Instrumental Polarization of the Goldstone 64-m Antenna System at 2388 MHz

G. S. Downs and P. E. Reichley
Communications Systems Research Section

Transmission of a signal in the right-circularly polarized mode using the Polarization Diversity S-Band (PDS) cone in fact results in a slightly elliptically polarized wave. After reflection from a distant surface and return to the antenna, the expected wave polarization is left-circular. Upon reception, a small component of right-circular polarization is present, and is partly the result of transmitting a small left-circular component. A similar fraction of the received left-circular wave is coupled into the received right-circular polarization. The total power in the received right-circular component is 1.2 ±0.2% of the power in the received left-circular component. The instrumental polarization is then 0.6 ±0.1%. The data leading to this result were obtained between July and November 1973 by transmitting radar signals to the planet Mars and subsequently measuring the power in the reflections.

I. Introduction

An electromagnetic wave transmitted by an antenna system is usually not perfectly polarized. This deviation from a perfect polarization is an instrumental effect. This deviation is present, for example, when we wish to transmit a presumably circularly polarized wave that in fact is slightly elliptically polarized. The reciprocal situation will occur in which a perfectly circularly polarized wave is intercepted by the antenna system, now used as a polarimeter. The measurement of the power in each polarization then indicates the wave is elliptically polarized. The main causes of this instrumental effect are reflection from the subreflector supports, imperfect isolation between feeds of orthogonal polarization, and internal reflections in waveguides. The ratio of the power in the undesired polarization to the total power in the wave is called the instrumental polarization.

The measurement of instrumental polarization is usually difficult. Many experimenters have measured the polarization of radiation from natural radio sources believed to be unpolarized. The measured polarization is then considered to be instrumental in origin. Difficulties are caused by possible polarization in the radio sources, random amplitude fluctuations in the received signal, and by the additive receiver noise. Often the desired accuracy of the measurements is less than the uncertainties caused by the random fluctuations. Hence one is tempted to measure the polarization by transmitting a strong signal with the antenna system to a colleague standing in the far zone with a polarimeter (another antenna followed by a receiver). If the curvature of Earth does not ruin the measurement attempt, polarized reflections from Earth's surface will. Placing a polarimeter in a satellite orbit has its special problems, including not knowing the instrumental effects of the polarimeter itself. Perhaps, then, a large spherical reflector placed in synchronous orbit would suffice. The antenna system is then used to transmit a polarized signal toward the reflector. The reflected signal is then received by the same antenna system now used as a polarimeter. The ratio of the power in the undesired component to the total power, called the radar instrumental polarization, is twice the one-way (transmit only or receive only) instrumental effect.

The planet Mars has been used recently in lieu of a spherical reflector. Between July 12 and November 24, 1973, radar signals were reflected off isolated regions approximately 8 km (E–W) by 110 km (N–S). A narrow band right-circularly polarized (RCP) wave was transmitted at 2388 MHz toward Mars using the Goldstone 64-m antenna fitted with the polarization diversity S-band cone. A perfectly smooth dielectric surface would convert the reflected signal into a specular component that is polarized in left circular polarization (LCP) near normal incidence. If some of the received signal were reflected twice by a rough terrain, or if asymmetrical rubble suppressed one component of linear polarization, the received signal would contain a small, diffuse RCP component. Also, if the transmitted signal is in fact elliptically polarized it would contain a small LCP component. This LCP deviate, when reflected, would return as an RCP wave. Hence in this series of measurements the two main difficulties were (1) the separation of the component of the received RCP signal induced by the surface of Mars from that inherent in the wave at transmission, and (2) the relatively large random fluctuations superimposed by receiver noise onto the weak received RCP signal.

