u>Anytime, anywhere</u>
  - Especially, at night time when visible observations are not available
- Use <u>GNSS</u> (Global Navigation Satellite System)
  - GPS, GLONSS, BeiDou, Galileo
  - ✓ GNSS Reflectometry (GNSS-R)
  - ✓ GNSS Interferometric R (GNSS-IR)

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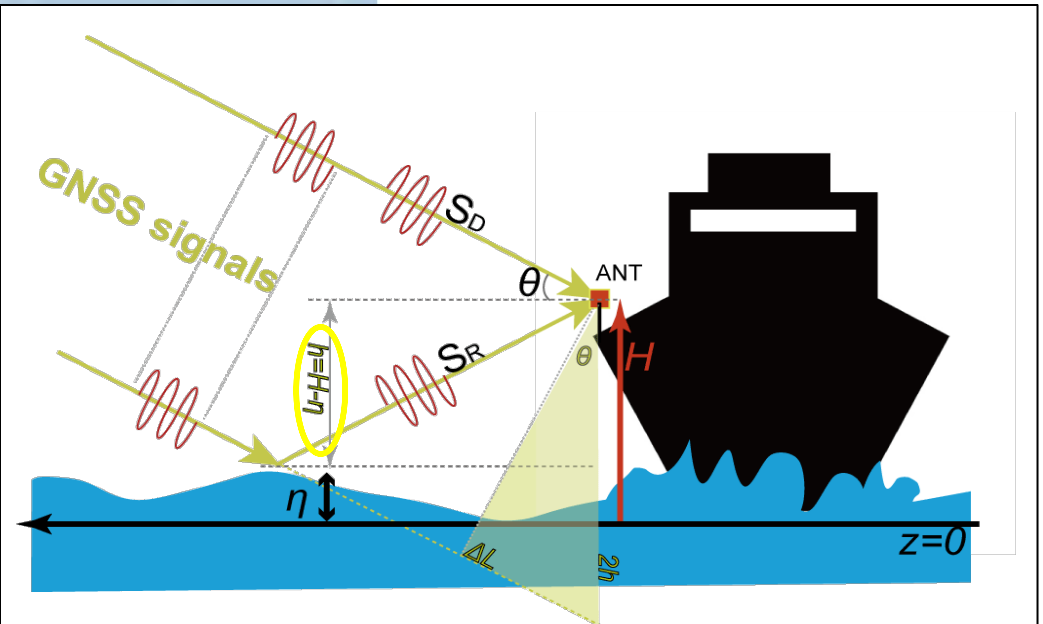
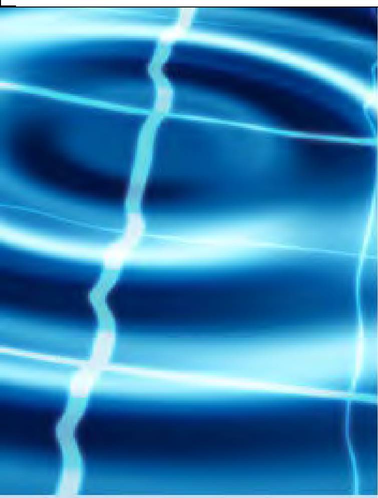


GNSS-IR

S_D : Direct GNSS signals
S_R : GNSS signals reflected from the sea surface
ΔL : Travel distance delay



