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A fast method of fully characterizing sputtering angular dependence

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A new method has been demonstrated in which a single experiment is used to fully define the sputtering angular dependence of a given material. The method subjects a circular rod of test material to a mono-energetic and highly collimated ion beam. The eroded profile is then measured using optical profilometry; the full sputtering angular dependence curve is then extracted using a numerical approach.

I. Introduction

Understanding the sputtering characteristics of electric propulsion (EP) thruster materials is important for predicting lifetime and performance. Sputtered material is also a contamination concern as it can be redeposited and degrade system performance.

The amount of sputtered material is a function of the energy (velocity) and angle of incidence of the impacting ions. Although analytical sputtering profiles exist for some monatomic metals,[1] the sputtering behavior of materials used in EP applications is typically obtained experimentally using weight loss and quartz crystal microbalance (QCM) measurements.[2] In each case, a flat plate is eroded by an ion source at a certain energy and a certain angle of incidence. These traditional methods are characterized by the time consuming task of performing the multiple experimental runs necessary to achieve sufficient angular resolution.

The method presented in this paper was previously employed by Barrie[3] et al. to measure the sputtering rate of an aluminum rod subjected to bombardment by Xenon particles from a 10 cm Hall Effect Thruster (HET). In this paper we investigate the effect of the non-uniform beam on the erosion profile by eroding three identical rods located at various axial distances from the thruster as well as differing angles from the thrust axis as seen in Figure 1 and Figure 2. The increased distance from the thruster results in a more uniform flow profile at the expense of a lower erosion rate.

II. Model

Yamamura gives the angular sputter yield as a correction factor to the normal sputter yield with Equation 1 below. The normal sputter yield, $Y(0)$, is calculated by Yamamura's method as summarized by Cheng.[4] f and Σ are fit parameters tabulated for a limited number of source and target combinations in literature.[1] θ is the incident angle relative to the surface normal.

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$$\frac{Y(\theta)}{Y(0)} = \cos^{-f}\theta \exp -\Sigma(\cos^{-1}\theta - 1) \tag{1}$$

where,

$$f = f_s\Big(1 + 2.5\frac{1-\zeta}{\zeta}\Big), \tag{2}$$

$$\Sigma = f\cos\theta_{opt}, \tag{3}$$

$$\zeta = 1 - \sqrt{\frac{E_{th\_ang}}{E}} \tag{4}$$

$$E_{th\_ang} = 1.5\frac{U_S}{\gamma}\bigg[1 + 1.38\Big(\frac{M_1}{M_2}\Big)^h\bigg]^2 \tag{5}$$

$$h = 0.834, M_2 > M_1$$

$$h = 0.180, M_2 < M_1$$

Where M_1 and M_2 are the source and target atomic masses respectively.

$$\gamma = \frac{4M_1M_2}{(M_1+M_2)^2} \tag{6}$$

$$\theta_{opt} = 90^\circ - 286(\psi)^{0.45} \tag{7}$$

$$\psi = \Big(\frac{a}{R_0}\Big)^{3/2}\bigg[\frac{Z_1Z_2}{\big(Z_1^{2/3} + Z_2^{2/3}\big)^{1/2}}\frac{1}{E}\bigg]^{1/2} \tag{8}$$

Table 1 lists the required constants needed to calculate f and Σ and the angular dependence curve for Xenon sputtering Aluminum.

Table 1. Published constants for Xe sputtering Al

Parameter	Al
M_1, source atomic mass	131.29
M_2, target atomic mass	26.982
Z_1, source atomic number	54
Z_2, target atomic number	13
f_s, Sigmund f	1.8
a, screening radius	0.1052
R_0, average lattice constant	2.56
U_S, sublimation energy [eV]	3.39

Using the parameters above and Equations 2-8, one arrives at an f and Σ of 7.84 and 4.01 respectively using the expected incident energy of 220 eV. Equation 1 is plotted in Figure 5 with these values and a normal sputtering yield of unity.

