Passive subsurface radar for exploration of the subsurface structures of Jupiter's icy moons by JUICE/RPWI

A. Kumamoto[1], Y. Kasaba[1], F. Tsuchiya[1], H. Misawa[1], T. Kimura[1], W. Puccio[2], J.-E. Wahlund[2], J. Bergman[2], B. Cecconi[3], W. Kofman[4]

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Expected performance of the passive subsurface radar sounding of Jupiter's icy moons by using JUICE/RPWI has been investigated. In passive radar observation, the Jovian radio waves are used as radar pulse. So it could be a complimentary observation to active radar. Jovian radio waves is noise for active radar while they becomes signal for passive radar. Passive radar with RPWI is possible to use wide frequency range. The roughness of the surface and subsurface reflectors with respect to the wavelength will be smaller in lower frequency range. We should note some demerits such that it is possible only in Jupiter side, and we can not control the radar pulse in order to apply usual radar techniques. In order to perform passive radar with RPWI, we are planning to prepare two kind of operation modes: PSSR-1 for continuous waves with long duration and PSSR-2/3 for burst waves with short duration. In PSSR-1, RPWI measures spectrogram including interference patterns caused by direct waves and reflected waves from the moon's surface and subsurface reflectors. In PSSR-2&3, RPWI measures waveforms and perform the cross correlation analysis among the waveforms. In estimation of detection depth, we have to confirm several parameters. The intensities of the Jovian radio waves and galactic noise were determined based on the previous spacecraft and ground-based observations. The attenuation in shallow part of the ice crust is ignorable (~0 dB/km). Therefore, the shallow reflectors within ice crust will be detectable. However, it would be difficult to detect echoes from the boundary between ice crust and liquid ocean due to strong attenuation in the ice around melting temperature. We are starting test analyses with simulated waveform, which will be useful for preparation of the onboard software and analysis tools used on the ground.

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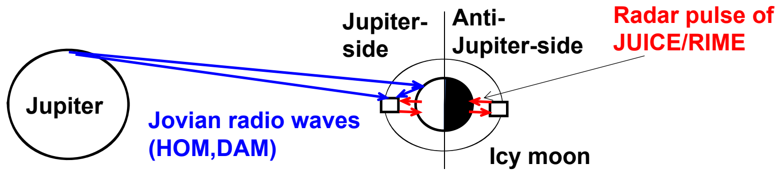
Active radar and Passive radar



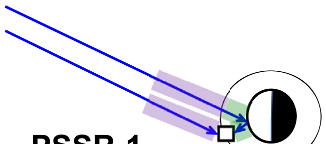
Merits of passive radar

- A complementary observation for subsurface radar sounding
  Jovian radio wave becomes noise for active radar
  but signal for passive radar
- Possible to use wide frequency range
  Lower attenuation, lower clutters can be expected
  in lower frequency range.

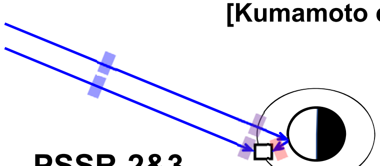
Demerits of passive radar

- Possible only in Jupiter side and only when radio wave is active
- Pulses are not controllable. Difficult to expect gain by usual radar technique (range & azimuth compressions)

Two RPWI operation mode for passive radar



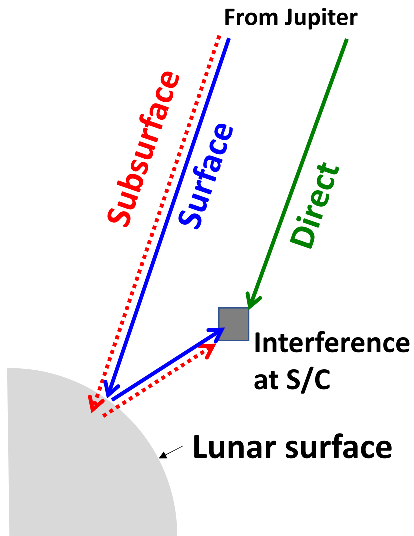
PSSR-1
Continuous waves with Long duration
→ RPWI measures spectrogram
including interference patterns
[Kumamoto et al. 2017]