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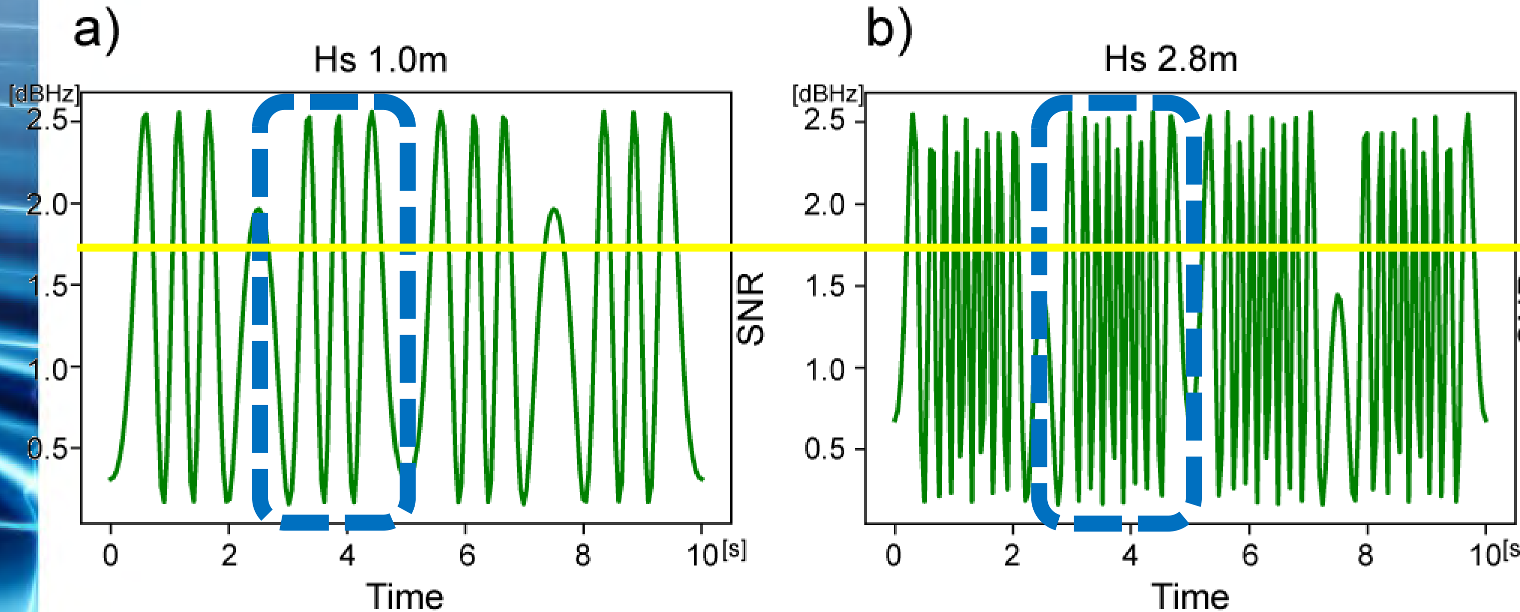
- S_R always delays from S_D
  - Delay ΔL depends on the antenna height from the sea surface ($h=H-\eta$) and the incident angle θ
- Signal strength (aka, SNR) depends on the phase difference between S_D and S_R
  - SNR becomes large/small every 0.2 cm (wavelength of GNSS signals) of ΔL change
- Therefore, temporal variations of η (*i.e.*, waves) can be determined from variations of SNR (as "interferometory")

Simple Simulation
sinusoidal waves



- Simulate 10 sec of 20 Hz SNR variations by simple sinusoidal surface waves
  - Wave period 5 sec
  - Different wave height (SWH; 1m, 2.8m)
- Higher-frequency variations for larger SWH
  - Faster *h* changes
- HF signals modulate periodically
  - Less *h* changes at wave troughs and crests

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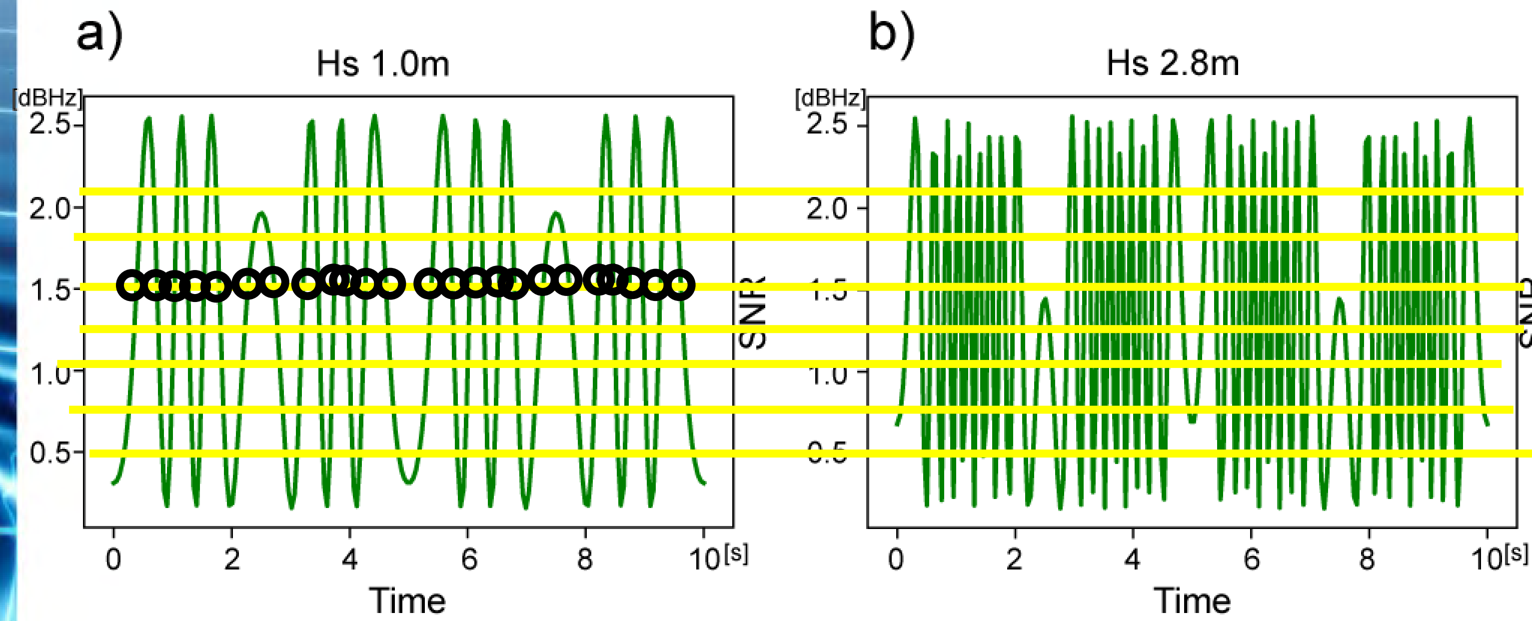
Index for HF variations



