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Ionospheric effects on Synthetic Aperture Radar at VHF

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Short title:

Abstract. Synthetic aperture radars (SAR) operated from airplanes have been used at VHF because of their enhanced foliage and ground penetration compared to radars operated at UHF. A satellite-borne VHF SAR would have considerable utility but in order to operate with high resolution it would have to use both a large relative bandwidth and a large aperture. The presence of the ionosphere in the propagation path of the radar will cause a deterioration of the imaging because of dispersion over the bandwidth and group path changes in the imaged area over the collection aperture. In this paper we present calculations of the effects of a deterministic ionosphere on SAR imaging for a radar operated with a 100 MHz bandwidth centered at 250 MHz and over an angular aperture of 23°. The ionosphere induces a point spread function with an approximate half-width of 150 m in the slant-range direction and of 25 m in the cross-range direction compared to the nominal resolution of 1.5 m in both directions.

1. Introduction

The range resolution of a SAR is given by $\rho_r \approx c/2B$ where B is the bandwidth and c is the speed of light. Therefore, as the center frequency, f_c, is reduced, a larger relative bandwidth, B/f_c, is necessary to attain the same resolution. The azimuth resolution of a SAR, ρ_a, is given by

$$\rho_a \approx \frac{c/f_c}{4\sin\frac{\Delta\theta}{2}} \tag{1}$$

where $\Delta\theta$ is the synthesized angular aperture. As the frequency is reduced the size of the aperture, $\Delta\theta$, must be increased to retain the same resolution. The first effect of the ionosphere on a SAR pulse is to produce a group path change; that is, the target will appear to be displaced in range, Δr. This effect depends upon the operating frequency, f_c, and the integrated electron column density (total electron content or TEC) along the ray path and is $\Delta r \approx 81\,\mathrm{TEC}/f_c^2$ meters if f_c is given in Hz and TEC in m^{-2}. Daytime values of TEC are approximately $10^{17}\,\mathrm{m}^{-2}$ so that for $f_c = 250\,\mathrm{MHz}$, $\Delta r \approx$ 130 m. Moreover, because the total electron content will vary as the satellite traverses its collection aperture the displacement will shift with the satellite position. The displacement will also be affected by refractive effects as the radar pulse traverses the ionosphere. The second effect of the ionosphere on the radar pulse is that of dispersion; that is, higher frequencies will return sooner than lower frequencies from the same target. The amount of spreading, $\Delta\rho_r$, depends upon the bandwidth of the pulse and is given by

$$\Delta\rho_r \approx \Delta r\left[\frac{1}{(1-B/2f_c)^2} - \frac{1}{(1+B/2f_c)^2}\right]. \tag{2}$$

For a 100 MHz bandwidth pulse centered at 250 MHz, $\Delta\rho_r \approx 110$ m which is considerably larger than $\rho_r \approx 1.5$ m. These effects combine to degrade the resolution of the SAR image both in the range and azimuth directions.

2. Ionosphere

We consider a simplified version of the satellite-borne SAR imaging problem in which the earth's surface is a plane and the satellite moves parallel to the surface at a uniform speed, v_R, at height Z_1. We desire to image a region centered at coordinates $x = 0, y = 0, z = 0$; the satellite moves parallel to the y direction at location $\mathbf{u} = (X_1, Y_1 + v_R t, Z_1)$. We consider an ionosphere which has a uniform electron density, ρ_e, distributed in a horizontal slab of thickness T. Assuming that there is no ambient magnetic field, the phase index of refraction, $n(f)$, at frequency f is $\sqrt{1 - f_p^2/f^2}$ where f_p is the plasma frequency. The plasma frequency is defined as $\sqrt{\rho_e c^2 r_e/\pi}$ where r_e is the classical electron radius. The raypath between the SAR platform at $\mathbf{u} = (X_1, Y_1 + u, Z_1)$ and a reflector at $\mathbf{r} = (x, y, 0)$ is made of three straight line segments. By Snell's law, the elevation angle θ_1 of the raypath is the same above and below the ionosphere; θ_2, the elevation angle within the ionosphere, is related to θ_1 by $\cos\theta_1 = n(f)\cos\theta_2$. The phase path, $s(f) = \int n(f) ds$, for the ray can be shown to be

