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Prospects of passive radio detection of a subsurface ocean on Europa with a lander

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ABSTRACT

We estimate the sensitivity of a lander-based instrument for the passive radio detection of a subsurface ocean beneath the ice shell of Europa, expected to be between 3 km and 30 km thick, using Jupiter's decametric radiation. A passive technique was previously studied for an orbiter. Using passive detection in a lander platform provides a point measurement with significant improvements due to largely reduced losses from surface roughness effects, longer integration times, and diminished dispersion due to ionospheric effects allowing operation at lower frequencies and a wider band. A passive sounder onboard a lander provides a low resource instrument sensitive to subsurface ocean at Europa up to depths of 6.9 km for high loss ice (16 dB/km two-way attenuation rate) and 69 km for pure ice (1.6 dB/km).

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In a previous study, Romero-Wolf et al. (2015) explored the sensitivity to detecting a subsurface ocean beneath the ice shell of Europa using Jupiter's decametric (DAM) radio emission with an orbiter. The technique exploits the fact that Jupiter's DAM, when active, is the brightest object in the 0.3–40 MHz band in Europa's sky. Surface and subsurface reflections of this signal can be detected by autocorrelation. This technique allows for a simple instrument for Jovian icy moon sounding, requiring a wire dipole antenna receiver and digitizing electronics with no transmitter. It was found that, under favorable conditions, a dipole antenna receiver using Jovian bursts as a signal of opportunity provided a sensitivity to subsurface oceans comparable to an active radar sounder.

In this paper, we estimate the sensitivity of a dipole antenna receiver and correlator on-board a lander on the subjovian side of Europa to reflections from a subsurface ocean at Europa (see Fig. 1). In Romero-Wolf et al. (2015) it was found that the main factors limiting the sensitivity were the surface roughness of the ice–atmosphere boundary and the $\lesssim$1-s limit on integration times due to the motion of the orbiter. For a lander these limitations are significantly reduced. The antenna would lie directly on the surface, which eliminates scattering and transmission losses due to surface roughness at the ice–atmosphere interface, a major source of uncertainty and clutter. The receiver is stationary, significantly increasing the possible integration time.

Recently, Grima et al. (2015) pointed out that Faraday rotation in the ionosphere of Europa would limit the minimum usable frequency of high altitude radar to 4–8 MHz. For a lander, not only does the radio signal traverse the ionosphere in only one direction, reducing dispersion effects, but also the direct and reflected signal both have nearly equal ionospheric dispersion, effectively canceling the effect after correlation. The dominant ionospheric effect will thus be the blockage of radio signals below the plasma frequency, which is ~1 MHz.

Jovian decametric emission is variable but predictable. The strongest bursts come from the Io-driven sources, which depend on the longitude of Jupiter and orbital phase of Io (Bigg, 1964; Payan et al., 2014). In Romero-Wolf et al., 2015, it was shown that the Io-driven source is compact enough (Dulk, 1970; Carr et al., 1970; Lynch et al., 1976) to be treated effectively as a point source for the purposes of sounding. The main limitation in integration time arises from the limited time of duration of the Io-driven sources on Europa and their motion on the sky. However, since Europa is tidally locked, the location of the Jovian DAM will shift by $\lesssim 1^\circ$ on the sky. At Europa, the Io-driven bursts are expected to last ~90 min on average and for as long as a couple of hours. These bursts occur at predictable times once every two to three days.