- Count the number of crossing a line of the given SNR value
- Take the mean of these numbers for 100 lines (*Nc*)

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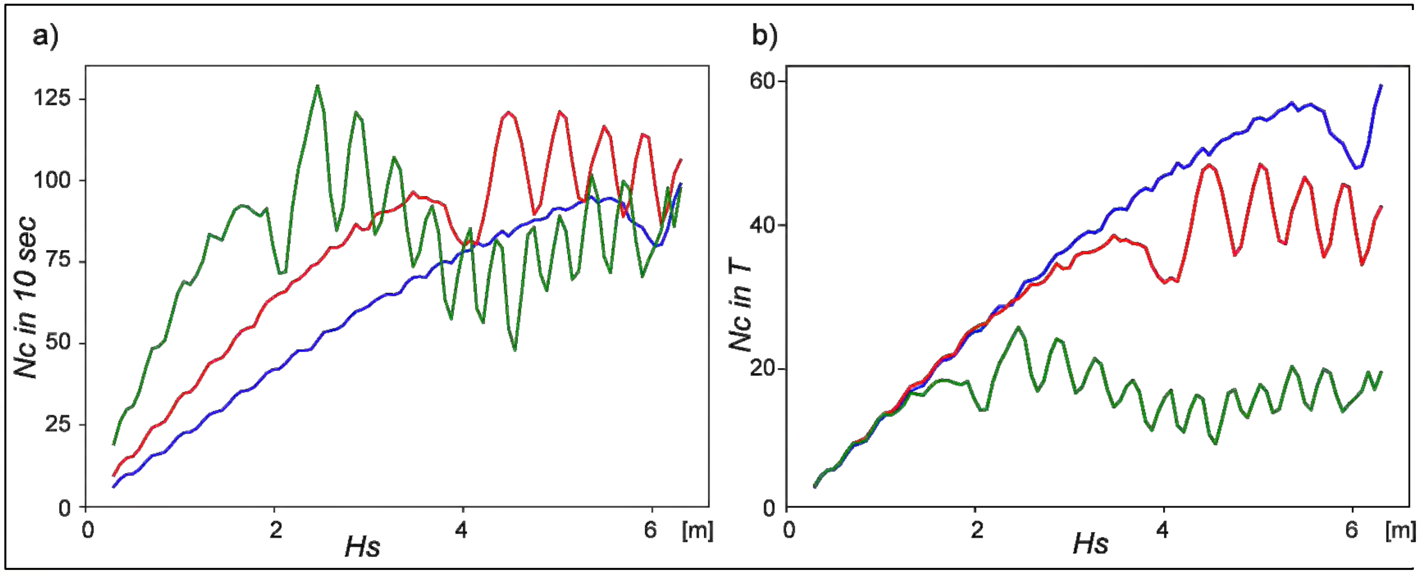
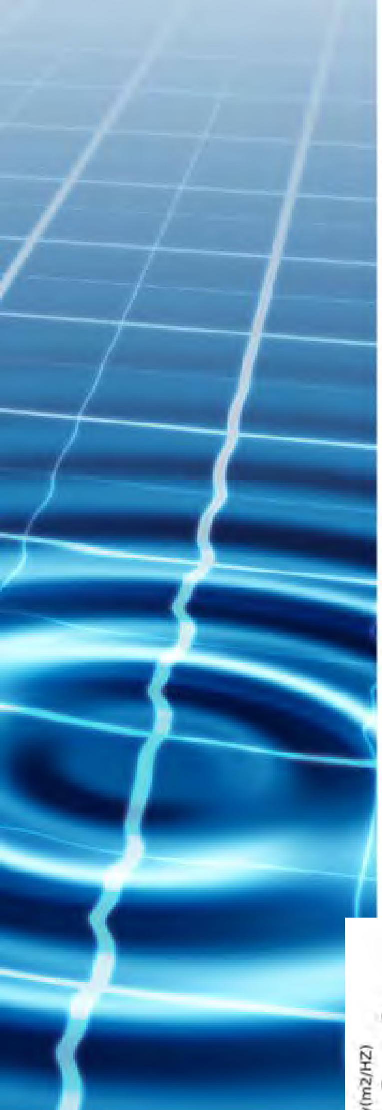
Nc - SWH relation



