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Initial Assessment of an Airborne Ku-band Polarimetric SAR

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Initial Assessment of an Airborne Ku-band Polarimetric SAR

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Abstract

Polarimetric synthetic aperture radar (SAR) has been used for a variety of dual-use research applications since the 1940's. By measuring the direction of the electric field vector from radar echoes, polarimetry may enhance an analyst's understanding of scattering effects for both earth monitoring and tactical surveillance missions. Polarimetry may provide insight into surface types, materials, or orientations for natural and man-made targets. Polarimetric measurements may also be used to enhance the contrast between scattering surfaces such as man-made objects and their surroundings. This report represents an initial assessment of the utility of, and applications for, polarimetric SAR at Ku-band for airborne or unmanned aerial systems.

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The authors would like to thank the various organizations, radar systems, and individuals whose work is exhibited in this report for illustrative purposes.

The first author would like to express her gratitude to Billy C. Brock and Douglas L. Bickel from Sandia National Laboratories for their willing mentorship and generous sharing of their time for this report. We are grateful for the informative discussions with Billy regarding polarimetric applications, specifically those related to coherent change detection and crevasse monitoring. We further are thankful for discussions with Doug related to the relevance of maritime applications for ship detection and Ku-band scatterometers to our study.

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FIGURES

NOMENCLATURE

dB	decibel
DOE	Department of Energy
FY	first-year
HH	horizontal transmit, horizontal receive co-polarization
HV	horizontal transmit, vertical receive cross-polarization
MY	multi-year
RF	radio-frequency
SAR	synthetic aperture radar
SNL	Sandia National Laboratories
VH	vertical transmit, horizontal receive cross-polarization
VV	vertical transmit, vertical receive co-polarization

1. INTRODUCTION

Polarimetric synthetic aperture radar (SAR) has been used for a variety of dual-use research applications since the 1940's.[1] By measuring the direction of the electric field vector from radar echoes, polarimetry may enhance an analyst's understanding of scattering effects for both earth monitoring and tactical surveillance missions. Polarimetry may provide insight into surface types, materials, or orientations for natural and man-made targets. Polarimetric measurements may also be used to enhance the contrast between scattering surfaces such as man-made objects and their surroundings.

Scattering interpretations are formed in terms of transmit and receive vertical (V) or horizontal (H) polarizations of the radar. For airborne systems, the direction of the electric field vector for horizontal polarization is parallel to the earth's surface, and vertical polarization is defined perpendicular to it. The same type of polarization transmission and reception is referred to as a co-polarization response, denoted VV or HH. The cross-polarization response is the transmission and reception of different orientations of the electric field, HV or VH, where the two responses are generally similar for co-located radar transmitters and receivers. Scattering mechanisms are interpreted by various decomposition methods of the polarimetric data. For example, the sum of co-polarization responses can indicate single (or odd) scattering bounces from planar surfaces such as bare soil. The difference of co-polarizations can indicate double (or even) scattering bounces from dihedral corners such as building-ground interactions. Cross-polarizations tend to indicate volume scattering from distributed natural targets like vegetation that produce randomly oriented radar returns. Select examples of such decompositions or the composite polarimetric response are shown in Figure 1 through Figure 3. Thus, knowledge of polarimetric reflectivity and scattering mechanisms can be beneficial additional information for many applications.

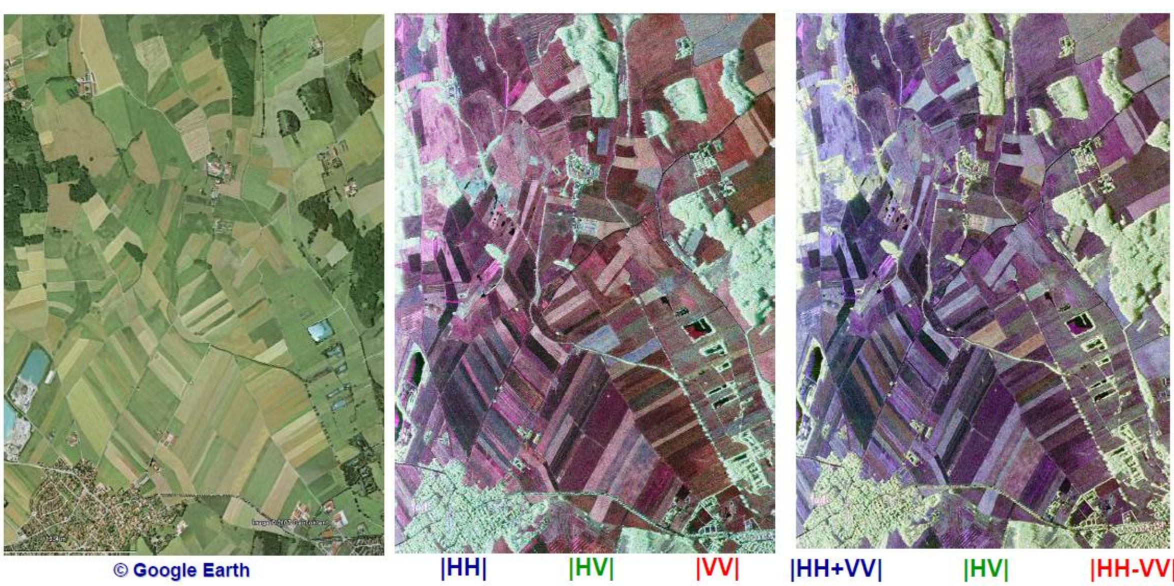


Figure 1. L-band land classification by optics versus SAR polarization and decomposition.[1]

