Ionospheric Structure Imaging with ALOS PALSAR

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Abstract
Ionospheric irregularities and scintillations can cause sufficient phase and amplitude changes in L-Band SAR returns to produce distortions in the SAR image formation. Ionospheric measurement data from scanning incoherent scatter radars have shown that near the equator the ionosphere breaks up into irregularities with scale sizes ranging from centimeters to kilometers. Space borne SAR measurement differs from the ground based radar because of the two-way transmission through the ionosphere. Inverse algorithms will be attempted. In particular, the Faraday rotation estimation based on the ALOS PALSAR fully polarimetric data has demonstrated its potential to obtain the ionospheric total electron content (TEC).

Keywords: Ionosphere, ALOS PALSAR, radar polarimetry, Faraday rotation.

I. INTRODUCTION

The objectives of this proposal are two fold: 1) To enhance our knowledge of ionospheric processes that produced field-aligned irregularities based on PALSAR measurements at HAARP in Alaska and three other sites at low latitudes, 2) To determine to what degree the ionosphere can distort SAR based images of the ground.

Currently, TEC is at a low of 11 year solar cycle. In the absence of ionospheric irregularities during SAR imaging, artificial field aligned scintillations can be produced with high power HF radio waves using ground transmitters from the High Frequency Active Auroral Research Program (HAARP) site at Gakona, Alaska. This is the main thrust of this research program. In addition, natural irregularity may distort SAR image near the equator. Measurements at Kwajalein and Indonesia may observe the effects of equatorial irregularities. Further SAR measurement will be used at low-mid latitudes with the National Astronomy and Ionosphere Center at Arecibo, Puerto Rico. All the ground sites have an extensive collection of instruments to provide independent validation. To verify the PALSAR ionospheric irregularity measurement of this proposal, radio beacon transmissions from the Taiwanese Formosat3/COSMIC and other satellites in low earth orbit will be collected at the sites simultaneously with the PALSAR images.

Due the late start of ALOS Research Announcement 2 – May 2007 – we only have the opportunity of obtaining 12 sets of PALSAR PLR data from Alaska and Kwajalein. However, based on these observations, we found that Faraday rotation angle estimation based on PALSAR PLR data is a robust way of evaluating ionosphere irregularity.

II. EXPERIMENT SITE DESCRIPTION

Actual data from scanning incoherent scatter radars have shown that near the equator the ionosphere breaks up into irregularities with scale sizes ranging from centimeters to kilometers. Three experiment sites at the low latitudes are selected: (1) the equatorial ionospheric radar called ALTAIR at Kwajalein, Marshall Islands (lat. 9.4º N, long. 167.47º E), (2) the Equatorial Atmosphere Radar (lat. 0.20° S, long 100.32° E) in Indonesia, and (3) the Arecibo Ionospheric Observatory in Puerto Rico (lat. 18.34° N, long 66.75° W).

At high latitude, artificial field aligned irregularities can be produced with power high frequency (HF) radio waves using ground transmitters at the HAARP site near Gakona, Alaska (lat. 62.39° N, long 145.15° W). Ground based radars and beacons at the ionospheric research sites will collect data during PALSAR observations.

In addition, all of the ground sites will be supported by an array of radio beacon receivers to provide measurements of the total electron content (TEC) and radio scintillations from the Tri-Band Beacon (TBB) on the Taiwan FORMOSAT3/COSMIC satellites. The TBB radiates three frequencies (150.012, 400.032, and 1066.752 MHz) which pass through the ionosphere to yield the desired measurements of the ionosphere.

Table 1. Description of Experiment Sites

LOCATION	(LAT., LONG.)	TIME PERIOD	PRODUCT LEVEL VOLUME	PRIMARY TRUTH SENSORS
Kwajalein	(9.4° N, 167.47°E)	Aug.-Sept.	1.0 and 1.1 (4-10 collections)	ALTAIR COSMIC
Indonesia	(0.20° S, 100.32° E)	Mar-Apr., Sept-Oct.	1.0 and 1.1 1.0 and 1.1 (4-10 collections)	EAR COSMIC
Alaska	(62.39°N,145.15° W)	Summer	1.0 and 1.1 (4-10 collections)	MUIR COSMIC
Puerto Rico	(18.34° N, 66.75° W)	Any time	1.0 and 1.1 (4-10 collections)	Arecibo Dish