- *Nc* (in 10 seconds) determined from waves with periods 2, 4 and 6 sec against SWH
- The curves become the same when normalized by the wave periods
  - Except high limits
- **Higher SWH produces larger Nc^T**



Practical simulation

- Change single-frequency sinusoidal waves to waves with ISSC (Bretschneider or modified Pierson-Moskowitz) spectrum

$$S(f) = \frac{5}{16} Hs^2 f_m{}^4 f^5 exp[-\frac{5}{4}(\frac{f}{f_m})^{-4}]$$

- Simulate 20 Hz SNR for 120 sec
  - With random frequency phases

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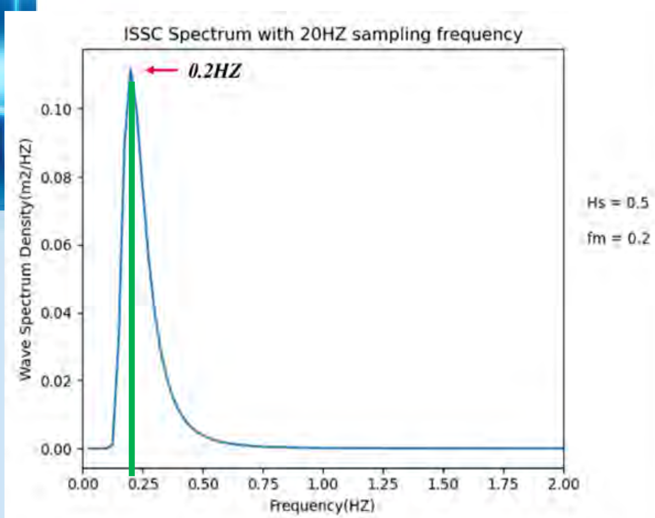
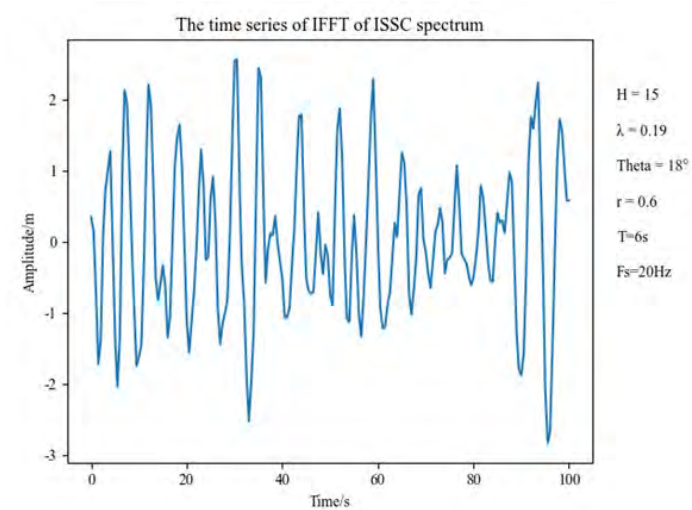
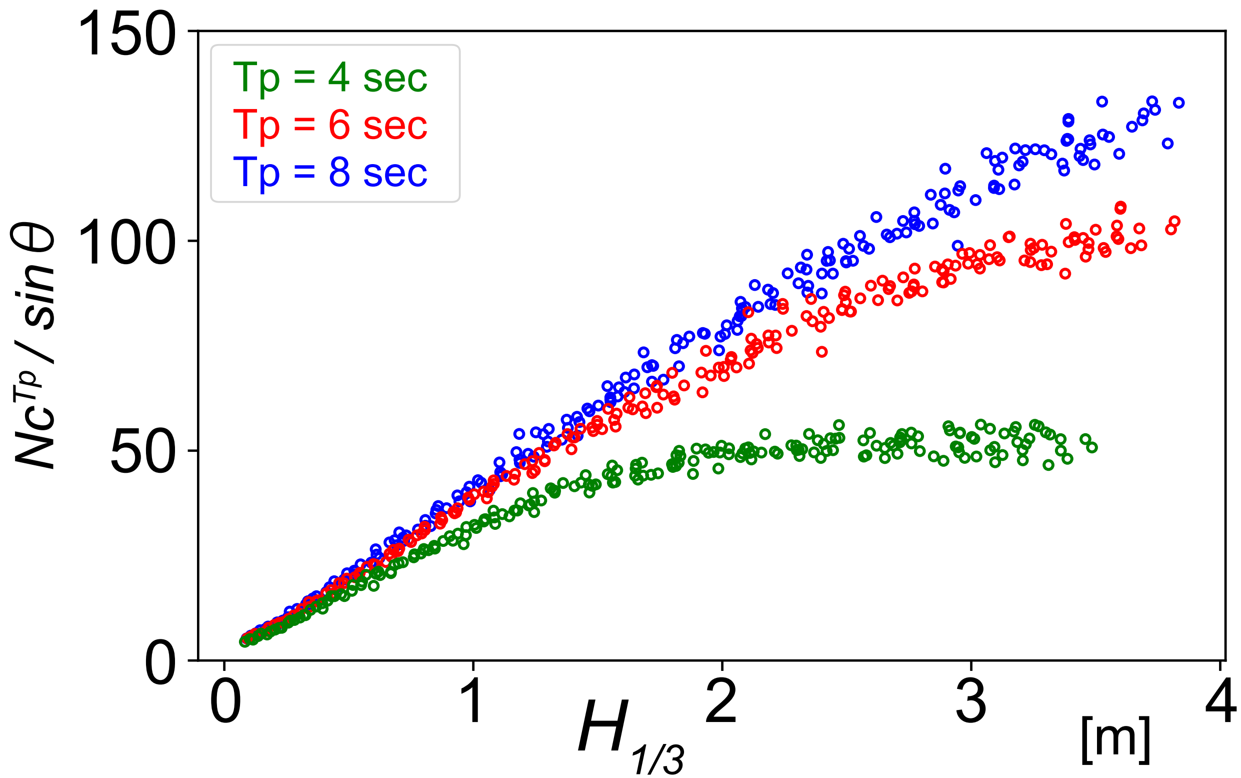
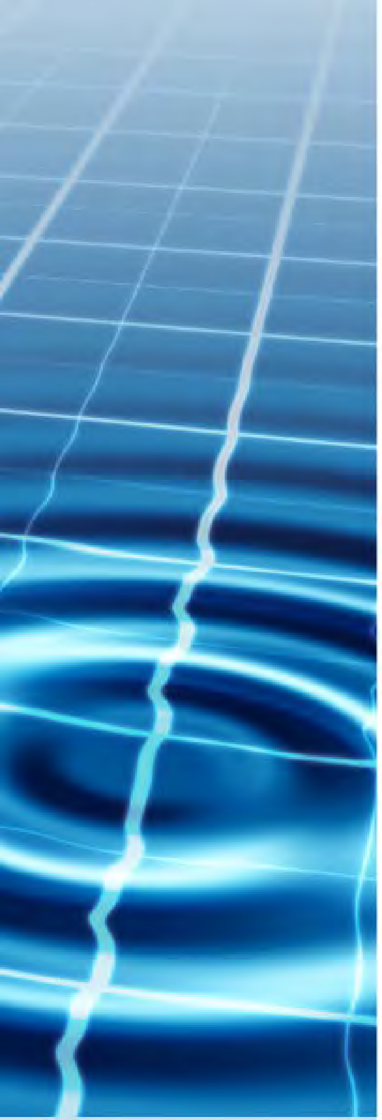