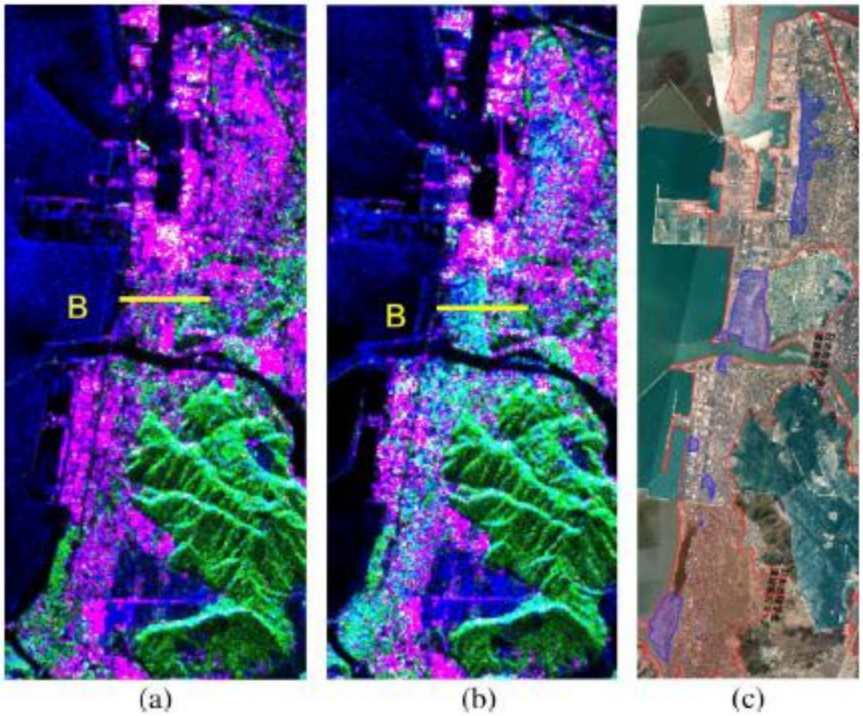


Figure 2. Polarimetric decomposition and terrain classification of a coastal area affected by a tsunami at L-band a) before, b) after, and c) using terrain classification. Complete or partial flooding of urban areas denoted in degree of scattering changes in an area (i.e. red to blue changes from man-made double-bounce to surface scattering from water).[2]

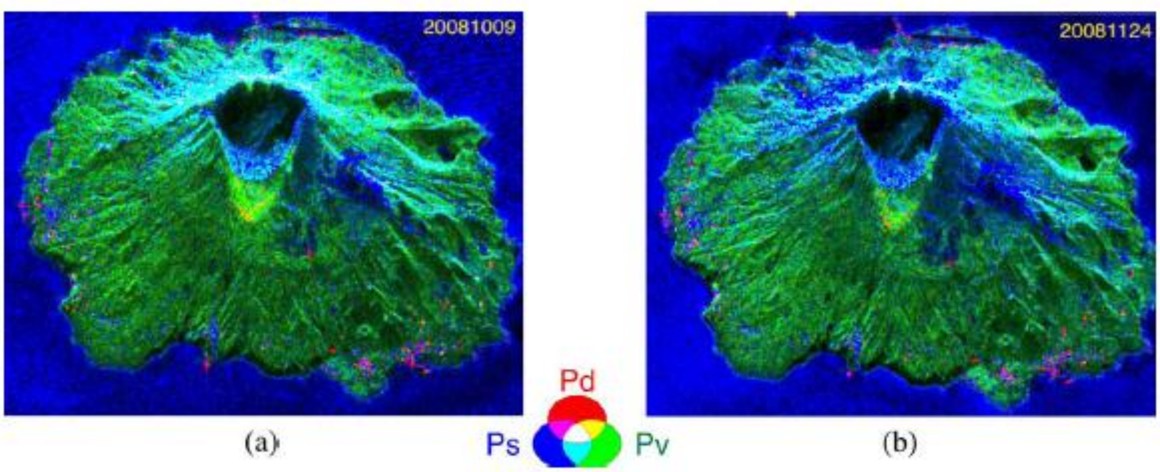


Figure 3. Polarimetric decomposition of a volcano eruption of sulfuric gas at L-band a) before and b) after. The eruption defoliated vegetation and exposed soil layers near the caldera (i.e. green to blue change from volumetric to surface scattering; red is man-made, double-bounce scattering).[2]