II. Measurement of Signal Power

Imagine that the planet Mars is a stationary, perfectly conducting sphere. The narrow band radar signal, reflected from the sphere and then received at Goldstone, will contain a predictable amount of power. The strength of the signal depends on transmitting power, distance to the target, the gains of the transmitting and receiving antennas, the wavelength of the radar signal, and the size of the spherical target. The measured power is generally expressed in square meters of radar cross section when the wave incident on the planet has an intensity of 1 W/m^2. The radar cross section for a sphere of the same radius as Mars is πa^2, where $a = 3393$ km. The reflections from this perfect planet are obtained primarily from a small region about the subradar point (a surface point on the line of sight between the antenna and the center of the planet). In this ideal case the measurement of the instrumental polarization would consist of transmitting an RCP signal, then measuring the fraction of the total received power in the expected (LCP) mode and the fraction in the orthogonal (RCP) mode. The fraction in the RCP component, called the radar instrumental polarization, is two times the one-way effect. The one-way effect is merely called the instrumental polarization.

The surface of the planet Mars is made up of rough regions. Therefore, reflections can be obtained from regions well outside the subradar point. The only restriction is that these rough regions contain elements whose surface normal points in the direction of the radar antenna. Since the surface is curved, the time-delay from all regions is not necessarily the same. The delay difference between the closest point on Mars and a region on the limb is 23 ms. In the case of the perfect sphere the observed spread in delays would be many orders of magnitude less than 1 μs. Also the planet Mars spins on its axis. A signal reflected from a spinning target is subject to doppler broadening of its spectrum. A narrow-band signal transmitted at 2388 MHz can be spread over 7400 Hz when reflected from Mars. A perfect sphere spinning at the same rate would produce no broadening.

Examples of the radar data obtained in the course of these measurements is presented in Fig. 1. Signal power was measured for a series of 32 time delays, each separated by 3 μs. The signal is not narrow band, but spread in frequency as described above, so the distribution of the signal power in doppler shift frequency is presented at each time delay. In this case the subradar point was at a latitude of $-15.5°$. Its longitude was $100.6°$. The radar signal was transmitted in the RCP mode and received in the LCP mode. The next day, when the longitude of $100.6°$ was again visible to the radar system, the experiment was repeated with reception being in the RCP mode. The bright specular reflection at low time delays corresponds to the region closest to the receiver. The parabola denotes the doppler equator, or the locus of maximum doppler shift possible at each time delay. This dashed curve is essentially a parallel of latitude at −15.5°. The wide-band component caused by receiver noise has been subtracted in this display. The scale in Fig. 1b is 30 times larger than that in Fig. 1a, so the system noise has been brought into view. The distribution of the power in the RCP mode in delay and Doppler shift is similar to the distribution of power in the LCP mode.

If the RCP component had been produced by (1) multiple reflections on the Martian surface or by (2) small asymmetrical rocks on the surface, the power in Fig. 1(b) would be spread nearly uniformly in the region lying about the parabolic curve. It was assumed in the results presented here that an RCP component induced by the planet is tied to the presence of a diffuse scattering component and decreases slowly wih an increasing angle of incidence. However, the RCP component due to instrumental effects will be subject to the same doppler shift and time delay effects as the LCP component. The instrumental RCP component will then be a constant fraction of the LCP component at all doppler shifts and time delays.

It was concluded that the RCP component is due to instrumental effects and represents a radar instrumental polarization of 1.4%. If Mars were replaced with the perfectly conducting, rotating sphere, the received LCP and RCP signals would appear in Fig. 1 as sharp spikes at a delay of 15 s. The ratio of the power in the RCP component to the total power (both components) would be 0.014.

III. An Estimate of the Instrumental Effect

Another view of the reflected power is shown in Fig. 2. By choosing to measure power only along the parabolic curve of Fig. 1, particular regions are viewed at a variety of angles of view. That is, the reflected power for a particular region is measured for different angles of incidence. The region from which the radar signals were reflected in Fig. 2 was effectively 8 km × 110 km centered at longitude 99.52° and latitude −15.5°. The transmitted signal was polarized in RCP so the expected polarization upon reception is LCP. The power is expressed in units of radar cross section. Note that the ratio of RCP power to LCP power does not vary significantly with angle of incidence. The RCP component is approximately 1.4% of the LCP component. This is the behavior expected from instrumental polarization, where the undesired component is proportional to the total power in the wave. If the RCP component had been induced by surface roughness, the RCP power would be nearly independent of the angle of incidence. An upper limit to the cross section of such an RCP component, provided by the lowest values of the RCP component presented in Fig. 2, is 3×10^{-6}. The peak RCP and LCP cross sections of Fig. 2 are 3.3×10^{-5} and 2.4×10^{-3}, respectively. Therefore the maximum radar instrumental polarization is 1.38% and the minimum is 1.25%. This represents only one estimate of several possible estimates of the radar instrumental polarization. The entire ensemble of measurements is considered next.