Nc^T for ISSC spectrum



- ➢ Almost similar tendency to Nc^T of simple sinusoidal waves
  - ✓SWH can be estimated from Nc^T even with ISSC spectrum



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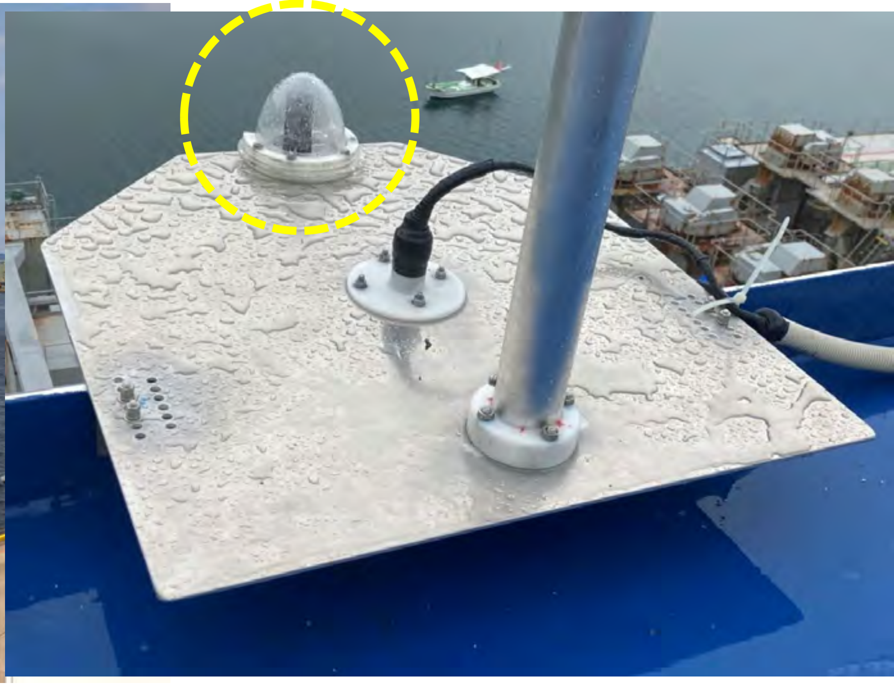
Actual Observations