$$s(f) \approx R_0 - \epsilon \frac{T}{2\sin\theta_0} - \epsilon^2 \frac{T}{8 Z_1 \sin\theta_0} \left[\frac{Z_1 - T}{\sin^2\theta_0} + T \right]. \tag{3}$$

where θ_0 is the elevation angle in the absence of the ionosphere, $R_0 = \sqrt{Z_1^2 + X_1^2}$, and $n^2 = 1 - \epsilon$.

3. Calculation

The effect of a slab ionosphere on SAR imaging may be calculated by constructing the received, distorted signal and applying the SAR algorithm. We assume that the target consists of a number of point reflectors; that is, $f(\mathbf{r}) = \sum_i f_i \delta(\mathbf{r} - \mathbf{r}_i)$ where $\mathbf{r}_i$ is the location of target i. The effect of dispersion is to convolve the transmitted waveform, p, with the impulse response of the ionosphere, d:

$$p_d(\mathbf{u}, t) = p(t) * d(\mathbf{u}, t). \tag{4}$$

The convolution (4) may be conveniently calculated in the frequency domain; if $P_d(\mathbf{u},\omega)$ is the Fourier transform of p_d then

$$P_d(\mathbf{u},\omega) = P(\omega)D(\mathbf{u},\omega) \tag{5}$$

where

$$D(\mathbf{u},\omega) = \exp\left[i2\omega s(u,\omega)/c\right]. \tag{6}$$

We assume a linear FM-CW waveform with 102 MHz bandwidth and duration of $4\,\mu$s so that the range resolution should be 1.5 m. We use a sample interval, dt, of 7.8125 ns and a total of 2048 samples per pulse giving a total time window of $16\,\mu$s per pulse. The imaged area has a radius of 500 m which gives a range of possible delay times of $6.7\,\mu$s To ease the computational burden, we have scaled down the geometry of the simulation but have retained the effects by increasing the electron density of the ionosphere. The altitude of the satellite is $Z_1 = 100$ km and the ground range is $X_1 = 50$ km; the look angle to the targets is therefore 26.6°. The angular aperture is 23°which should give a cross-range resolution of 1.5 m. We use a total of $n_p = 32768$ pulses at a repetition frequency of 5 kHz which gives an aperture of 45.6 km at a speed of $v_R = 7$ km/s.

We consider three point reflectors located at positions $(x, y) =$ (0.,0.), (-400.,400.), and (400.,-400.) meters where x refers to the range and y to the cross range. The result of applying the SAR imaging algorithm to the simulated data without an ionosphere produces almost point-like responses. The geometry of the simulation causes a foreshortening in the slant range direction so that the image points are appear closer together than their actual ground locations. We next simulate SAR imaging with the same system parameters but with an ionosphere with a plasma frequency, f_n, of 18 MHz over a thickness, T, of 25 km; the vertical TEC for the ionosphere is $1 \times 10^{17}\,\mathrm{m}^{-2}$. The SAR image produced after propagation through this distorting ionosphere shows that the images are displaced in slant range because of the group delay effect of propagation through the ionosphere. In addition, the images are greatly broadened both in slant-range and cross-range. The spread amounts to about 150 m in slant-range and 25 m in cross-range. The spread is approximately invariant over the dimensions of the imaged area. Other simulations indicate that the spread in slant-range is produced by the band-width of the radar while the spread in cross-range is proportional to the synthesized aperture.

4. Discussion

Our simulations indicate that the daytime ionosphere will produce a significant degradation in the performance of a satellite-borne SAR operating at vhf. Furthermore, the simulations indicate that the better the desired performance in terms of range and cross-range resolution the worse the degradation becomes. These simulations indicate that for a deterministic, simplified ionosphere we can calculate the ionospheric degradation (point spread function) for the SAR image so that the image could be restored to full resolution. Extension to a more realistic geometry with a more realistic ionosphere would not be expected to lead to greatly different point spread functions.