2. APPLICATIONS

The earth monitoring SAR community has been using polarimetry for well over 30 years.[1] Ocean monitoring of waves, currents, winds, ice, and tidal levels are the primary maritime applications. Land-based uses for terrain classification and resource monitoring of crops, soil, glaciers, water, urban areas, and forest biomass are increasingly prevalent for taxation, precision agriculture, urban planning, and global warming reasons. Damage assessment or landscape changes from natural disasters such as volcanos, tsunamis, landslides, floods, fires, oil spills, or earthquakes have also been demonstrated.[2]

Despite a wealth of civilian applications for polarimetry, the earliest motivation for its use was for tactical surveillance, specifically aircraft characterization.[1] Target signature decomposition, orientation, and contrast enhancement of man-made objects or facilities remains an important polarimetric application for target characterization and identification. Earth monitoring for national security missions is also useful for the detection of buried or hidden targets in snow, terrain, or forests; or crop monitoring of plantations of interest.

Interferometry and change detection coupled with polarimetry can also be important modalities for parameter estimation of height, temporal terrain differences, or the nature and location of the scattering medium.

Examples of some of the aforementioned civilian and defense applications for polarimetry are shown in Figure 1 through Figure 7.

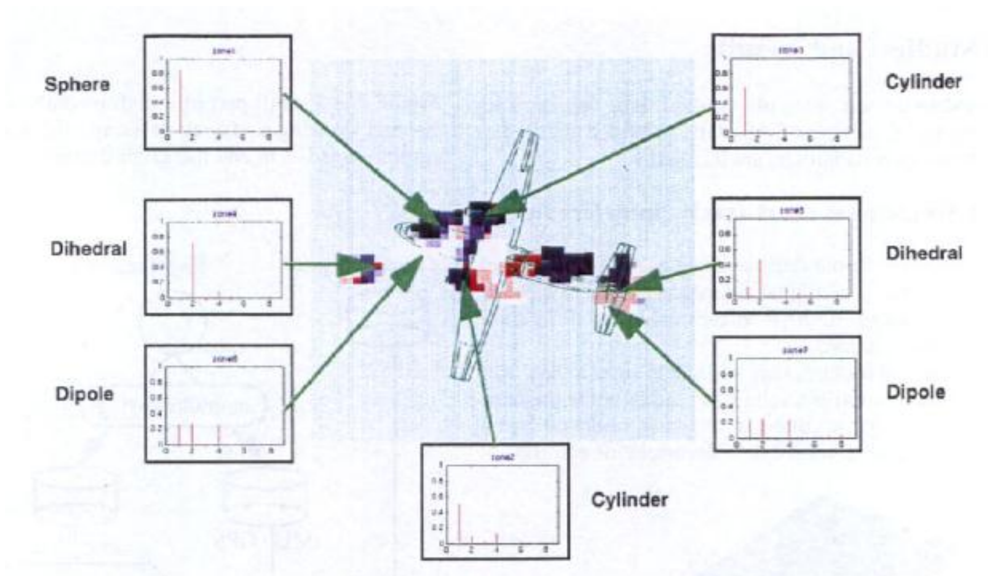


Figure 4. Polarimetric target decomposition of the scattering mechanisms of an aircraft.[3]

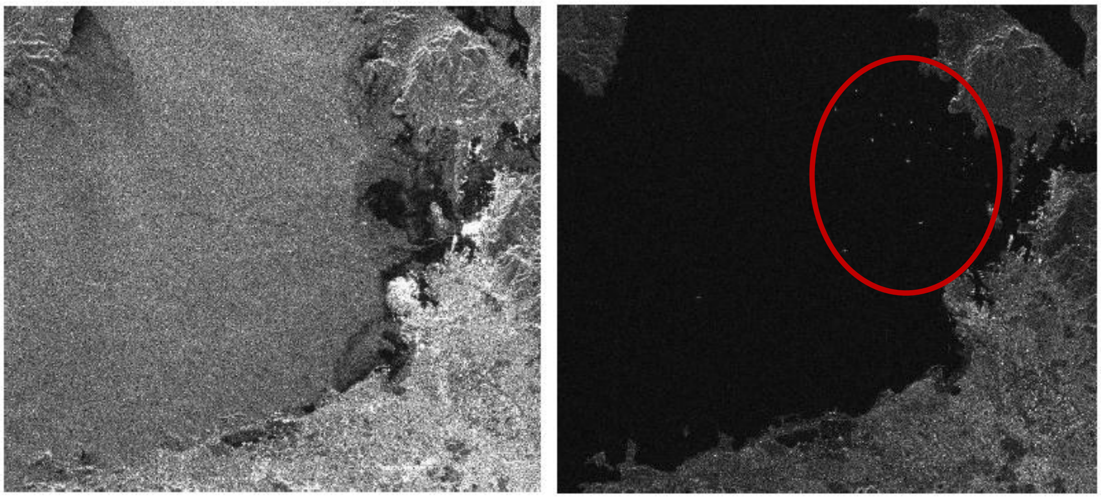


Figure 5. Ship detection contrast at C-band for VV (left) versus HV (right) polarization.[4]