III. FARADAY ROTATION ESTIMATION

The Faraday rotation angle related to the TEC by the following equation [1, 2]:

$$\Omega = \frac{K}{f^2} H \cos\theta \sec\chi\, (TEC) \qquad (1)$$

In (1), Ω is the Faraday rotation angle of one way transmission through ionosphere. H is the intensity of earth magnetic field, K is a constant, f is the radar frequency. χ is the radar look angle, and θ is the angle between the magnetic field and the radar line of sight. Near the equator, $\cos\theta$ is small, but is near one at the north or south magnetic poles. At high latitudes in Alaska, the small angle θ ($\cos\theta \approx 1$) produces measurable Faraday rotation even though typical TEC values are lower. Based on this equation, TEC can be estimated, if Ω is known.

With fully polarimetric SAR data, several methods have been introduced to estimate the Faraday rotation angle [2-5]. PALSAR PLR data has low cross-talk, and the PLR 1.1 data is reasonably well calibrated. Under the assumption that amplitude and phase have been corrected, the received scattering matrix for a reciprocal medium can be represented by (Freeman [4]),

$$\begin{bmatrix} Z_{hh} & Z_{hv} \\ Z_{vh} & Z_{vv} \end{bmatrix} = \begin{bmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{bmatrix} \begin{bmatrix} S_{hh} & S_{hv} \\ S_{hv} & S_{vv} \end{bmatrix} \begin{bmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{bmatrix} \qquad (2)$$

It is straight forward to derive

$$\tan 2\Omega = \frac{Z_{hv} - Z_{vh}}{Z_{hh} + Z_{vv}}, \qquad -\frac{\pi}{2} \le \Omega \le \frac{\pi}{2} \qquad (3)$$

In this equation, the estimation of Ω is not well defined, because $(Z_{hv} - Z_{vh})$ and $(Z_{hh} + Z_{vv})$ are normally not in phase. Based on (3), Freeman proposed another formula, but the requirement of pre-selection of reflection symmetry areas and the high speckle effect associated with single look complex data makes this algorithm less effective and difficult to apply.

A robust algorithm has been proposed [3, 5] based on the correlation of circular cross-polarizations. The right-left and left right circular polarizations can be easily derived from the basics of wave polarimetry:

$$Z_{RL} = \frac{1}{2}[Z_{hv} - Z_{vh} + j(Z_{hh} + Z_{vv})] \qquad (4)$$

and

$$Z_{LR} = \frac{1}{2}[Z_{vh} - Z_{hv} + j(Z_{hh} + Z_{vv})] \qquad (5)$$

Based on the assumption of (2), we can derive

$$Z_{RL} = \frac{1}{2}[(S_{hh} + S_{vv})\sin 2\Omega + j(S_{hh} + S_{vv})\cos 2\Omega] \qquad (6)$$

$$Z_{LR} = \frac{1}{2}[-(S_{hh} + S_{vv})\sin 2\Omega + j(S_{hh} + S_{vv})\cos 2\Omega] \qquad (7)$$

And

$$\begin{aligned} Z_{RL}Z_{LR}^* &= \frac{1}{4}[|S_{hh} + S_{vv}|^2 (\cos^2 2\Omega - \sin^2 2\Omega) \\ &\quad - j\,|S_{hh} + S_{vv}|^2\, 2\cos 2\Omega \sin 2\Omega] \\ &= \frac{1}{4}|S_{hh} + S_{vv}|^2 (\cos 4\Omega - j\sin 4\Omega) \\ &= \frac{1}{4}|S_{hh} + S_{vv}|^2 e^{-j4\Omega} \end{aligned} \qquad (8)$$

The Faraday rotation angle can be estimated by

$$\Omega = -\frac{1}{4} Arg(Z_{RL}Z_{LR}^*), \quad -\frac{\pi}{4} \le \Omega \le \frac{\pi}{4} \qquad (9)$$

To reduce the speckle effect, the estimate is based on the averaged second order statistics,

