Radar Ambiguities and Signal Processing Design Trade-offs in the REASON Radar Sounder

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***Abstract*—NASA's planned Europa Clipper mission would carry a radar sounder which operates at HF and VHF frequencies that can penetrate the icy shell of Europa. The sounder would be used to characterize subsurface bodies of liquid water and to measure the thickness of the icy shell. The spacecraft would make observations during flyby to reduce radiation exposure. The varying geometry during the flyby is expected to cause varying radar ambiguity and surface clutter contamination. At the same time, data down-link restrictions would require on-board pulse summation to reduce data volume which would require on-board Doppler filtering to control clutter and ambiguity contamination levels. This paper will study some of the design trade-offs involved in specifying the on-board Doppler filtering.**

I. Introduction

NASA is planning a Europa mission scheduled for launch in the early 2020's. The planned Europa Clipper mission would perform a detailed study of the surface, sub-surface, and any atmosphere of Jupiter's moon Europa. A radar sounder called REASON (Radar for Europa Assessment and Sounding) is one of 9 instruments planned for this mission. The sounder's main purposes are to measure the thickness of the moon's ice shell and search for subsurface bodies of liquid water. The sounder will also be used to obtain topographic profiles, measure surface roughness properties and assess potential future landing sites. To meet these and other science goals, the radar sounder makes 4 types of measurements;

- Subsurface Sounding
- Altimetry
- Reflectometry
- Plasma and Particle Detection

This paper will concentrate on the subsurface sounding measurements. The radar sounder will operate at 60 MHz (VHF band) and 9 MHz (HF band). The VHF frequency will be used for higher resolution shallow sounding which can be performed globally over all of Europa. These measurements will be used to characterize subsurface bodies of liquid water. The HF frequency will be used for deep sounding at lower resolution. These measurements will be used to quantify the ice shell thickness and look for a subsurface ocean boundary. Jupiter produces large amounts of HF radio noise [1], so HF sounding will be limited to the anti-Jovian side of Europa where the bulk of Europa will shield the instrument.

Prior planetary radar sounders such as the Mars advanced radar for subsurface and ionospheric sounding (MARSIS) [2], and the Shallow Radar Sounder (SHARAD) on the Mars Reconnaissance Orbiter [3] operated in circular orbits which provide uniform geometry. In contrast, the Europa mission will perform flyby of Europa to reduce radiation exposure in the intense Jovian radiation environment. Operating a radar in planetary flyby poses more challenges due to the varying geometry. In this paper we will focus on some design issues raised by the special needs of a radar sounder operating during Europa flyby.

II. Radar Sounding and Surface Clutter

The REASON instrument will operate by transmitting short pulses of RF energy with a linear frequency modulation to provide better range resolution. Range compression sorts the echo energy into range bins spaced at 15 m for the VHF band and at 150 m for the HF band. The nadir point below the spacecraft produces the first echo power in the sequence of range bins. Subsequent bins correspond to successively larger subsurface depths. The VHF band is intended for higher resolution shallow sounding down to a depth of 4.5 km while the HF band is intended for lower resolution deeper sounding down to a 30 km depth.

Ideally only subsurface structures will produce echo power making the radar-gram easy to interpret. In practice, however, echo power will return from any scattering structure that lies at the same range as the desired subsurface level. This includes a circular arc of surface area that also lies within any given range bin. The surface has strong dielectric contrast between the vacuum of space and the icy material of Europa's crust. Surface scattering power which we call surface clutter is expected and can confound the measurement of subsurface structures. Using very low sounding frequencies helps because the scattering response function for low frequencies striking a smooth or slightly rough surface is very sharply peaked in the specular (forward scattering) direction [4]. Nonetheless, surface structures that tilt a surface area so that it appears normal to the sounder's radio transmission will generate strong surface clutter returns. The REASON radar sounder reduces surface clutter with Doppler filtering of the range compressed data. Such processing actions reduce the surface areas that can contribute clutter power to a measurement cell.

