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A passive probe for subsurface oceans and liquid water in Jupiter's icy moons

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ABSTRACT

We describe an interferometric reflectometer method for passive detection of subsurface oceans and liquid water in jovian icy moons using Jupiter's decametric radio emission (DAM). The DAM flux density exceeds 3000 times the galactic background in the neighborhood of the jovian icy moons, providing a signal that could be used for passive radio sounding. An instrument located between the icy moon and Jupiter could sample the DAM emission along with its echoes reflected in the ice layer of the target moon. Cross-correlating the direct emission with the echoes would provide a measurement of the ice shell thickness along with its dielectric properties. The interferometric reflectometer provides a simple solution to sub-jovian radio sounding of ice shells that is complementary to ice penetrating radar measurements better suited to measurements in the anti-jovian hemisphere that shadows Jupiter's strong decametric emission. The passive nature of this technique also serves as risk reduction in case of radar transmitter failure. The interferometric reflectometer could operate with electrically short antennas, thus extending ice depth measurements to lower frequencies, and potentially providing a deeper view into the ice shells of jovian moons.

1. Introduction

Subsurface oceans in Jupiter's icy moons could provide a present-day setting for extra-terrestrial life within our Solar System. Of the three jovian icy moons, Europa is favored as having the greatest potential to sustain life, based on strong evidence for a persistent ocean directly in contact with rock. Galileo radio science measurements indicate Europa is differentiated, with a low density water-rich layer between 80 and 170 km thick (Anderson et al., 1998; Carr et al., 1998). Galileo magnetometer measurements of an induced near-surface response to Jupiter's time-varying field provide compelling evidence for a present-day ocean (Kivelson et al., 2000; Zimmer et al., 2000).

Estimates of the ice shell thickness of Europa are uncertain (Pappalardo, 2010). Thermal models of the ice shell of Europa predict a thickness of $\leqslant$30 km (Ojakangas and Stevenson, 1989). Galileo magnetometer-derived oceanic conductivities, combined with radio Doppler data-derived interior models and laboratory conductivity vs. concentration data, constrain the ice thickness to be <15 km with a best fit value of ~4 km (Hand and Chyba, 2007). Galileo imaging of pits, domes, and dark spots provides an ice shell thickness constraint of 3–10 km (Pappalardo et al., 1998). Crater analyses, also obtained from Galileo images, constrain Europa's ice thickness to >3 km (Turtle and Pierazzo, 2001) based on the need to isostatically support central uplifted features, and to at least 19–25 km thick from the thermal state inferred from depth-size relationships (Schenk, 2002).

The most promising technique for directly detecting subsurface oceans and liquid water in jovian icy moons is ice penetrating radar (IPR). A dual-frequency system, such as that described by Bruzzone et al. (2011), is capable of providing high-resolution images at shallow depths (<5 km) and characterizing the depth of the ice up to 30 km with 100 m resolution. Unambiguous observation of a subsurface ocean demands that the detection technique have as high depth sensitivity as possible. To achieve this, the use of low frequencies (<30 MHz) has been proposed (Bruzzone et al., 2011). The main challenges involved with IPR are surface clutter and radio absorption of the ice, which can be reduced by use of low frequencies. However, the loud radio environment of Jupiter at frequencies <40 MHz requires a relatively strong transmitter.

Here we explore a passive interferometric reflectometry technique that makes use of Jupiter's decametric (DAM) radio emission in the 1–40 MHz band. We argue that the DAM background that interferes with low frequency IPR can be used as a source for ice-depth sounding. This technique could be an attractive complement

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to a radar system because it can share the same dipole antenna and requires very low power passive components. Interferometric reflectometry also could extend the frequency band of observation to lower frequencies by operating as an electrically short dipole, further increasing the sensitivity to deep subsurface oceans. A passive measurement system could also serve as a backup to IPR in case of transmitter failure, thereby reducing the risks associated with the instrument.

Interferometric reflectometry was first applied in the Dover Heights radio astronomical observatory in the 1940s (Bolton, 1982). In that setup, an antenna placed on a cliff observed both the direct emission of a radio source and its reflection on the sea surface. The signal was autocorrelated forming a virtual two-element interferometer. The baseline formed by the sea surface reflection provided one of the first demonstrations of radio emission from discrete sources (Bolton and Stanley, 1948), along with the first identification of cosmic radio sources including Centaurus A and the Crab Nebula (Bolton, 1948). It is worth mentioning that this technique was born out of limited resources, not unlike the case for deep space probes.

The interferometric reflectometry technique is currently applied in the measurement of snow depth using GPS signals (Larson et al., 2008; Gutmann et al., 2012). The interference between the GPS signal and its subsurface reflections modulates the signal to noise ratio with a sinusoidal wave whose frequency is directly proportional to the snow depth (Larson et al., 2008). The technique has been successfully demonstrated and validated by comparison with other measurements (Gutmann et al., 2012).