IV. An Estimate Based on all Available Data

In the absence of an RCP component induced by a rough planet, the estimate of the peak power A_p (RCP) in the RCP component divided by the estimate A_p (LCP) is approximately the radar instrumental polarization. Estimates of A_p (RCP) and A_p (LCP) were made for reflections from 193 small regions. The signal-to-noise ratio of the RCP component was not always as high (about 10) as that exhibited in Fig. 2. In some cases the RCP component was buried in the receiver noise. In the absence of noise one would expect to obtain, for small regions of differing cross sections A_p (LCP), an RCP cross section A_p (RCP) that is a constant fraction of the LCP cross section. Hypothetical results are presented in Fig. 3(a) in which the LCP cross section is continuously increased, corresponding to increasing reflectivity or smoothness. Curves of the expected RCP cross section A_p (RCP) for radar instrumental polarizations R_I of 0.5, 1.0 and 2.0% are shown.

If, in addition to the instrumental effect, significant RCP power were produced by the planet, the measured cross section would lie above the line corresponding to the true value of R_I. To illustrate how the planet might affect the measured ratios, break the transmitted wave into the dominant RCP component and the perturbing LCP component. The vector $\mathbf{P}_{TX}$, representing the transmitted wave becomes

$$\mathbf{P}_{TX} = (1 - \alpha) P_T \mathbf{U}_L + \alpha P_T \mathbf{U}_R$$

where P_T is the transmitter power, α is close to 1.0, and the orthogonal vectors $\mathbf{U}_L$ and $\mathbf{U}_R$ represent the two components of the wave. Upon reflection from the planet, the polarization of each component will be reversed. Extreme roughness will perturb the wave by converting a small amount of incident RCP power into diffusely scattered power in LCP and RCP. The same effect will perturb the RCP wave. A fraction $\rho_0 + \rho_{d0}$ of the incident circularly polarized wave will be of the opposite polarization upon reflection. The coefficient ρ_o is associated with the specular component and ρ_{do} with the diffuse component. A fraction ρ_{ds}, associated with the diffuse scattering, will be reflected into the same polarization as the incident wave. The reflected wave $\mathbf{P}_{REF}$ is then, letting $\beta = 1 - \alpha$,

$$\mathbf{P}_{REF} = [\alpha\rho_o + \alpha\rho_{do} + \beta\rho_{ds}]\, P_T\mathbf{U}_L + [\beta\rho_o + \beta\rho_{do} + \alpha\rho_{ds}]\, P_T\mathbf{U}_R$$

After reception, and hence after the experiencing of further perturbation by the antenna, the received wave $\mathbf{P}_{RCV}$ becomes

$$\mathbf{P}_{RCV} = [(\alpha^2 + \beta^2)(\rho_o + \rho_{do}) + 2\alpha\beta\rho_{ds}]\, P_T\mathbf{U}_L + [2\alpha\beta\rho_o + (\alpha^2 + \beta^2)\rho_{ds} + 2\alpha\beta\rho_{do}]\, P_T\mathbf{U}_R$$

The ratio $A_p\,(RCP)/A_p\,(LCP)$ is then given by

$$\frac{A_p\,(RCP)}{A_p\,(LCP)} = \frac{2\alpha\beta(\rho_o + \rho_{ds} - \rho_{do}) + \rho_{ds}}{\rho_o + \rho_{do} - 2\alpha\beta(\rho_o + \rho_{do} - \rho_{ds})}$$

where use is made of the relation $\alpha + \beta = 1$. In one extreme case of depolarization one expects $\rho_{ds} = \rho_{do} = \rho_d$.