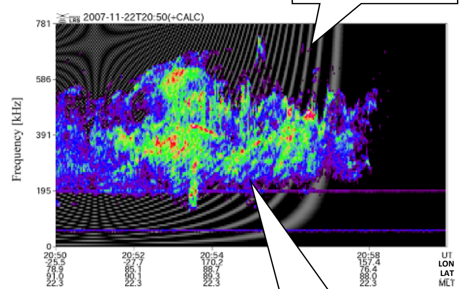
PSSR-2&3
Burst waves with Short duration
→ RPWI measures waveform
→ auto-correlation analysis
[Romero-Wolf et al., 2015;
Schroeder et al., 2016]

PSSR-2 (by Japan team)
Low data rate
One E component
PSSR-3 (by Sweden team)
High data rate
Three E components

PSSR-1 for continuous waves



Calculated interference pattern (Gray)

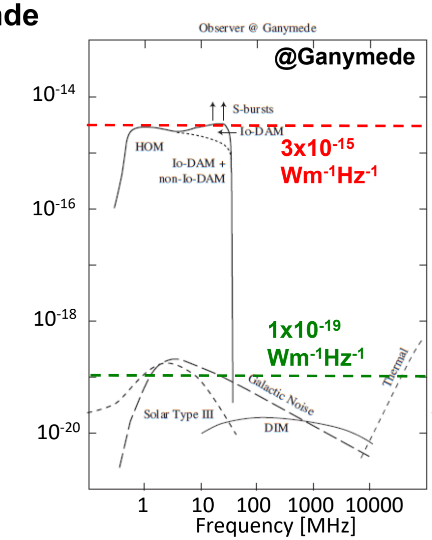


[Ono et al., 2010]

AKR spectrogram with Interference patterns measured by SELENE (Color)

Maximum detection depth of PSSR

Intensity of Jovian radio waves and Galactic noise at Ganymde

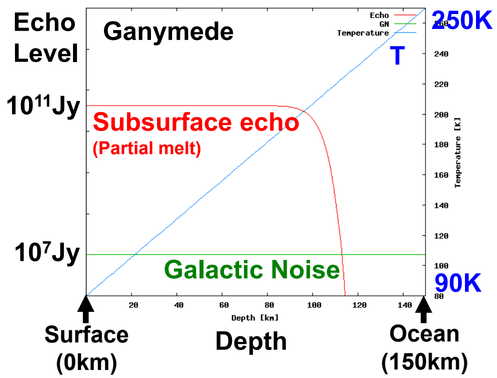


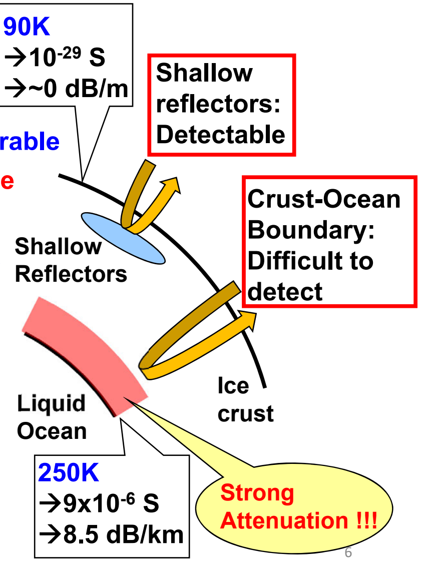
[Cecconi et al., 2012]