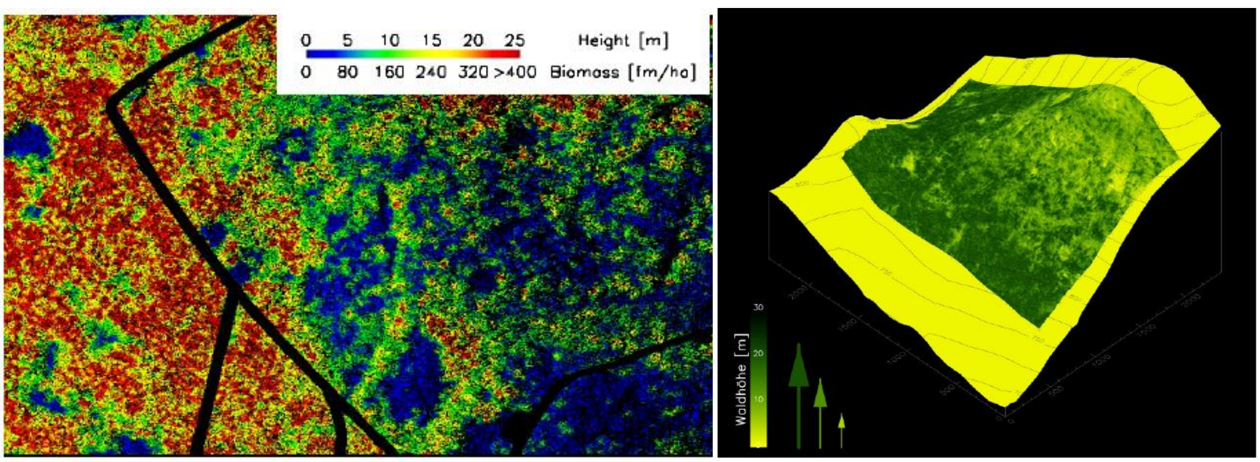


Figure 6. Vegetation height estimation using polarimetric interferometry with corresponding biomass estimation (left) and topography (right).[5]

Figure 7. X-band ground truth, HH, and fully polarimetric coherent change detection comparison of man-made tracks (from left to right), showing improved observation.[6]

3. TECHNOLOGICAL DEVELOPMENT CHALLENGES

Although polarimetry is a fairly mature technology with an abundance of literature, development and application challenges do exist for organizations wanting to enter this area. This section addresses some of these challenges in antenna development, frequency selection, and scattering interpretation.

3.1. Antenna Isolation and Calibration

The development of any polarimetric SAR is a challenge due to the antenna isolation and calibration necessary for the different channels of the radio-frequency (RF) front-end. Designs and implementations that meet the isolation requirements of the cross-polarizations and calibration requirements of the co-polarizations are often the bottleneck in achieving adequate performance and utility from a polarimetric SAR. In addition, readily available resources regarding common antenna design setbacks are rare, with tacit knowledge and expertise usually being developed and contained within polarimetric centers of excellence.

3.2. Frequencies and Utility of Scattering Information

The utility of polarimetric scattering information versus a single-channel system depends highly on the optimization of frequencies used, incidence angles of data collection, scattering physics that are attempting to be understood or leveraged, and ability to relate environmental factors that affect interpretation. Each application where polarimetry proves beneficial is as much a theoretical and experimental science as it is a highly esoteric art in modeling, data collection, and analysis.

Many polarimetric SAR systems are multi-frequency in order to extract even further scattering information from the relative surface roughness apparent to each wavelength and, to facilitate surface penetration versus resolution tradeoffs as a function of wavelength.[1] Thus, most presently active polarimetric SAR systems world-wide tend to operate at X-, C-, L-, S-, and P-band, or any combination thereof. Only L-, S-, and P-band systems are capable of penetrating forests for biomass height estimation or other deep structure monitoring like glacier characterization or terrain classification. X-band and C-band, radars provide higher resolution monitoring capabilities for more tactical purposes with some penetration of snow, ice, or soil. Ku- and Ka-band tend to be used for surface, canopy, or high resolution target applications.

Few applications are mentioned for Ku-band polarimetric SARs in the literature. The RAMSES system produced by France's defense agency, ONERA, is exceptional among polarimetric SARs in that it includes Ku- and W-band in its multi-frequency repertoire from P- through W-band.[1,3] ONERA's use of the X- and Ku-band frequencies, which includes polarimetric interferometry capabilities, is primarily for the monitoring of vertical obstructions, electric power lines, and urban structures. RAMSES is undoubtedly a target detection, recognition, and identification polarimetric radar as evidenced by the aircraft scattering decomposition in Figure 4 produced by the system, though its lower frequencies such as P-band are science-driven rather than tactical.