Figures 1 and 2 illustrate some of the geometric features of the sounder measurements. The black curve shows the spacecraft nadir track for a simulated flyby with a closest approach of 25 km. The track is shown for for a 16 minute interval centered on the closest approach point which includes

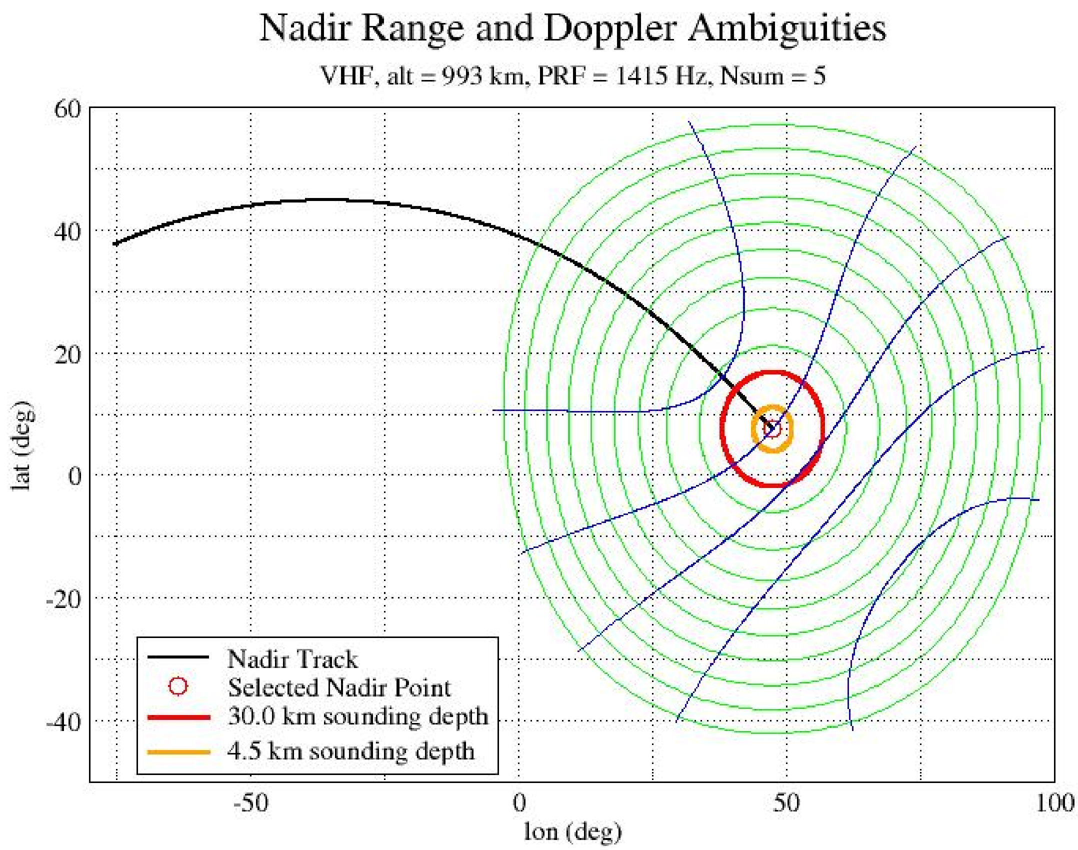

Fig. 1. Geometry of a simulated 25 km Europa flyby with the spacecraft at an altitude of 1000 km. The black curve shows nadir track for -8 min to +8 min relative to closest approach which corresponds to altitudes below about 1000 km. The nadir point at close approach is in the middle of the black curve. The actual nadir point below the spacecraft location is at one end (marked by the small red circle). The orange thick circle shows the iso-range contour on the surface that corresponds to a subsurface point 4.5 km below the nadir point. The red thick circle shows the iso-range contour on the surface that corresponds to a subsurface point 30 km below the nadir point. Green circles show iso-range contours spaced at one PRI in delta range from the range to the nadir point. Blue arcs show iso-Doppler contours spaced at one PRF intervals in delta Doppler shift from the Doppler shift of the nadir point. Both iso-range and iso-Doppler contours end at the limb. This illustration shows results for the VHF band with an actual PRF of 1415 Hz and an effective PRF of 283 Hz after summing each 5 pulses together.

altitudes up to about 1000 km which is the highest altitude planned for radar sounding operations. The sounding measurement will show a vertical radar-gram profile for each point of this track. At one end of the track some iso-range and iso-Doppler contours are drawn to illustrate key response areas on the surface. The orange thick circle is the set of surface points that lie at the same range as a subsurface point 4.5 km below the nadir point which is near the depth limit expected for VHF sounding. An annular ring centered on this circle with width corresponding to the range resolution will generate surface clutter power that can obscure the subsurface echo power. The red thick circle shows a similar clutter ring for a depth of 30 km which is near the depth limit expected for HF sounding. The area inside these circles is the potential surface clutter area for sounding measurements. The blue curve which passes through the center of the orange and red circles is an iso-Doppler contour with the same Doppler shift as the nadir point. When Doppler filtering is performed, the clutter circle is reduced to two areas centered on the crossing points of the central blue iso-Doppler contour with the red and orange circles. The Doppler width of these areas will depend on the Doppler resolution and the parameters of the Doppler filtering.