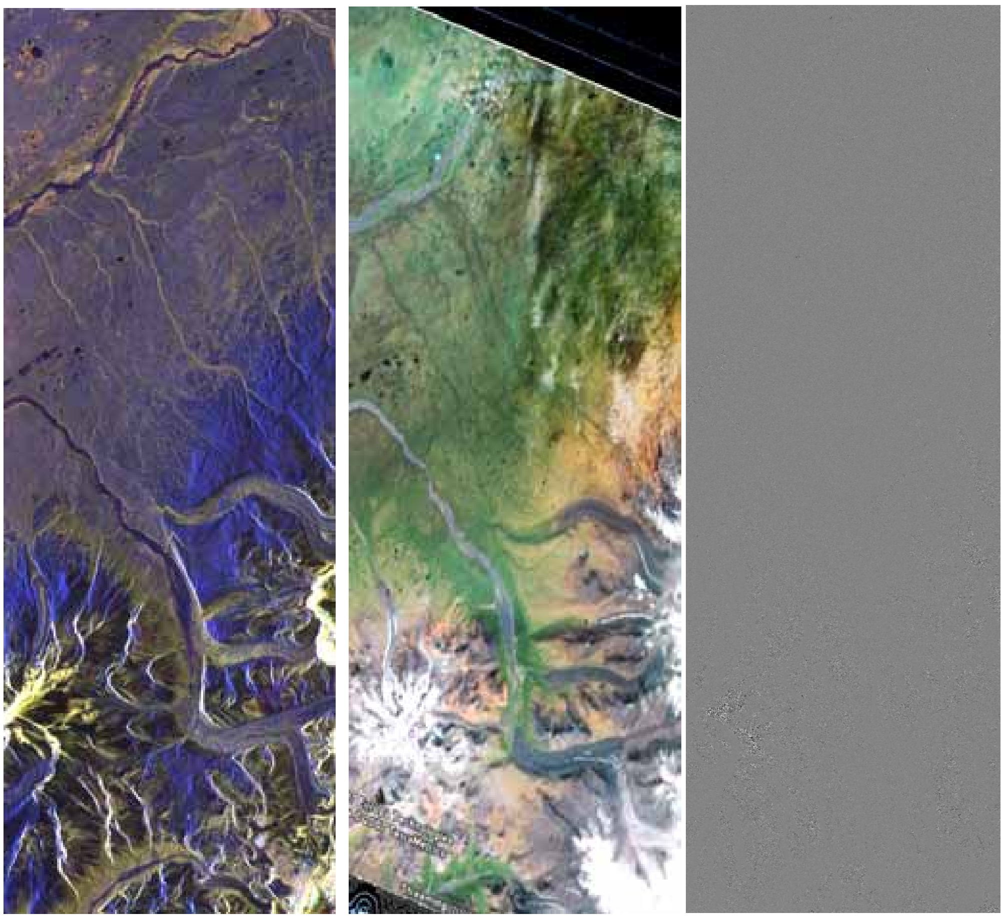
$$\Omega = -\frac{1}{4} Arg(< Z_{RL}Z_{LR}^* >) \qquad (10)$$

Equation (10) is well defined, and it is known that $Z_{RL}Z_{LR}^*$ is rotational invariant [6]. Hence, it is expected that (10) is less sensitive to polarization orientation angle variation induced by azimuth slopes.

IV. FARADAY ROTATION ANGLES ESTIMATED FROM ALOS PALSAR DATA

Due to the late start of this research program, and the limited number of fully polarimetric data that we could acquire, we tested 10 sets of data from Alaska and one from Kwajalein to confirm the capability of Faraday rotation estimation. Among these data, four were provided by Alaska Satellite Facility, and the rest are archived data obtained under the contract of ALOS RA2. For speckle and data volume reduction, covariance matrices were averaged down 4 pixels into 1 in the azimuth direction, and then 4x4 pixels were averaged down to one pixel. Here, we will provide three examples.