3.2.1. Ku-band Tactical Assessment

Potential Ku-band land and maritime tactical applications for SAR polarimetry are examined next. For instance, polarimetric SAR power line detection may be of particular importance for low-flying aircraft and helicopter safety or facility monitoring.[7] VV and HV returns are higher than HH at aspect angles away from normal incidence and for steeper grazing angles due to the imperfect, groove-like, strand structure of power lines that creates a dihedral surface with tilt variations. (An example power line backscatter response at millimeter waves demonstrating the mentioned characteristics as a function of incidence angle and polarization is shown in Figure 8.) VV and HV returns are also highly correlated due to the power line structure, such that their product, coupled with multi-look averaging, can afford a significant gain in the signal-to-clutter of the power line signature versus a VV return alone. This advantage is especially evident in cases where the background clutter overwhelms the co-polarization response. These results have been verified experimentally at millimeter waves, but performance is likely comparable at Ku.

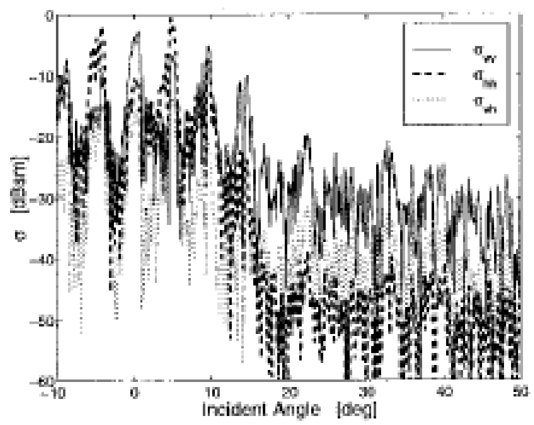
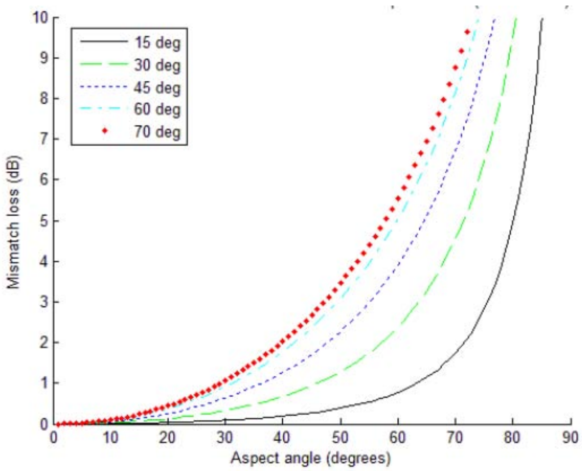
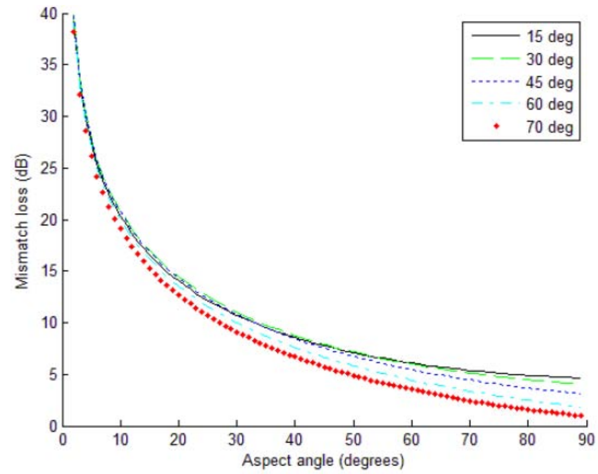


Figure 8. Power line normal incidence backscatter with grazing angle at millimeter waves, where VV and VH are stronger than HH at steeper angles and comparable otherwise.[7]

Polarimetric SAR may also be beneficial for other linear feature detections at Ku-band. For example, perfectly linear and axially symmetric features above a ground plane, such as fences, will produce strong flashes at normal incidence by the feature's alignment with the co-polarization directions.[7] These responses can be merged to provide more accurate fence delineations of posts and rails. (The HV return, useful for power line signal-to-clutter gain, is unfortunately not correlated with - and weaker than - the co-polarization response for such linear features.) Additionally, in the case of horizontal linear features on a ground plane, research suggests similar angular behavior for VV as for power lines.[8] However, HH gives stronger returns than VV at shallow grazing angles and normal incidence than for power lines, which have similar HH and VV returns. These conclusions are derived based on the polarization mismatch loss between the target and each co-polarization in Figure 9 at an unknown frequency. Thus a system with both co-polarization responses may provide greater angular detection coverage of the linear feature. Any imperfections in the horizontal linearity of the features along the ground plane may also create the tilted dihedral response of power line structures, which strengthens and correlates the vertical and cross-polarization responses for signal-to-clutter gain. (The latter information is unconfirmed in the literature and highly speculative.)



a)



b)

Figure 9. Polarization mismatch loss of horizontal linear features at 15- to 70-degree grazing angles and 7.6 km altitude versus aspect angle for a) HH and b) VV polarizations, in which HH shows greater response at shallow grazing and normal incidence than VV.[8]