Doppler filtering can be performed by ground processing if all the collected data are down-linked. To meet down-link restrictions, however, the radar sounder will perform some on-board pulse summation. This reduces the effective pulse repetition frequency (PRF) and restricts the amount of Doppler filtering that can be done by ground processing. To make up for this, on-board processing will perform Doppler filtering before pulse summation occurs to reduce clutter. On-board pulse summation will be applied at higher altitudes where Doppler ambiguities are more widely spaced.

III. Radar Ambiguities

Range ambiguities are areas on the surface and volumes in the subsurface that lie one or more pulse repetition intervals (PRI) away in range from a given range bin. Doppler ambi-

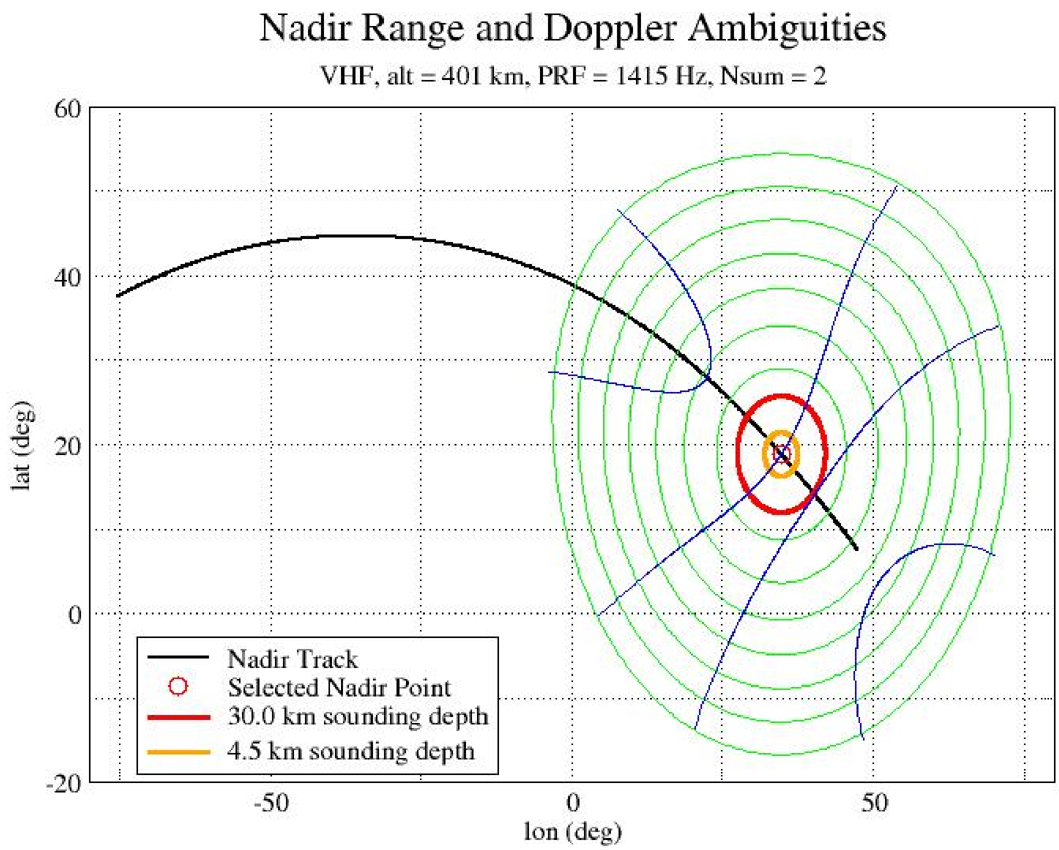

Fig. 2. Geometry of a simulated 25 km Europa flyby with the spacecraft at an intermediate altitude of about 400 km. The black curve shows nadir track for -8 min to +8 min relative to closest approach which corresponds to altitudes below about 1000 km. The nadir point at close approach is in the middle of the black curve. The actual nadir point below the selected spacecraft location is near the right end of the black curve (marked by the small red circle). The orange thick circle shows iso-range contour on the surface that corresponds to a subsurface point 4.5 km below the nadir point. The red thick circle shows iso-range contour on the surface that corresponds to a subsurface point 30 km below the nadir point. Green circles show iso-range contours spaced at one PRI in delta range from the range to the nadir point. Blue arcs show iso-Doppler contours spaced at one PRF intervals in delta Doppler shift from the Doppler shift of the nadir point. Both iso-range and iso-Doppler contours end at the limb. At the lower altitude of 400 km, fewer pulses are summed together resulting in fewer Doppler ambiguity arcs compared to situation at 1000 km altitude. This illustration shows results for the VHF band with an actual PRF of 1415 Hz and an effective PRF of 708 Hz after summing each two pulses together.