Maximum detection depth of PSSR

Conductivity of the ice

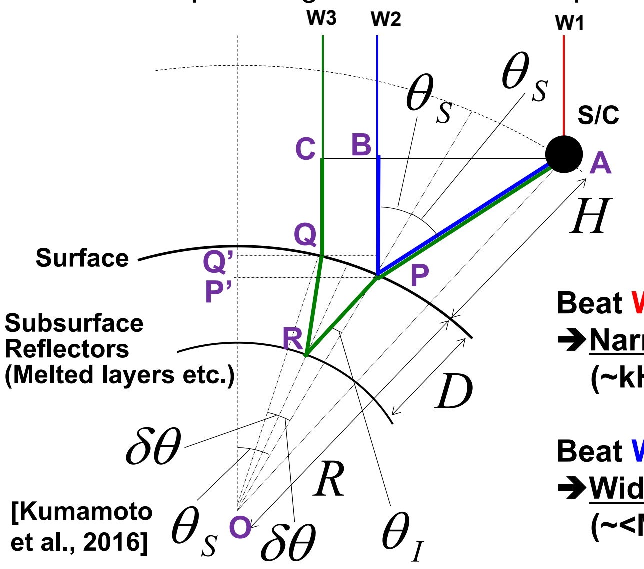
T [K]	Conductivity σ [S]	Attenuation α [dB/km]	
80	1.35×10^{-29}	1.26×10^{-23}	Ignorable
250	9.28×10^{-6}	8.51	Large





Expected spectrum in PSSR-1

Difference of path length → Interference patterns

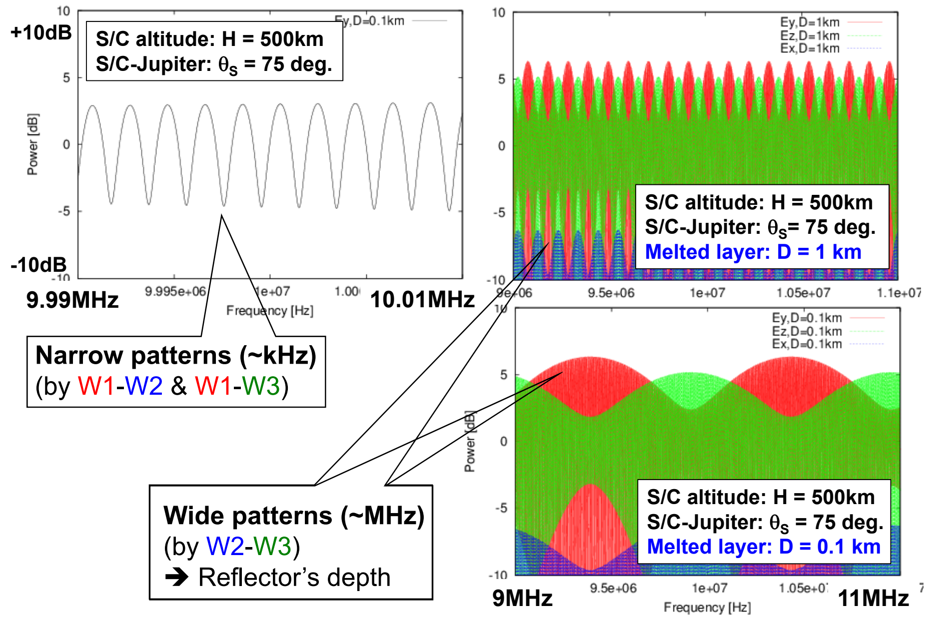


[Kumamoto et al., 2016]

Beat W1-W2, W1-W3
→ **Narrow patterns (~kHz)**

Beat W2-W3
→ **Wide patterns (~<MHz)**

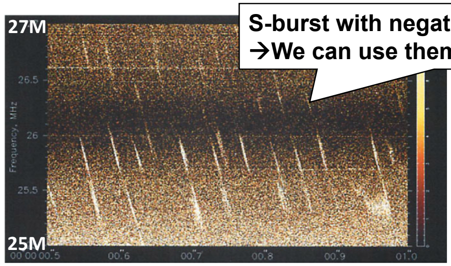
Expected spectrum in PSSR-1



Narrow patterns (~kHz)
(by W1-W2 & W1-W3)