We estimate the signal strength of subjovian decametric emission for a lander located at θ_{SJ} defined as the angle between the lines connecting the center of Europa to the sub-Jovian point and the center of Europa to the position of the lander. The fraction of the Jovian DAM power transmitted into the ice layer is given by

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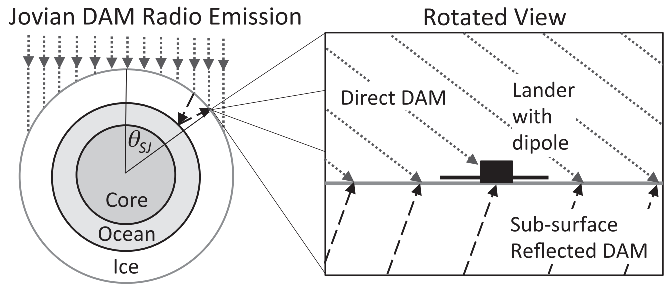

Fig. 1. Passive detection of subsurface oceans in icy moons using Jupiter's radio emission and its echoes with a lander. The Jovian decametric (DAM) emission is incident on the subjovian side of Europa approximately as a plane wave (gray arrows) and illuminates the ice. The dipole antenna on a lander at an angle θ_{SJ} from the subjovian point samples the direct radio emission from Jupiter (dotted gray line). The Jovian DAM emission refracts into the ice shell, reflects off the subsurface ocean (arrows with dashed-dotted lines), and propagates to the lander. Correlation of the direct and reflected emission results in a delayed peak traceable to the thickness of the ice shell.

$(1-\rho_{ice-atm})$, where $\rho_{\text{ice-atm}}$ is the reflection coefficient of the ice–atmosphere interface and depends on the angle of incidence. The path length from the surface entry point to the subsurface ocean at depth d is given by $D = d/\cos\theta_r$, where θ_r is the refracted angle given by Snell's law. The geometric relations between the angle of incidence, the refracted angle θ_r, and the location of the observer θ_{SJ} are provided in Romero-Wolf et al. (2015). The signal losses due to propagation and absorption in ice is given by $10^{-\alpha D/10}$, where α is the two-way attenuation rate in ice given in dB/km. The reflection off the ice–ocean interface contributes a factor of $\rho_{\text{ice–ocn}}$, which is expected to be near unity. Given the radio flux density of Jupiter S_J incident on the surface of Europa, the flux density S_R of the signal transmitted through the ice–atmosphere layer, propagated down to the ice-ocean layer, reflected off this layer, and propagated back through the ice–atmosphere layer is

$$S_R = 10^{-\alpha D/10}(1-\rho_{ice-atm})^2\rho_{ice-ocn}S_J. \quad (1)$$

As discussed in Romero-Wolf et al. (2015), the dominant noise source is, by far, the Jovian decametric emission itself. For a correlation averaged over time ΔT and bandwidth Δf, the amplitude signal-to-noise ratio given by $SNR = \sqrt{\Delta T\Delta f S_R/S_J}$, which, combined with Equation (1), results in

$$SNR = 10^{-\alpha D/20}(1-\rho_{ice-atm})\sqrt{\rho_{ice-ocn}}\sqrt{\Delta T\Delta f}. \quad (2)$$

For a detection threshold signal-to-noise ratio of SNR_{thr}, the maximum detectable depth is given by

$$d_{max} = \frac{20}{\alpha}\cos\theta_r \log_{10}\left[(1-\rho_{ice-atm})\sqrt{\rho_{ice-ocn}}\frac{\sqrt{\Delta T\Delta f}}{SNR_{thr}}\right]. \quad (3)$$

The first factor in the logarithm, due to transmission through the ice and reflection of the subsurface ocean, is near unity. The ice shell two-way attenuation rate α was estimated for Europa by Moore (2000) and Blankenship et al. (2009) to be 1.6 dB/km for pure ice and 16 dB/km for high loss ice.

We estimate values of the maximum detectable depths with the following assumptions. We use an integration time of 90 min, corresponding to the average duration of a Jovian burst. The bandwidth of integration is 20 MHz limited by the ionospheric cutoff of 1 MHz on the low end and the magnetic cutoff at 40 MHz, with allowance for all frequencies not being active over the period of the burst. The requirement for detection is that the signal-to-noise ratio be greater than one. These assumptions, in the case of $\theta_{SJ} = 0°$, where the performance is best, result in a maximum detectable depth of 6.9 km for high loss ice and 69 km for pure ice. We can compare these sensitivities to the current bounds on the ice shell thickness of Europa. The lowest estimates of the ice shell thickness of Europa are $\gtrsim$3 km from Pappalardo et al. (1998) and Turtle and Pierazzo (2001). The upper bound on the ice shell thickness of Europa is 30 km (Ojakangas and Stevenson, 1989).