Since the angular sputter yield depends on angle of incidence and incoming energy, a circular cylinder was placed in a uniform and mono-energetic flow. When a circular cylinder is subjected to a uniform flow perpendicular to its axis, the angles of incidence from 90° to 0° are achieved simultaneously. One would expect the greatest initial erosion to occur at the angle of optimal erosion, θ_{opt}, which is in the vicinity of 60° off the surface normal. Furthermore, the Yamamura model predicts no erosion when the flow is tangent to the surface ($\theta = 90^\circ$) and simply normal erosion when the flow is perpendicular to the surface ($\theta = 0^\circ$). Since we cannot measure erosion after a very short time, the surface was eroded over a long period of time resulting in the surface normals changing significantly. A numerical scheme was implemented to simulate the changing surface normals and allowed for the proper determination of the experimental f and Σ values.

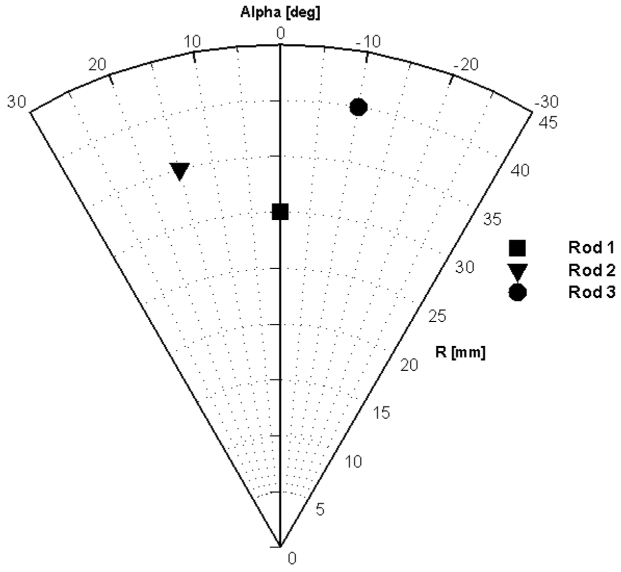


Figure 1. Placement of the rods in the chamber relative to the thruster, firing from $R = 0$ through $\alpha = 0°$ parallel to the page.

III. Results

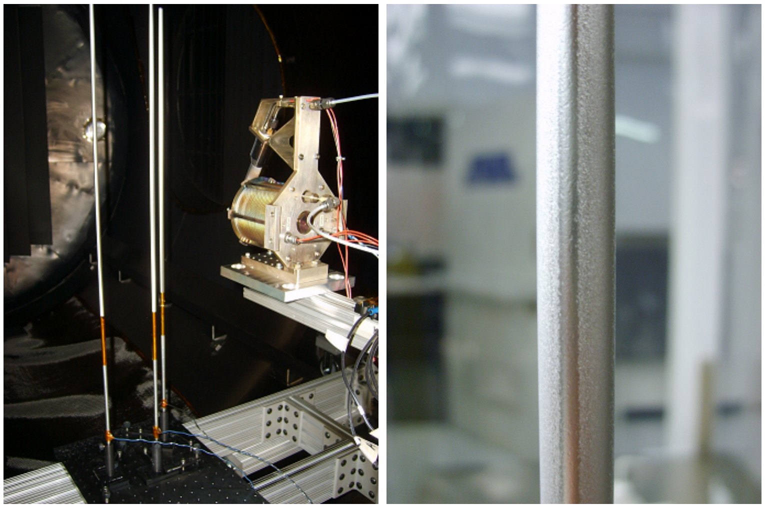
In an effort to subject the rods to a more uniform and mono-energetic flow of Xenon ions from a HET, the rods were placed at a greater distance from the source compared to the previous experiment and at various angles from the thrust axis. Locations beyond 15 degrees off the thrust axis and 30 cm from the source, plasma densities drop off quickly resulting in lower erosion rates.

After firing for 135 hours the rods were removed from the vacuum chamber, exposed to the atmosphere and their surface profiles were measured using an optical profilometer. Ten circumferential scans were performed on each rod across a 1 mm swath centered at the height of the thruster. Each of the ten scans was averaged for each rod and this data was numerically smoothed to 128 points. Figure 3 shows the 64 smoothed points from each rod that experienced erosion. The uneroded profile is plotted in the same figure and has a radius of 3.98 mm. Rod 1 obviously eroded the most because it was the closest to the source and was placed on the thrust axis whereas rods 2 and 3 eroded significantly less but in a similar way to each other due to similar plasma densities.