The geometry for the application of interferometric reflectometry to jovian moon ice depth measurements is shown in Fig. 1. Jupiter's radio emission arrives from a distance of $\gtrsim 6 \times 10^8$ km to the vicinity of an icy moon. At the sub-jovian point, where the spacecraft lies directly between Jupiter and the icy moon, an antenna receiver system records a sample of the decametric radio emission. The same emission strikes the surface of the icy moon and its echoes arrive at the spacecraft at a later time. The antenna beam pointed at the icy moon samples the echoed radio emission, which is cross-correlated with the direct emission to produce interference fringes. The cross-correlation peaks at delays corresponding to the moon surface and subsurface ice-water boundary reflection layers. The amplitudes of the cross-correlation peaks are related to the dielectric properties of the ice so it has the potential to reveal the presence of sharp boundaries associated with a subsurface ocean or liquid water deposits in the ice shell.

In this paper, we will describe the physics of the passive interferometric reflectometer concept. In Section 2 we briefly review the properties of Jupiter's decametric radio emission. Section 3 gives a summary of the properties of jovian moon ice shells. Section 4 describes the mathematical details of interferometric reflectometry and provides estimates for the sensitivity and resolution of the technique. Section 5 compares the expected sensitivity of interferometric reflectometry with ice penetrating radar. Section 6 summarizes our results and outlines the next steps in the development of this measurement technique.

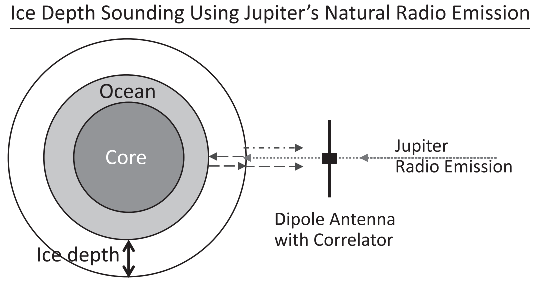

Fig. 1. Passive detection of subsurface oceans in icy moons using Jupiter's radio emission and its echoes. The dipole antenna samples the radio emission from Jupiter (shown as an arrow with dotted line). The radio signal is then reflected from the surface of the icy moon (arrow with dashed-dotted line) as well as the subsurface ocean (arrow with dashed line). The dipole antenna detects both echoes. Correlation of the direct emission and reflected signals result in delays and amplitudes of the echoes.

2. Jupiter's decametric radio emission

2.1. Signal strength

Jupiter's decametric radio emissions are some of the brightest signals in the Solar System for frequencies between 1 and 40 MHz. The strength of the signal is due to a resonance interaction called the Cyclotron Maser Instability (Wu and Lee, 1979; Treumann, 2006). The emission has a sharp cutoff at 40 MHz, which corresponds to the electron cyclotron frequency for the jovian magnetic field lines. Radiation above 40 MHz, due to the synchrotron emission of electrons in Jupiter's magnetic field lines, is significantly weaker.

The flux density of Jupiter's radio emission, as seen from Europa, Ganymede, and Callisto, is shown in Fig. 2. Below 40 MHz, the decametric radiation from Jupiter is more than several thousands of times above the galactic background. In this frequency band, Jupiter is the most luminous object in the sky. Unlike the galactic background, which is diffuse, Jupiter's brightness distribution is confined to a small region in the sky seen by the icy moons (see Section 2.2). As will be discussed in Section 4.6, this means that the depth resolution will not be source structure limited.

2.2. Spatio-temporal characteristics

There are several different sources of strong decametric emission from Jupiter, each with different characteristics (Carr et al., 1983). The "Io sources" refer to emissions that are active during certain ranges of the rotational phase of Jupiter and orbital phase of Io. The "non-Io" sources, on the other hand, are solely dependent on the rotational phase of Jupiter, given in System III central meridian longitude (CML III). The various types of jovian decametric emissions occur regularly but with varying duty cycles (instantaneous probability of activity).

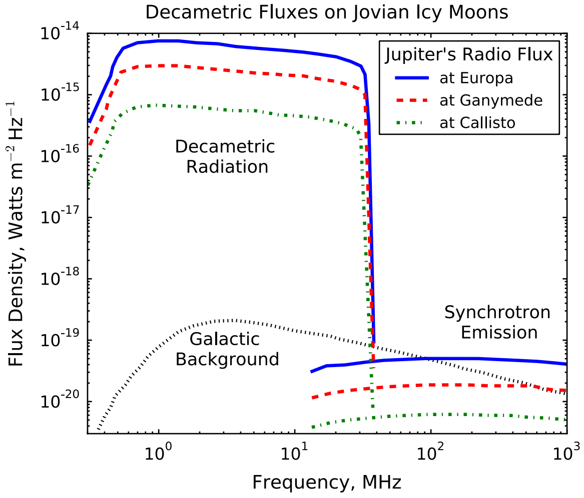

Fig. 2. The average decametric flux density of Jupiter's radio emission in the vicinity of its icy moons far exceeds the galactic background. The curves shown are for the peak hectometric radiation (<3 MHz) and the decametric radiation (3–40 MHz) due to the Io and non-Io sources. The decametric S-bursts (not included in this figure) can exceed the flux shown here by a few more dB. The figure is adapted from Cecconi et al. (2012).