A. Near HAARP, Gakona, Alaska (62.282N, 144.643W), imaged on May 17, 2007

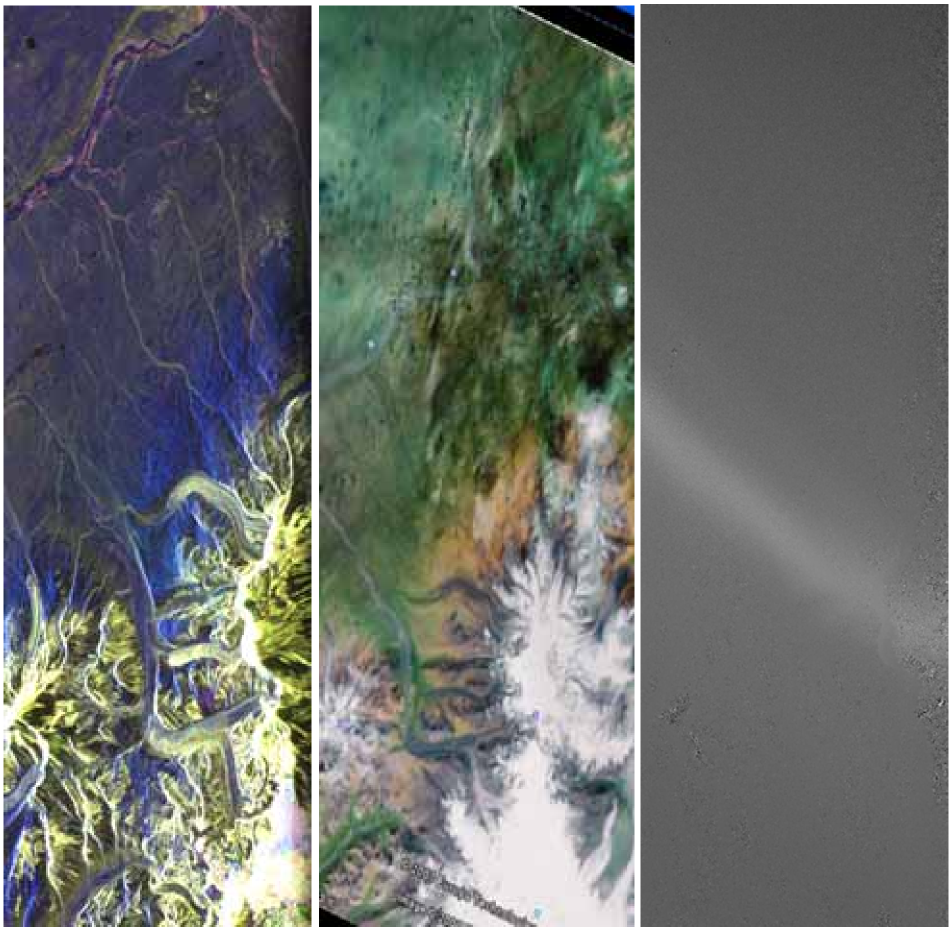


(A) Pauli vector display (B) Google Earth image (C) Estimated Faraday rotation

Fig. 1 Faraday rotation angle estimation from PALSAR PLR data of Gakona, Alaska: (A) The scene displayed with |HH-VV| in red, |HV|+|VH| in green, and |HH+VV| in blue, (B) the corresponding optical image from Google Earth, and (C) Faraday rotation angles computed based on circular polarizations.

These PALSAR PLR data were imaged near the HAARP site, and the result is shown in Fig. 1. The color image in Fig. 1A is displayed with Pauli vector components: |HH-VV| in red, |HV|+|VH| in green, and |HH+VV| in blue. The image reveals the rugged terrain, and the smooth areas in blue (surface scattering). For a visual comparison, we obtained an optical image (Fig. 1B) from Google Earth. We do not know the observation date of the Google optical image, but it is reasonably to interpret the areas in white as covered by snow. The estimated Faraday rotation angle computed by (10) is shown in Fig. 1C. The Faraday rotation values are heavily concentrated at its mean value of 2.6167° with a small standard deviation of 0.297°. The small standard deviation indicates that Faraday rotation angles are very homogeneous. This strongly demonstrated that the Faraday rotation angle computed with circular polarizations (10) is independent of azimuth slopes of this area of rugged terrain. We noticed that there are noisy pixels in radar shadow areas due to zero radar return.

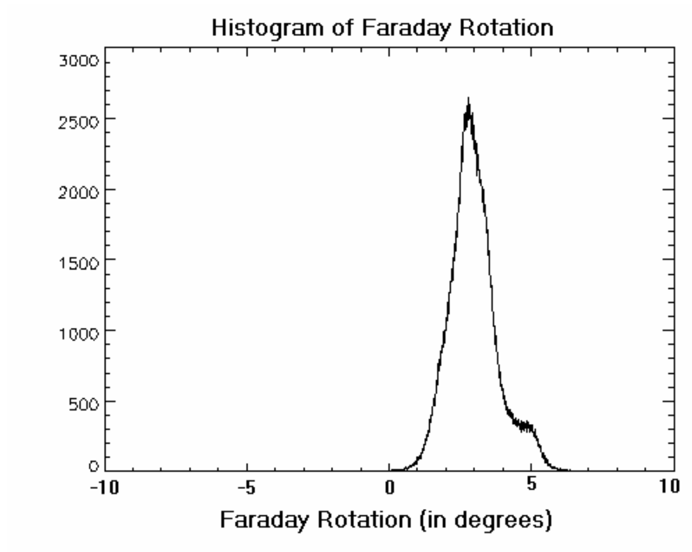
B. Gakona, Alaska imaged on April 1, 2007