Polarimetric change detection and interferometry may hold some utility at Ku-band as well. Polarimetry change detection may improve the crispness, amount, and types of change detectable by a single-channel system alone.[6] (The Australian defense agency has shown such promising work with an X-band system for detecting man-made change from vehicles and foot traffic, as shown in Figure 7, which should be applicable at Ku-band.) Also, polarimetric interferometry may allow the material of a target at a given location to be deduced by its scattering characteristics for target identification and analysis.[5] (Unfortunately, the more exciting polarimetric interferometry applications are at low frequencies, where the detection of targets beneath foliage is enhanced by the contrast in interferometric coherence for foliage, which is invariant with polarization, versus man-made targets which are not. Height-mapping and the distinction of various vegetative layer types from the canopy to the underbrush, as shown in Figure 6, are also only possible at the lower frequencies which allow for foliage penetration.) In short, some land-based tactical and surveillance benefits for Ku-band polarimetry are feasible.

Furthermore, the maritime arena could also benefit from Ku-band polarimetry. Sea spikes, which are known to cause false alarms for detection techniques in maritime wide area search systems at high frequencies, have significantly lower cross-polarization responses.[4] Thus, polarimetric SAR may be used to enhance the contrast of maritime detection and identification of difficult targets as well. (This has been demonstrated at C-band, as shown in Figure 5, but Ku-band performance should presumably improve, too.) In addition, the detection of multi-year versus first-year arctic ice at Ku-band based on theoretical reflectivity at HH seems to be most distinguishable and stable amidst seasonal fluctuations versus other radar bands at incidence angles away from the normal, as shown in Figure 10, which could be valuable for the protection of the arctic.[9] (Actual C-band SAR polarimetric data shows this advantage for HH and even more so for HV as shown in Figure 11. The ratio of co-polarizations is also useful to classify open water from ice in order to observe edge effects.) Note that although polarimetric SAR at lower frequencies has been determined useful for ice thickness measurement, the penetration of ice or snow at Ku-band wavelengths is theoretically expected to be surficial, at less than a meter depth, under the best conditions of low-salinity ice or low-moisture snow as shown in Figure 12.

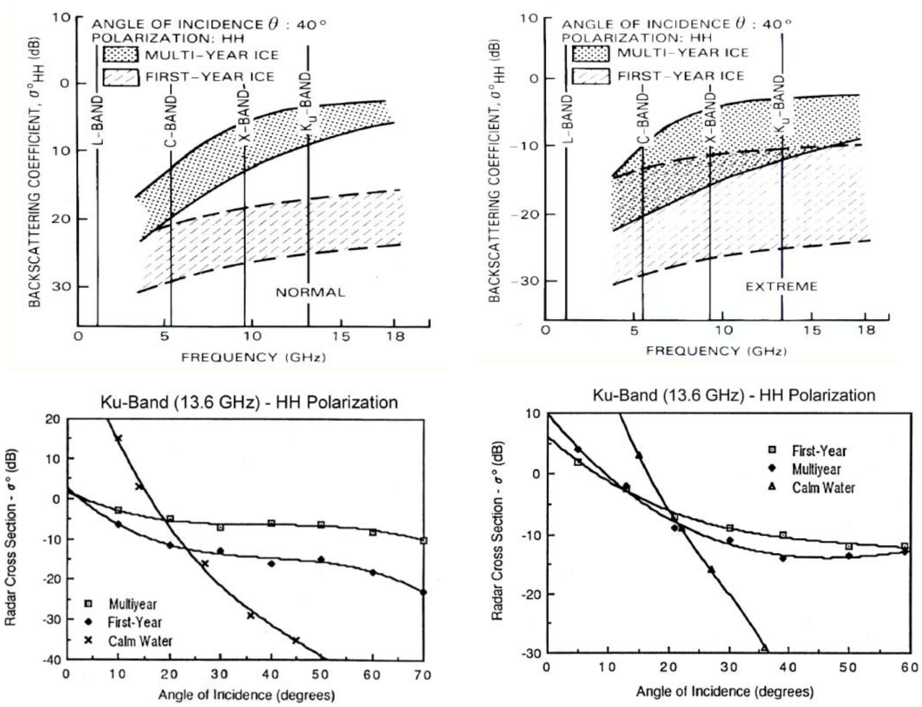


Figure 10. HH first-year and multi-year sea ice backscatter with frequency (top) and incidence angle (bottom) for normal winters (left) and extreme summers (right), showing good distinction at Ku-band versus lower frequencies at angles away from normal.[9]