guities lie one or more effective PRF's away from a given measurement bin and an integer number of PRI's away in range. Range and Doppler ambiguities introduce another form of clutter power that can confound the desired nadir subsurface measurements. Using on-board pulse summation reduces the effective PRF which can increase the number of Doppler ambiguities and the corresponding clutter problems. However, due to low dielectric contrast, subsurface structures are less likely to produce ambiguity power compared to scattering from surface regions. Furthermore, horizontally oriented dielectric interfaces will produce very little coherent back-scatter away from the nadir profile. For these reasons, we focus on surface clutter issues in this paper while still keeping in mind the possibility of subsurface clutter depending on the level of dielectric inhomogeneities in Europa's near surface volume.

In Fig. 1 green circles show range ambiguities as iso-range contours spaced at one PRI intervals in range from the selected nadir point range. Blue arcs show Doppler ambiguities as iso-Doppler contours spaced at the effective PRF, again referenced to the nadir point Doppler shift. The intersections of green and blue lines are the centers of range Doppler ambiguity patches for the nadir point. Subsurface nadir points also have range Doppler ambiguity patches on the surface shifted outward from those of the surface nadir point. Each of these patches has an area determined by projecting the range and Doppler resolution of the nadir measurement cell. Echo power originating from the ambiguous patches will be indistinguishable from subsurface echo power due to both overlap in the time domain, and aliasing in the frequency domain. Total ambiguity power will be determined by summing echo power from all the range Doppler ambiguity areas. The ratio of the expected subsurface echo power to the ambiguity power is called the signal to ambiguity ratio. This ratio needs to be large to avoid problems interpreting the subsurface radar-gram.

TABLE I. POWER CALCULATIONS AT 2 DIFFERENT ALTITUDES.

Parameter	HF	VHF	HF	VHF	Unit
Alt	401	401	993	993	km
Pt	10	10	10	10	dBW
λ^2	30	14	30	14	dBm^2
G^2	2	16	2	16	dBi
Propagation loss	-140	-140	-148	-148	dBm^{-2}
Power at perfect reflector	-98	-100	-105	-108	dBW
Noise bandwidth	1.2	12.0	1.2	12.0	MHz
Noise temperature	400000	10000	400000	10000	K
Raw radar potential	14	18	6	10	dB
Range compression gain	20	30	20	30	dB
Doppler compression gain	30	25	32	28	dB
Processed radar potential	64	73	58	68	dB
PRF	1415	1415	1415	1415	Hz
Number of pulses summed	2	2	5	5	
Ambiguity σ_0	-10	-10	-10	-10	dB
Total number of ambiguities	14	48	18	80	
Number of excludable ambiguities	0	26	0	62	
Average range resolution	167	16	179	17	m
Average azimuth resolution	5959	2419	7976	3164	m
Average ambiguity area	966832	38446	1381017	53377	m^2
Integrated ambiguity area G^2/R^4	-163	-167	-172	-177	dBm^{-2}
Ambiguity power	-163	-186	-172	-196	dBW
Nadir perfect reflector to ambiguity ratio	66	86	67	88	dB

IV. RADAR POTENTIAL

The expected subsurface echo power depends on the level of subsurface losses due to attenuation and scattering and the back-scatter strength of any dielectric interfaces. HF and VHF attenuation in ice is a function of temperature and the level of impurities [5], [6]. The REASON radar instrument is designed to have enough signal power relative to noise power (SNR) to see a variety of subsurface structures over a range of conditions. The key performance parameter is called the radar potential which is the thermal SNR for a perfect reflector on the surface. Requirements are being formulated for an altitude of 400 km, with a radar potential of about 60 dB allowing for sounding of a water-ice dielectric interface to a few kilometers depth at VHF frequencies, and to a few tens of kilometers at HF frequencies given reasonable temperature and impurity conditions [7].