Then

$$\frac{A_p\,(RCP)}{A_p\,(LCP)} = \frac{2\alpha\beta\rho_o + \rho_d}{(1 - 2\alpha\beta)\,\rho_o + \rho_d}$$

In another extreme case, $\rho_{do} = 0$, $\rho_{ds} = \rho_d$, and

$$\frac{A_p\,(RCP)}{A_p\,(LCP)} = \frac{2\alpha\beta\rho_o + (1 + 2\alpha\beta)\rho_d}{\rho_o - 2\alpha\beta\,(\rho_o - \rho_d)}$$

If the diffuse component of the received RCP is small compared to the specular component, as in Fig. 2, and if $\beta << 1$, so $\alpha \approx 1$, then the ratios above approach 2β, the true radar instrumental polarization. However, the diffuse component of RCP may not be comparably small at lower LCP cross sections. Both of the ratios above will then be larger than if the diffuse components were comparably small. The effect is to induce a curvature into the straight lines of Fig. 3(a) such that a straight line, when fit to the data in a least-squares sense, will not pass through the origin. The y-intercept will be greater than zero.

The results for the planet Mars are presented in Fig. 3(b). A weak but definite correlation appears in Fig. 3(b) between the power in the RCP component and that of the LCP component. Ideally, in the absence of noise, the data pairs would be confined to a straight line of the form $y = mx$. The instrumental effect to be measured would then be m. Therefore a straight line was fit to the data in a least-squares sense. The result, the dashed line of Fig. 3(b), was a line of the form $y = mx + b$ where

$$m = (0.96 \pm 0.10) \times 10^{-2}$$

$$b = (1.0 \pm 0.3) \times 10^{-5}$$

(one-sigma errors are quoted). Since $b \neq 0$ there may have been a planetary effect present. The solid line in Fig. 3b was then fit with $b = 0$, obtaining

$$m = (1.19 \pm 0.10) \times 10^{-2}$$

V. Conclusion

All the possible values of radar instrumental polarization presented above are included in the adopted value of 1.2 ± 0.2%. This is considered to be a conservative estimate of the two-way instrumental polarization that is introduced in a signal transmitted at 2388 MHz using the 64-m antenna, then, after reflection from a distant object, received by the same antenna. The one-way effect is then 0.6 ± 0.1%. This result is dependent on the belief that an RCP component induced by the planet is tied to a diffuse scattering component.

Acknowledgement

The authors are grateful to D. A. Bathker, R. R. Green, and R. M. Goldstein for their helpful comments.

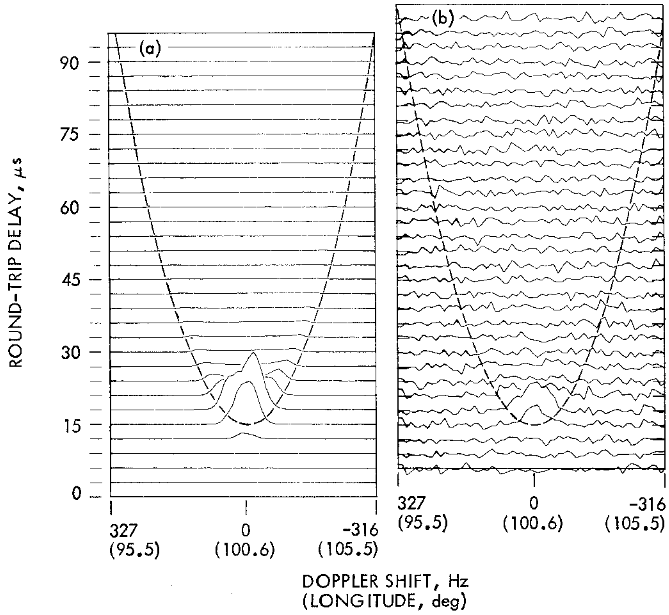

Fig. 1. Examples of reflected signal power arranged by time delay and doppler shift: (a) the antenna polarization is in LCP, (b) reflected RCP power from the same region as in (a)