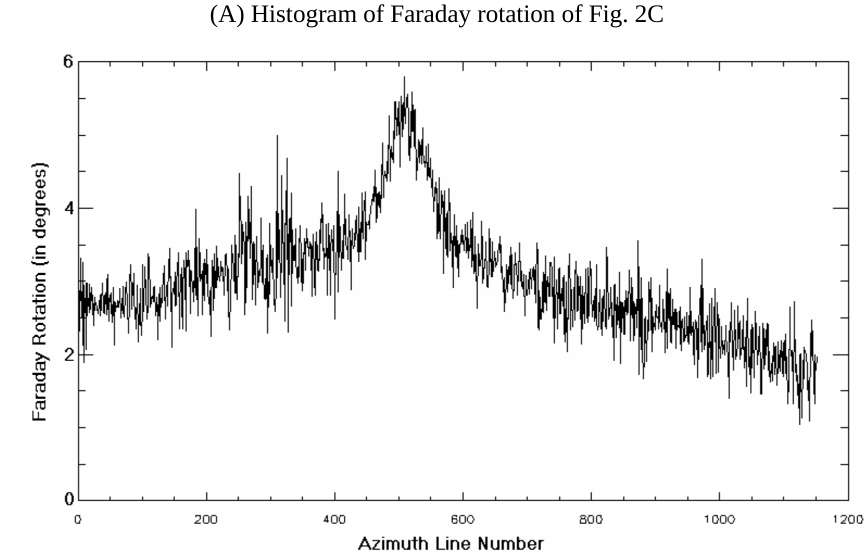
(A) Pauli vector display (B) Google Earth image (C) Estimated Faraday rotation

Fig. 2 Faraday rotation angle estimation from PALSAR PLR data of Gakona, Alaska – an interferometric pair of Fig. 1: (A) The scene displayed with |HH-VV| in red, |HV|+|VH| in green, and |HH+VV| in blue, (B) the corresponding optical image from Google Earth, and (C) Faraday rotation angles computed based on circular polarizations. Note that the bright feature in the center of the image, which could be affected by an irregularity in the ionosphere.

This data was taken 46 days earlier than the one shown in Fig. 1, and they represent an interferometry pair with this image slightly shifted to the east. The result is shown in Fig. 2A. The snow covered mountains are shown in yellow indicating high volume scattering (high |HV|) and higher double bounce returns (higher |HH-VV|). Fig. 2B shows the Google earth image of the area. The Faraday rotation computed with the circular polarization is given in Fig. 2C, where a brighter stripe crossing the middle part of the Faraday rotation image. We assume that this peculiar effect is due to ionospheric irregularity, but we do not have independent, simultaneous measurements to confirm it. Fig. 3A shows the histogram of Fig. 2C, revealing the Faraday rotation angle is concentrated at 2.9°, and a bump at about 5° from the micro ionosphere irregularity. A vertical line profile across the middle of Fig. 2C is shown in Fig. 3B. It indicates that the peak of the white stripe is about 5.5°, about 2.5° higher than the mean. The TEC value should be about twice as high at the stripe in comparison to the surrounding TEC values.