Wide patterns (~MHz)
(by W2-W3)
→ Reflector's depth

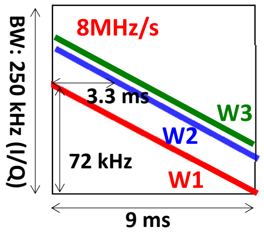
PSSR-2&3 using Burst waves



S-burst with negative frequency drift
→We can use them as chirp radar pulse

0.5 sec

Typical spectrogram of Jovian S-burst



Apply auto-correlation analysis to waveform including W1, W2, and W3

Depth of the reflectors

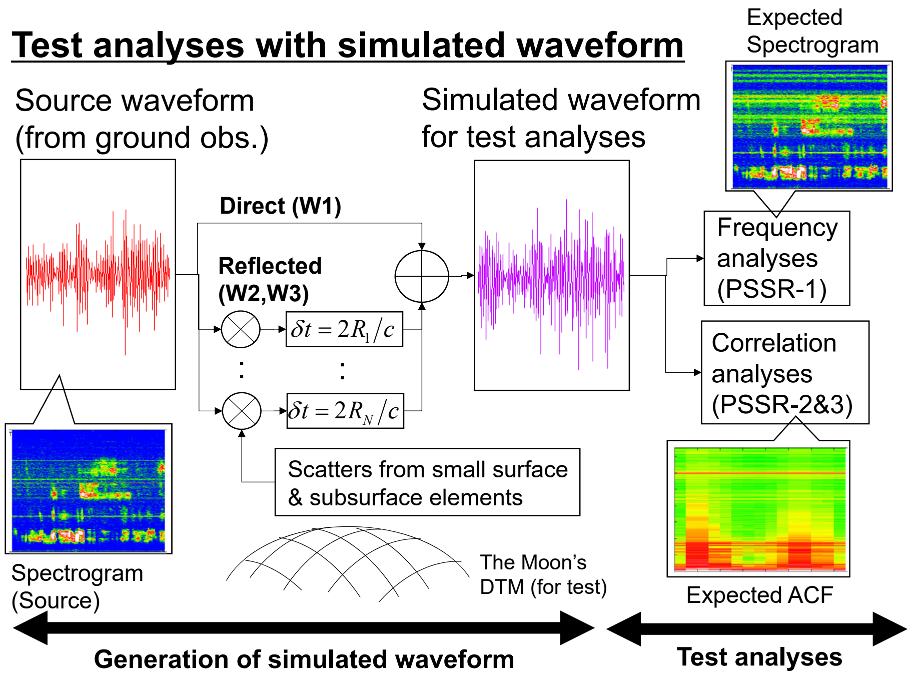
Requirements to JUICE/RPWI Receiver

PSSR-1 (Spectrogram) (by Japan)
Frequency range: 9 - 11 MHz
(δh < ~30 m and δTEC < 9.3x10[12] /m[2])
Bandwidth (Onboard): < 100 Hz (S/C height: 500 km)
Bandwidth (TLM): 1kHz
Frequency step number: 2000
Channel number: 4 ($|E_x|^2$, $|E_y|^2$, $Re(E_xE_y^*)$, $Im(E_xE_y^*)$)
Observation interval: < 3.1hour /360 = 30 sec
(Ganymede, 1-deg.-resolution, S/C height:500 km)
→3.2 kbps (=2000 step x 4 ch x 12 bit / 30 sec)

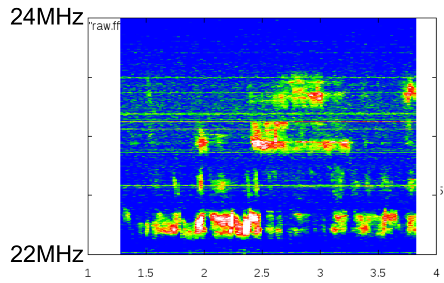
PSSR-2 (Waveform) (by Japan)
Frequency range: 9.875 - 10.125 MHz (Resolution:2km)
(δh < 30 m and δTEC < 9.3x10[12] /m[2])
Sampling frequency for IF signal: 330kHz
Number of sampling data: 4096 points
Autocorrelation (or Pulse compression)
Observation interval: < 3.1hour /360 = 30 sec
(Ganymede, 1-deg.-resolution, S/C height:500 km)
→1.69 kbps (=4096 pts x 12 bit / 30 sec)