The depth resolution for this technique is, at best, given by $c/(2\Delta f)$, where c is the speed of light (see Romero-Wolf et al., 2015). For 20 MHz bandwdith this gives a lower bound on the depth resolution of 7.5 m. The resolution could be degraded by the non-ideal autocorrelation characteristics of the Jovian burst. However, the autocorrelation function of the Jovian bursts at and around zero delay provides the impulse response function. This allows for the quantification of the resolution from the data itself. It is expected that the resolution is in the order-of-magnitude scale of 10 m.

We estimate the maximum detectable depth for an active radar instrument on-board a flyby spacecraft and compare it to the sensitivity of a lander-based passive sounder. The received signal strength of an active radar instrument is given by the radar equation

$$P_R = P_T G\frac{A_{eff}}{4\pi\left(2(h+d)\right)^2} \times (1-\rho_{atm-ice})^2\rho_{ice-ocn}L_{rough}10^{-\alpha d/10} \times \tau_p\Delta f\Delta T^2\ \text{PRF}^2 \quad (4)$$

We assume a high frequency (HF) radar system operating at 9 MHz with transmitter power P_T=10 W using a dipole antenna with gain G=1.5 corresponding to an effective area A_{eff} = 130 m^2. We consider a radar with altitude h=100 km. The received power includes propagation losses due to distance and transmission through the ice and reflection off the ice ocean surface. The surface roughness losses are denoted by L_{rough}. The system has a compression gain of $\tau_p\Delta f$ given by a radar pulse width τ_p = 100 μs and bandwidth Δf = 1 MHz. The radar signals with pulse repetition frequency PRF and integration time ΔT can be added coherently leading to a received power gain of ΔT^2PRF^2. For a Europa flyby mission, we assume the integration time ΔT is determined by the spacecraft velocity of ~4 km/s relative to ground and Fresnel zone of ~2.6 km to give $\Delta T \sim 0.6$ s. We consider a pulse repetition frequency PRF=250 Hz. For an active HF radar on the antijovian side, which is occulted from Jupiter's DAM emissions, the dominant source of noise is due to the galaxy. The galactic noise at 9 MHz has a flux $\Phi_{gal} \sim 1.3\times10^{-19}$ W/m^2/Hz. The noise power due to the galactic background is given by $P_{noise} = \frac{1}{2}\Phi_{Gal}A_{eff}\ \Delta f\ \Delta T$ PRF, which includes the effective area of the antenna, receiver bandwidth, and the incoherent amplitude stacking of the noise. For the system described above, this results in noise power $P_{noise} \sim 7.4\times10^{-10}$ W. With these parameters, the SNR of the coherently summed return radar pulse amplitudes is given by an amplitude $SNR = \sqrt{P_R/P_{noise}} \sim 2.4\times10^3\sqrt{L_{rough}}10^{-\alpha d/20}$.

With the values given above, we estimate the maximum detectable ocean depth for a flyby HF radar. In the optimistic case where there are negligible losses from surface roughness, we estimate $d_{max} \sim$ 4.0 km for high loss ice and $d_{max} \sim$ 40 km for pure ice.

Fig. 2 compares the sensitivity of a passive sounder on a lander to the estimates derived for active sounding on a flyby. Additional considerations for signal loss are included in both cases. The passive technique on a lander requires, at the very least, that Jupiter be in view of the instrument. The reflection path is optimal if it is incident normal to the ice surface, which coincides with the subjovian point $\theta_{SJ} = 0°$, where the path length in the ice would be minimized and the Fresnel transmission coefficient is highest. At locations away from the subjovian point, the transmission coefficient is decreased and the propagation path length in the ice is