- Install a helix GNSS antenna (TOPGNSS TOP107) to a ferry "*New Camellia*" (Camellia Line Co. Ltd., 19,961 Gross Tons)
  - ✓ Sample SNR at 20 Hz by a receiver (ublox F9P)

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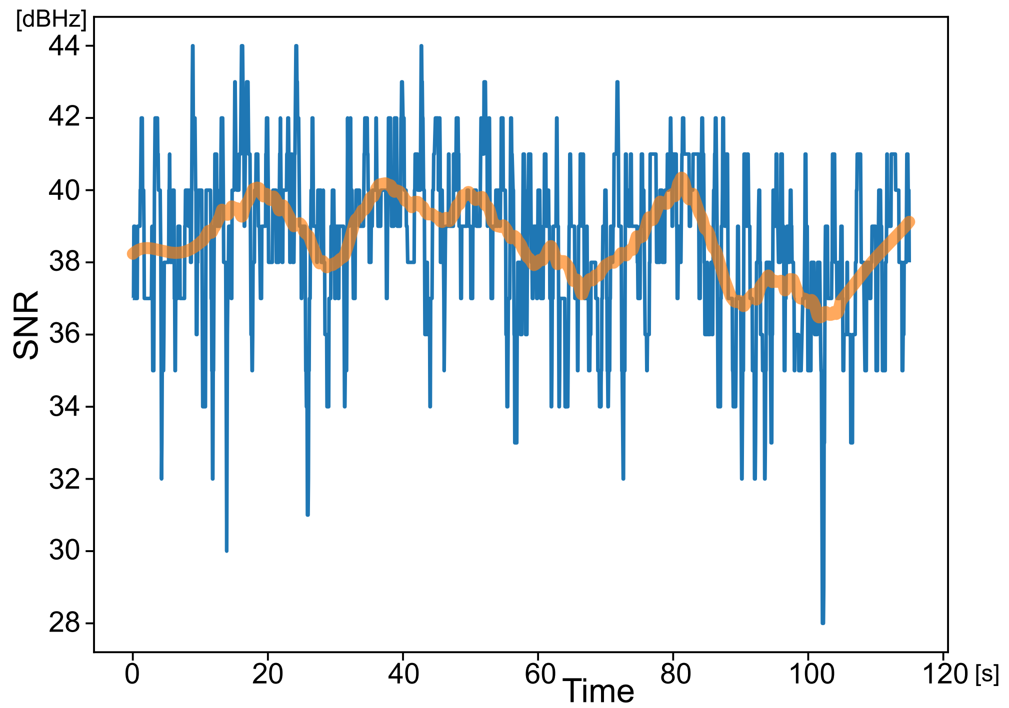
Real SNR data



- 2 min sampling (2400 samples)
- Remove variations longer than 20 sec, which could be affected by ship motions