The depth of erosion was calculated and plotted in Figure 4. Wings of higher erosion are apparent in the profiles as sputter rates are higher at incident angles beyond normal. According to published fit parameters and Yamamura's model, initial erosion depth should be the highest around 60°, this was not observed because the surface was eroded to a measureable depth and consequently, the surface normals changed significantly. As the surface normals changed, the assumption of a uniform flow striking a circular cylinder was not valid and the surface eroded in a complex way.

The fit parameters were extracted from the eroded profiles in Figure 3 using a numerical simulation which applied Equation 1 on a meshed 2D circular model of the uneroded rod. In each simulation, the rod was eroded in very small steps according to Yamamura's model until the point of normal sputter yield ($\theta = 0°$) reached the respective measured normal sputter depth. This effectively normalized the simulations in time and rate of erosion was not considered. An optimization routine was used to determine f and Σ values which yielded best agreement with the measured eroded profiles and are found in Table 2.

The sputter yield angular dependence curve is plotted in Figure 5 for each rod using the experimental fit parameters along with published results; for ease of comparison, a sputter yield of unity was assumed. It is immediately apparent the experimental curves predict lower sputter yields than the published curve. This could be due to the fact that the ion flow was neither truly mono-energetic nor uniform as was assumed in the experiment. The angular dependence was not captured with rod 1 as cross-flow from the thruster exit resulted in a wider range of normal incidence upon the rod. Rods 2 and 3 captured more of the angular dependence due to more ideal flow characteristics at their locations in plume. Rods 2 and 3 over and under



(a) (b)

Figure 2. Experimental setup and clearly visible erosion

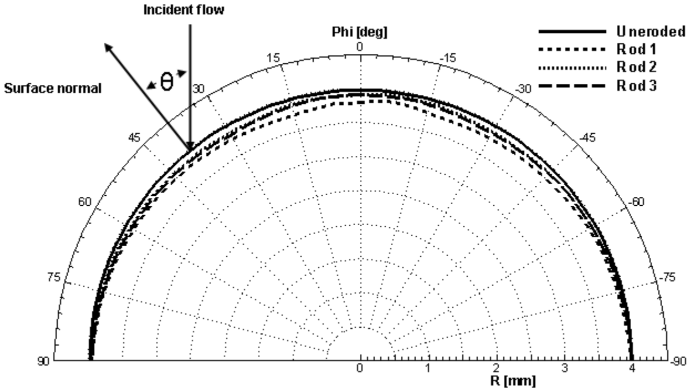


Figure 3. Eroded profiles of the three rods compared to the original rod.

predict the angle of optimal erosion respectively; this could be due to slight thruster misalignment as the rods were on either side of the thrust axis. Figure 6 compares the measured eroded profiles with the expected profile calculated numerically using published fit parameters, with Φ indicating the angular position along the rod. In each case, the simulation showed a characteristic maximum erosion yield at an angle of incidence of nearly 60° as expected. Experimental results show good agreement with their respective simulations for shallow angles of incidence. As the angle on incidence increases; however, the expected erosion yield was not observed.

Figure 7 compares measured eroded profiles with their respective simulations using values of f and Σ from the optimizer routine. Figure 8 compares the simulated eroded profiles for each rod using their respective experimental values of f and Σ with that of the published values. In each case, the surface mesh was eroded until the normal sputter yield matched experimental measurements.

IV. Conclusion and Future Work

This work was a continuation of the experiment by Barrie[3] et al. in which a new method of determining the sputtering angular dependence characteristics of a material was studied. Current methods of determining the sputtering characteristics of a material involve multiple time consuming steps. This paper further studies

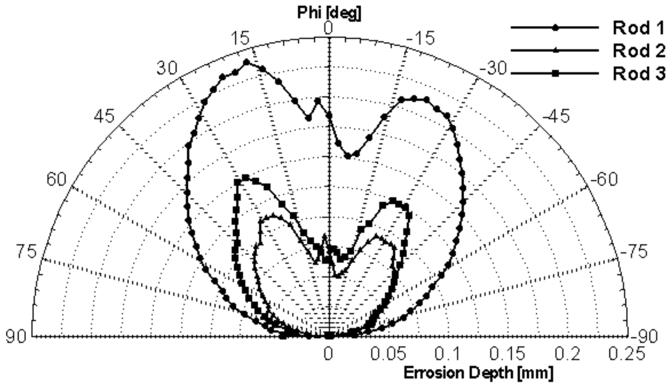


Figure 4. Erosion depth for the three rods as a function of angular position.