The top part of table I shows the radar potential calculations at two different altitudes for the REASON radar. These calculations assume a synthetic aperture length equal to the Fresnel Zone width which corresponds to unfocused SAR processing. The processed radar potential compares power from a perfect reflector at the surface nadir point with internal thermal noise power. The bottom part of table I shows the corresponding ambiguity power calculations. The nadir reflector to ambiguity ratio in the last row compares the power from a perfect reflector at the surface to the total diffuse surface ambiguity power expected. As long as the nadir reflector to ambiguity ratio is higher than the radar potential, then the ambiguity power is weaker than the thermal noise power.

The PRF was kept constant in the calculations of table I assuming a single pulse in flight. The number of pulses summed on-board will be adjusted during the flyby to balance data volume limitations against the desire to keep the first Doppler ambiguities out of the surface clutter rings of the maximum depth measurement. The values of 2 and 5 for pulses summed in table I were chosen here to keep the first Doppler ambiguity out of the 30 km clutter ring. The level of surface back-scatter (σ_0) was set conservatively here to -10 dB. This is a fairly large back-scatter cross-section assumption for high

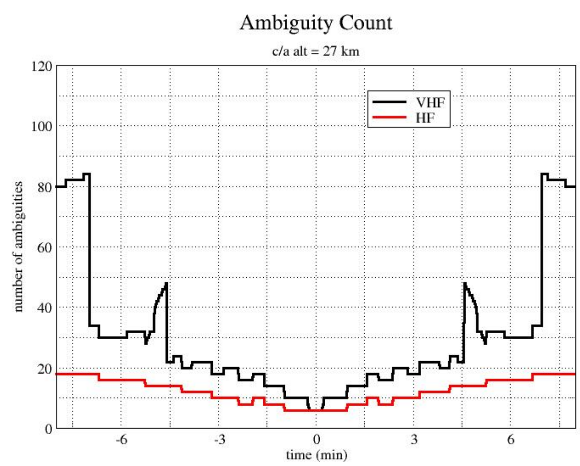

Fig. 3. Number of ambiguities at VHF and HF during a typical Europa flyby.

incidence ambiguities. As shown in Fig. 3, the number of ambiguities varies during the flyby depending on the effective PRF, and the viewing geometry. The number of excludable ambiguities refers to the extra Doppler ambiguities introduced by reducing the effective PRF through on-board pulse summation. The HF band does not suffer from excludable ambiguities because the longer wavelength leads to much more widely spaced Doppler ambiguities compared to VHF. Even at the reduced effective PRF, the HF excludable Doppler ambiguities are off the limb and not counted. For VHF measurements, ground processing cannot filter out the excludable ambiguities because the down-linked summed pulses have already aliased in these contributions. However, on-board Doppler filtering can reduce the power from excludable ambiguities because the data from the actual PRF is available. Non-excludable ambiguities are present due to the actual or raw PRF. Power from non-excludable ambiguities is always present and cannot be mitigated by processing on-board nor on the ground. Average range resolution is the average of the range resolutions from all the ambiguity patches. VHF has better range resolution than HF because a 10 MHz chirp is used versus 1 MHz for HF. Average azimuth resolution is the average of the Doppler extent on the surface of all the ambiguity patches. VHF has better azimuth resolution than HF in these calculations because it has a shorter wavelength. Combining these makes HF ambiguity patches larger than VHF ambiguity patches which results in better ambiguity performance for VHF despite its larger number of ambiguities. The integrated area G^2/R^4 term represents the summation of ambiguity powers in the radar equation resulting in the final summed ambiguity power. The final ratio compares the summed ambiguity power to the power from a perfect reflector at the nadir point, just like the radar potential. The values of the nadir reflector to ambiguity ratios are larger than the radar potentials indicating that the contamination due to diffuse surface scattering from the ambiguity patches will be less than the thermal noise power.

V. Conclusion

The REASON radar sounder needs to balance many competing design considerations. Some on-board processing of the radar data with variable parameters will be needed to preserve clutter reduction while reducing down-linked data volumes. Range and Doppler ambiguities are distributed according to the effective PRF and the observing geometry. Preliminary calculations show that HF and VHF diffuse surface ambiguity and clutter powers should be below the thermal noise power for the REASON radar at altitudes below 1000 km. This indicates that diffuse surface scattering will not impose a significant constraint on the on-board Doppler filter design which can therefore use a low-order filter and conserve on hardware resources. Coherent back-scattering structures on the surface and at depth could still generate observable clutter, so an on-board Doppler filter is still desired for maximum clutter rejection.

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