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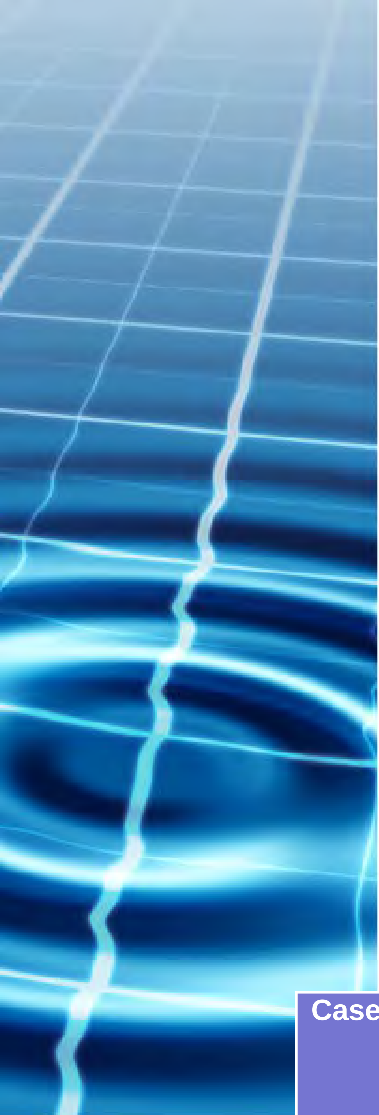
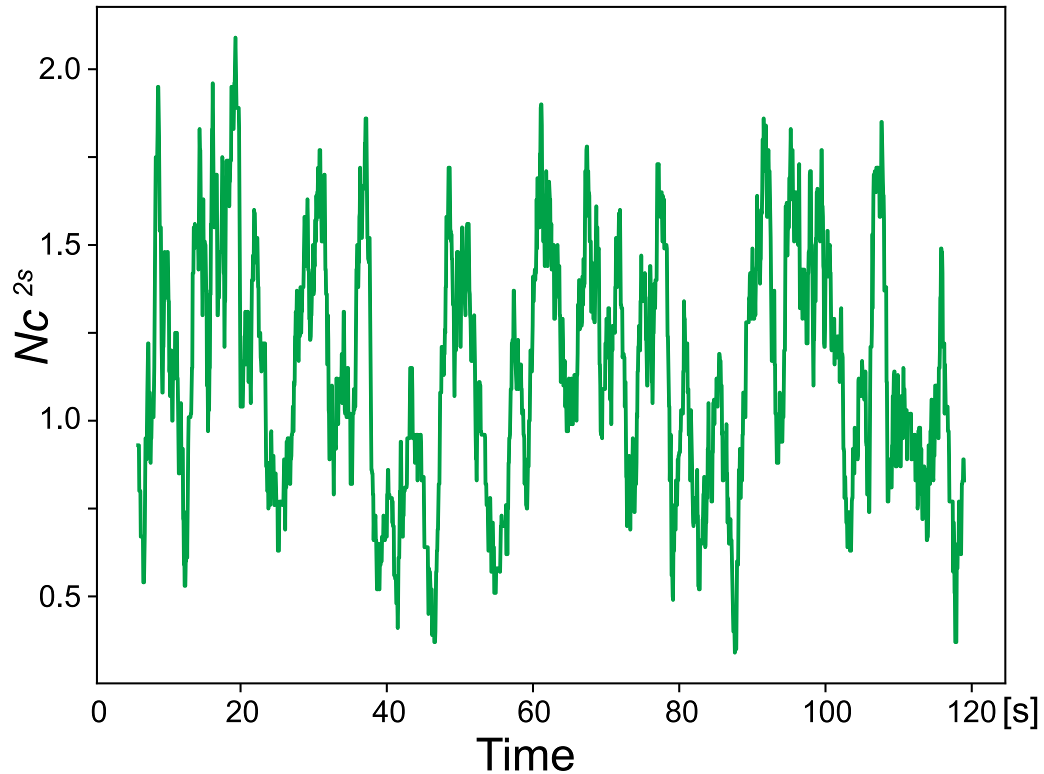


Different sea states

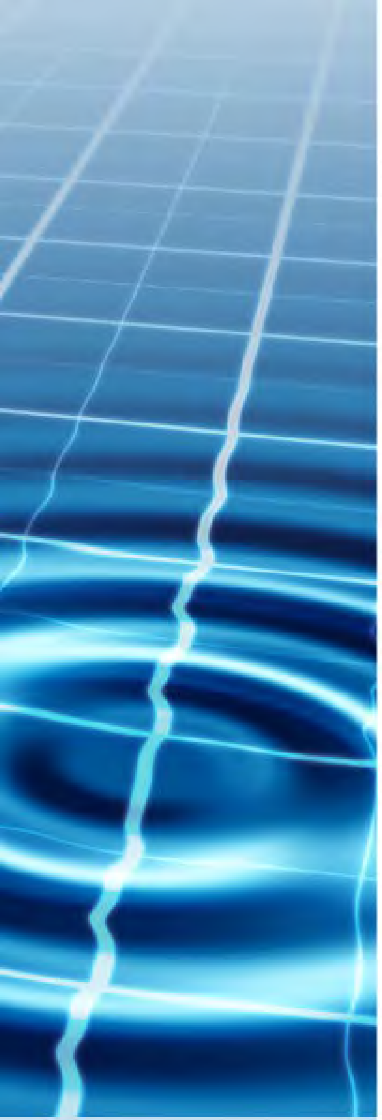
- Examples of 3 different sea states:
  - Calm (2022/5/18)
  - Ordinary (2022/6/14)
  - Rough (2022/6/24)
    - hindcast data by JWA POLARIS wave model
- Select 2 low-elevation satellites for each case
    - Interferometry occurs only when elevation angles are low (due to GNSS signal polarization)