PSSR-3 (Waveform) (by Sweden)
Frequency: 1.2 MHz
Channel number: 2ch / 3ch
Sampling resolution: 20 bit
Sampling rate: 149kbps / 298kbps
(Depth resolution: ~1000m/500m)
Sampling number: 193824 or 387648 points
Observation interval: 10 sec
→ 5Mbps (3ch x 298kSPS)

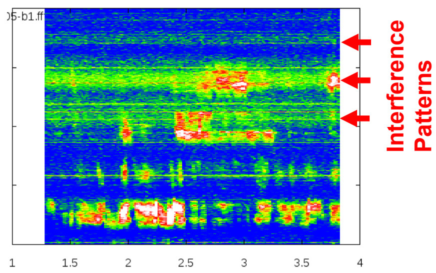
Test analyses with simulated waveform



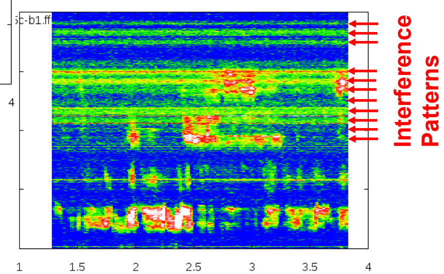
Test analysis of PSSR-1



Spectrogram (without echoes)



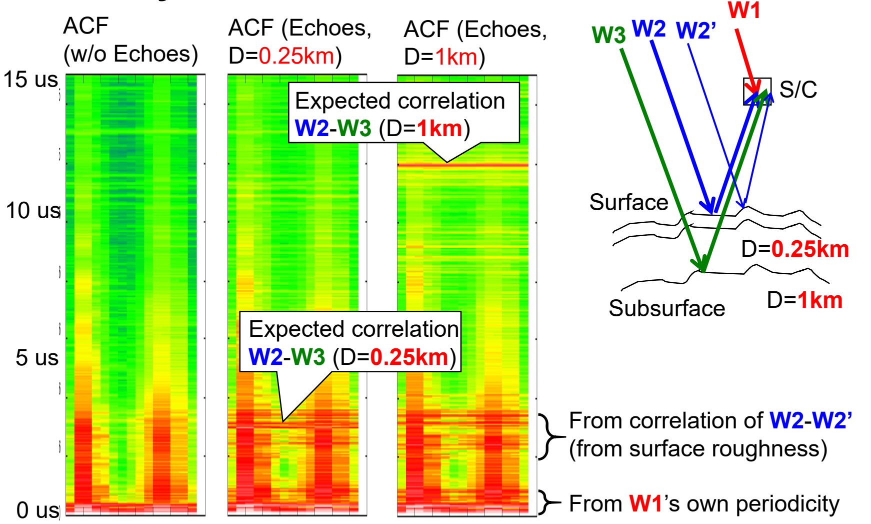
Spectrogram (with surface and subsurface echoes, D=0.25km)



Spectrogram (with surface and subsurface echoes, D=1km)

Jovian radio waves spectrogram often include band structures. (Inconvenient for PSSR-1...)

Test analysis of PSSR-2&3



We should avoid mistaking them for expected correlations (W2-W3).

Summary

- **Passive radar for continuous waves (PSSR-1):** RPWI measures **interference patterns** in Jovian radio wave spectrogram.
- **Passive radar for burst waves (PSSR-2&3):** RPWI measures **waveform** in order to perform **autocorrelation analysis**.
- The **attenuation in shallow part of the ice crust** is ignorable **(~0 dB/km).** Therefore, the **shallow reflectors within ice crust** will be **detectable.** There would be **strong attenuation** around the **boundary between ice crust and liquid ocean**.
- We are starting **test analyses with simulated waveform**, which will be useful for preparation of the onboard software and analysis tools used on the ground.