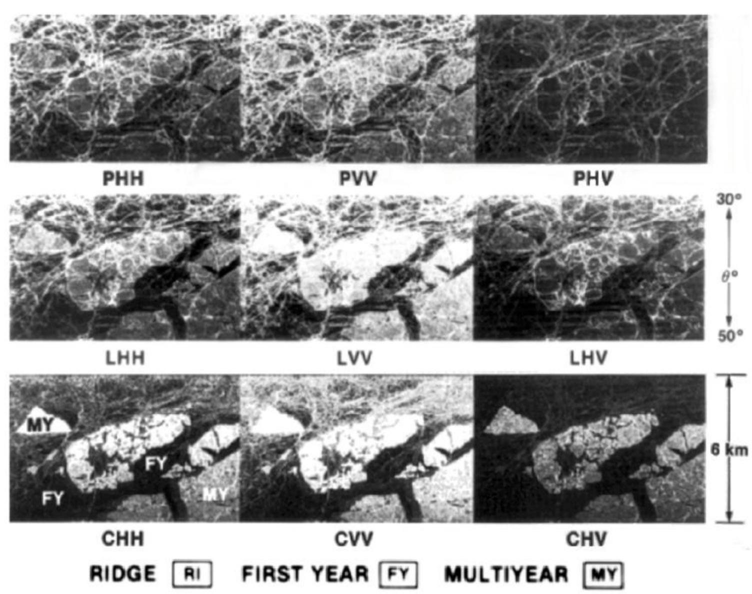


Figure 11. Multi-year (MY) and first-year (FY) sea ice classification in the arctic for HH, VV, and HV polarizations (left to right) at P-, L-, and C-band (top to bottom) denoting the better capability to crisply detect ice types at C-band, particularly with HV.[9]

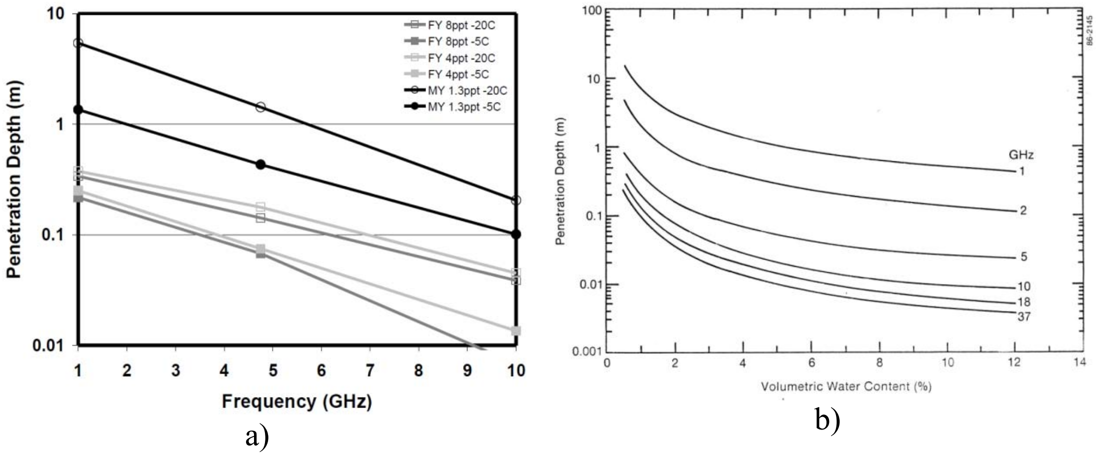


Figure 12. Penetration depth versus frequency for a) multi-year and first-year sea ice of a given temperature and salinity and, b) snow of a given water content, showing less than a meter of penetration at Ku-band is to be expected versus lower frequencies.[9]

3.2.2. Ku-band Earth Monitoring Assessment

Finally, although Ku-band polarimetric SARs are rare, scatterometers at Ku-band are not uncommon and can provide some insight on polarimetric SAR applications and performance for earth monitoring. Scatterometer systems have been tested for the determination of liquid versus ice content in precipitating clouds,[10] ocean vector winds measurements for hurricane prediction,[11] dry snowpack measurements,[12] crop canopy yields,[13] and oil spill classification.[14] The first two applications are spaceborne and likely out of scope for airborne or unmanned aerial systems.

However, in the case of dry snow observation, VV and HH reflectivity at X- and Ku-band has proven very sensitive to temporal snow-water-equivalent increases over many terrain types rather than lower-frequency airborne systems.[12] (For example, Figure 13 shows the vertical co-polarization response at Ku-band of snowpack accumulation in an area of Colorado with varied terrain and vegetation over the course of the winter months, where a 0.15 to 0.5 dB increase in backscatter signifies about a 1-centimeter change in snow-water-equivalent.) The HV response is also useful for the classification of vegetation affected by the snowpack. Additionally, although highly speculative, under shallow, dry snow conditions where Ku-band penetration is more likely, polarimetry may enhance the determination of the orientation of crevasses hidden under snow bridges. (Although tangentially related to the discussion, it is noteworthy to mention that Ku-band altimeters are common for determining surface height in snow or ice-prevalent scientific explorations due to their finer resolution and minimal penetration, which yields greater accuracy over other frequencies and suggests potential interferometric SAR opportunities.)

For crop canopy monitoring, versatility in polarimetric choices is desirable, as performance varies between polarizations depending on the crop.[13] For instance, rice patty crop grain yield is highly correlated with HV and VV responses, whereas leaf area index measurements of wheat, corn, and sorghum canopies are most highly correlated with VV and HH at Ku-band. Further, if an understanding of the crop stems and soil are desired, then C-, L-, and P-band polarimetry is additionally needed.