Case	Date in 2022	Time [UTC]	Latitude [°N]	Longitude [°E]	SWH [m]	Wave Period [s]	Subcase	PRN	Elevation angle [°]
1	5/18	14:10-14:12	34.196	129.926	0.17	3.6	1G	G08	12.9
							1R	R18	8.2
2	6/14	16:10-16:12	34.702	129.574	1.51	5.3	2G	G04	12.7
							2C	C33	7.6
3	6/24	14:10-14:12	34.138	129.951	2.56	6.4	3G	G03	13.8
							3R	R24	12.0

Period Estimation



- Estimate *Nc* in every 2 seconds
- From this time series of Nc^{2s} , wave periods are estimated from its auto-correlation

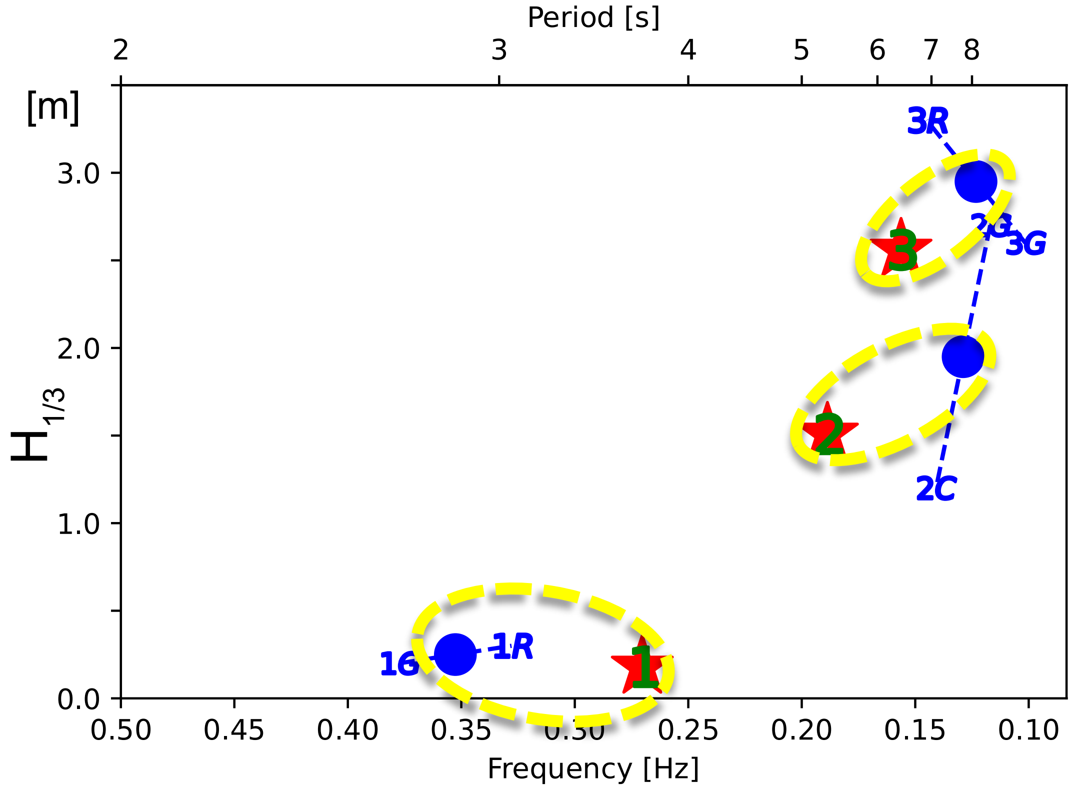


SWH estimation

- SWH values are estimated by using the previous **Nc^T-SWH simulations** with the ISSC spectrum
  - We need period-normalized Nc^T
    - Use estimated period Tg

Case	Subcase	Wave Period Tg [s]	SWH [m]	
				Average
1	1G	2.7	0.2	0.3
	1R	3.1	0.3	
2	2G	8.6	2.7	2.0
	2C	7.1	1.2	
3	3G	9.8	2.6	3.0
	3R	6.9	3.3	

Comp. with wave model



- **Averaged estimations** qualitatively **agree with the model (star marks)**
  - ✓ Individual estimations have large discrepancies

- We can improve *Nc*-SWH relationship by more comparisons

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Summary

- A new method is proposed to measure wave periods & heights from moving vessels using GNSS-IR
  - Waves cause high-frequency SNR variations by interferometry of direct and reflected GNSS signals
  - Wave periods can be estimated from modulations of h-f SNR variations
- Reasonable results have been achieved from actual samples
  - Practically, *Nc*-SWH look-up tables can be established from sufficient cases
    - This table could depend on areas and seasons because of different wave spectrums

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