(A) Histogram of Faraday rotation of Fig. 2C

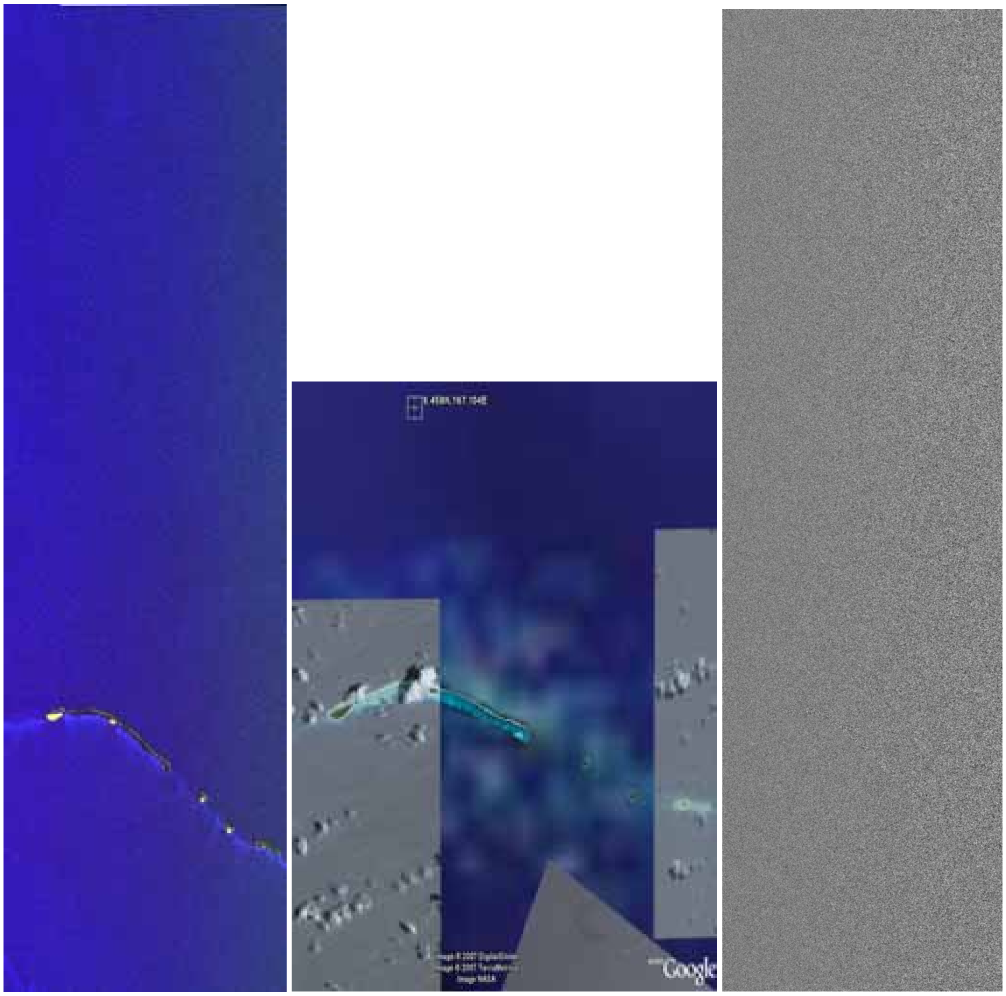


(B) A vertical line profile across the middle of Fig. 2C

Fig. 3 The histogram and a line profile of Faraday rotation

C. Near Kwajalien (9.458N, 167.106E), the observation date is 2007/03/14

Near the equator, the cosine angle nears 90°, and Faraday rotation angles are expected to be lower in value. Fig. 4 shows the SAR image, the corresponding Google image, and the estimated Faraday rotation. The mean is 0.373°, and the standard deviation remains small at 0.199°. This indicates that low backscattering expected from ocean surface does not affect Faraday rotation estimation.



(A) Pauli vector display (B) Google Earth image (C) Estimated Faraday rotation

Fig. 4 Faraday rotation estimation from ALOS PALSAR data of Kwajalien: : (A) The scene displayed with |HH-VV| in red, |HV|+|VH| in green, and |HH+VV| in blue, (B) the corresponding optical image from Google Earth, and (C) Faraday rotation angles computed based on circular polarizations. The low backscattering from ocean surface does not hinder Faraday rotation estimation. The mean is 0.373°, and the standard deviation remains small at 0.199°.

V. DISSCUSSION

The late start of ALOS RA2 made it impossible to request fully polarimetric SAR data, because PLR mode collection cycle was long passed. Fortunately, the collaboration with ASF provided a few PLR data sets of Alaska for this study. In addition, we found that RA2 PI does not allow "Observation Requests". The short lead time of "Observation Plan" makes it difficult to coordinate experiment setup at the four experiment sites. For the benefit of ionosphere research, land use and crop remote sensing, and hazard monitoring, it is highly desirable to have more cycles allocated to PLR mode.

VI. CONCLUSION

From the experiment results obtained up to now, we have demonstrated that Faraday rotation angle can be estimated reasonably well from ALOS PALSAR PLR data. The high resolution of PALSAR data can be used as a calibration tool for other ionosphere radars which have resolutions several orders of magnitude worse.

During the current low solar activity period, the ability to generate irregularities in the ionosphere by HF transmitters at HAARP will aid ionospheric research. However, coordination between PALSAR observations and HAARP is difficult due to the short lead time allowed by the "Planned Observation" schedule and the inability to submit "Observation Requests".

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