For oil spills, Ku-band and C-band detection is certainly feasible with HH scatterometer data due to damping of surficial gravity and capillary waves.[14] However, classification studies with C-band SAR polarimetric target decomposition, in order to reduce false alarms of biogenic versus anthropogenic spills, produce mixed results depending on the biogenic agent.[15] Hence, the benefit of Ku-band SAR polarimetry for this purpose is dubious versus an HH radar.

In sum, scatterometers do signal potential utility for polarimetric Ku-band SARs in certain types of earth surface monitoring arenas, with the caveats that these scatterometers are generally multi-frequency for optimum performance and certain applications are generally out of scope because a spaceborne system is needed for safety reasons.

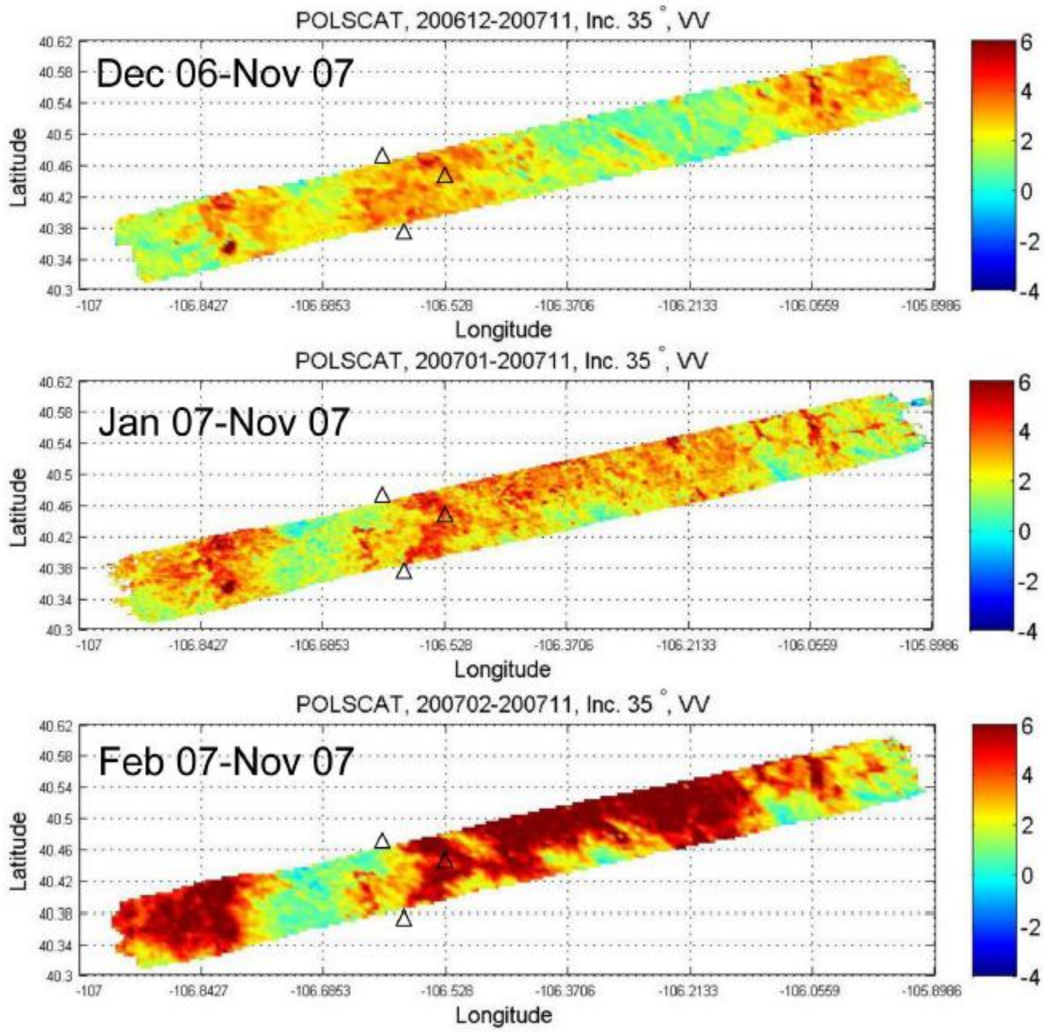


Figure 13. VV polarization snow pack accumulation over time of a Ku-band scatterometer.[12]

4. CONCLUSIONS

Polarimetric SARs provide additional radar data for many earth and man-made target observations. Whether that data can be translated into beneficial information highly depends on the scattering phenomenology wishing to be studied, the frequencies and incidence angles used, the environmental context, and the ability to decompose or contrast returns into physically meaningful elements. As much as upgrading a SAR to be fully polarimetric may appear to involve a simple modification to the RF front-end, the realities of development are much harder. Ku-band polarimetry is limited for earth monitoring applications that involve surface penetration without multi-frequency augmentation, but strong in high-resolution tactical, maritime monitoring, and specific surficial snow- or ice-observing applications.

Is the world the way it is, because it is the way it is, or because we are the way we are?

-Franz Kafka

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