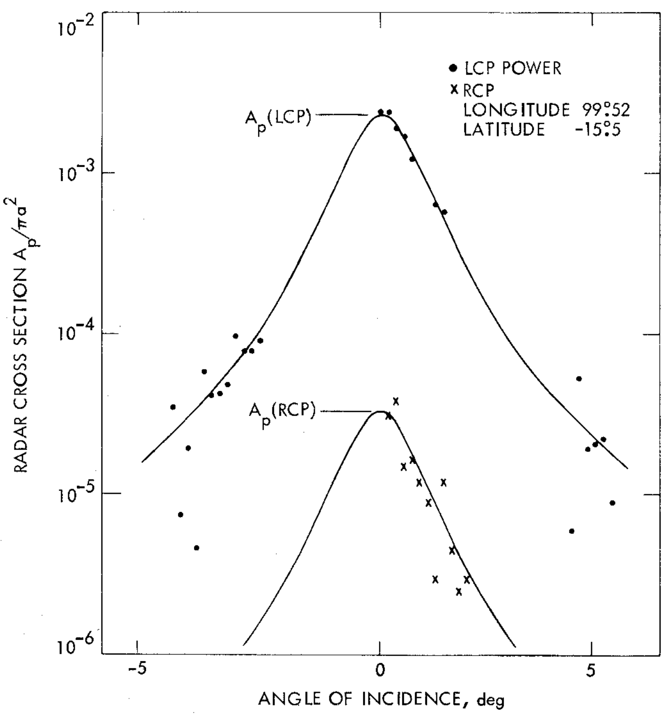

Fig. 2. Reflected power versus angle of incidence for a small Martian region 8 × 110 km

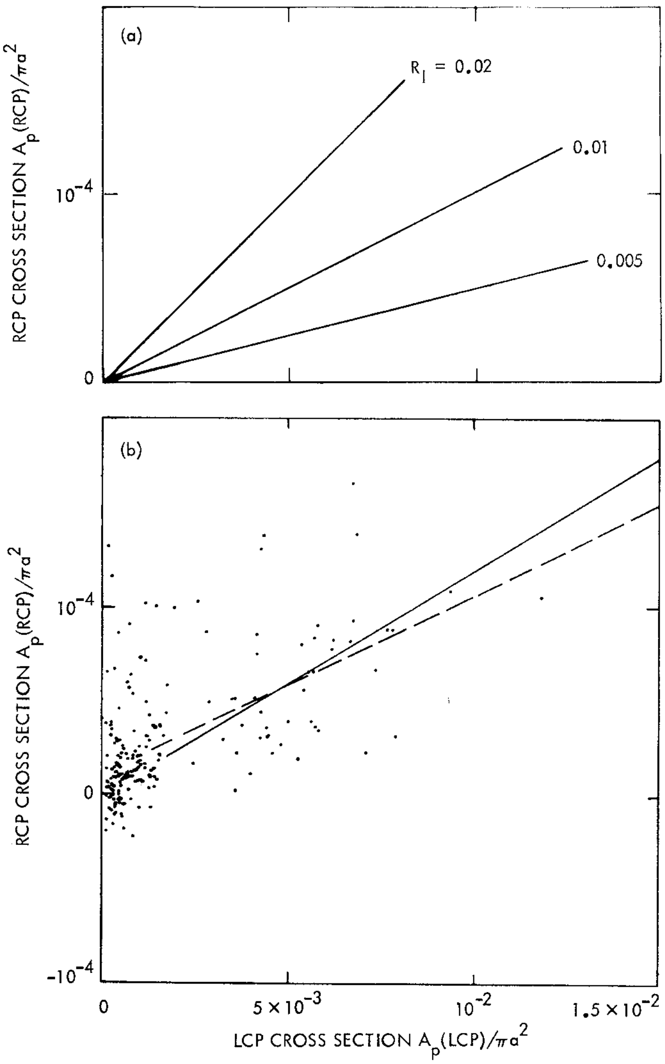

Fig. 3. RCP cross sections vs corresponding LCP cross sections: (a) expected RCP cross section vs the LCP cross section for radar instrumental polarizations R_I of 0.005, 0.01, and 0.02, (b) the peak radar cross sections (power) measured in the RCP component vs the corresponding power in the expected (LCP) polarization when the transmitted signal was right-circularly polarized