Table 2. Extracted f and Σ for the three rods and published values

	f	Σ
Rod 1	0.8	0.3
Rod 2	2.1	0.9
Rod 3	8.9	5.7
Published	7.84	4.01

the feasibility of determining sputter yield angular dependence in a single measurement.

Three ground aluminum circular cylinders were subjected to the plume of a HET at differing off thrust axis angles and distances from the plume source. The cylinders were bombarded for 135 hours and visible erosion occurred. The eroded surfaces were measured using an optical profilometer and compared to their respective uneroded surfaces. Optimal fit parameters f and Σ for use in Yamamura's sputter yield angular dependence equation were then extracted from the measured profiles using an erosion simulator and an optimization routine. The extracted fit parameters yielded close agreement with experimental measurements.

The fit parameters calculated in this experiment did not match closely with published values, but were in better agreement than in the first attempt. Much of the sputter yield angular dependence was captured but not to the correct scale. By moving the rods farther away from the thruster exit and at greater angles away from the thrust axis, a more uniform and mono-energetic flow was achieved. The more uniform flow in this experiment subjected the rods to a flow closer to that which was assumed. The most likely reason for the discrepancy among the fit parameters is the nature of the HET plume structure. Even at the distances the rods were placed, cross flow from the thruster exit introduced a certain degree of flow non-uniformity which altered way the rods were eroded.

A significant increase in accuracy of the experimental fit parameters compared to past work was achieved simply by moving the rods to a more uniform region of the HET plume; one would expect better results if a rod were placed even further. When using a HET for this experiment, a compromise exists between flow uniformity and the required time to erode to a measureable depth. A better source could be used such as an ion thruster which would yield the desired flow characteristics this experiment requires.

V. Acknowledgements

The authors would like to thank Dr. William Hargus for formulating the idea of sputtering a circular cylinder as means of measuring a material's erosion characteristics. Additional thanks goes to Mr. Bryan Taylor for his aid with the erosion and optimization routines employed in this work.

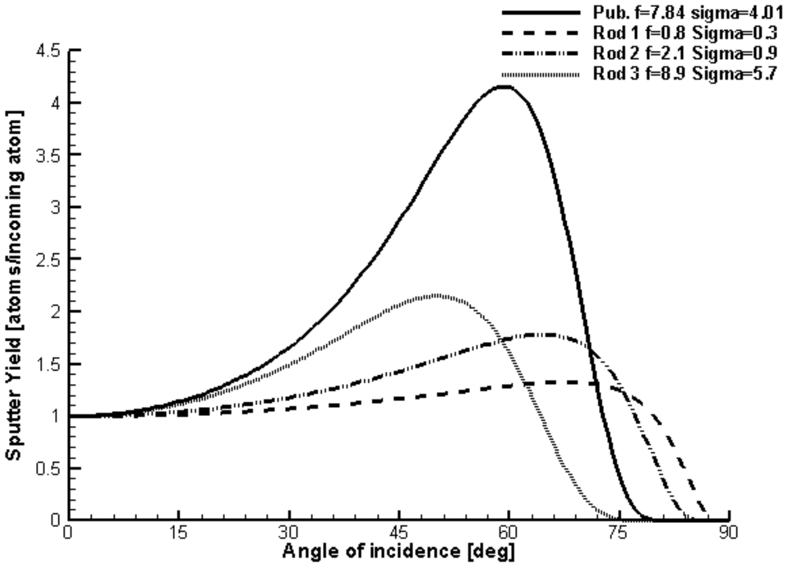


Figure 5. Sputtering yield as a function of incident angle.

References

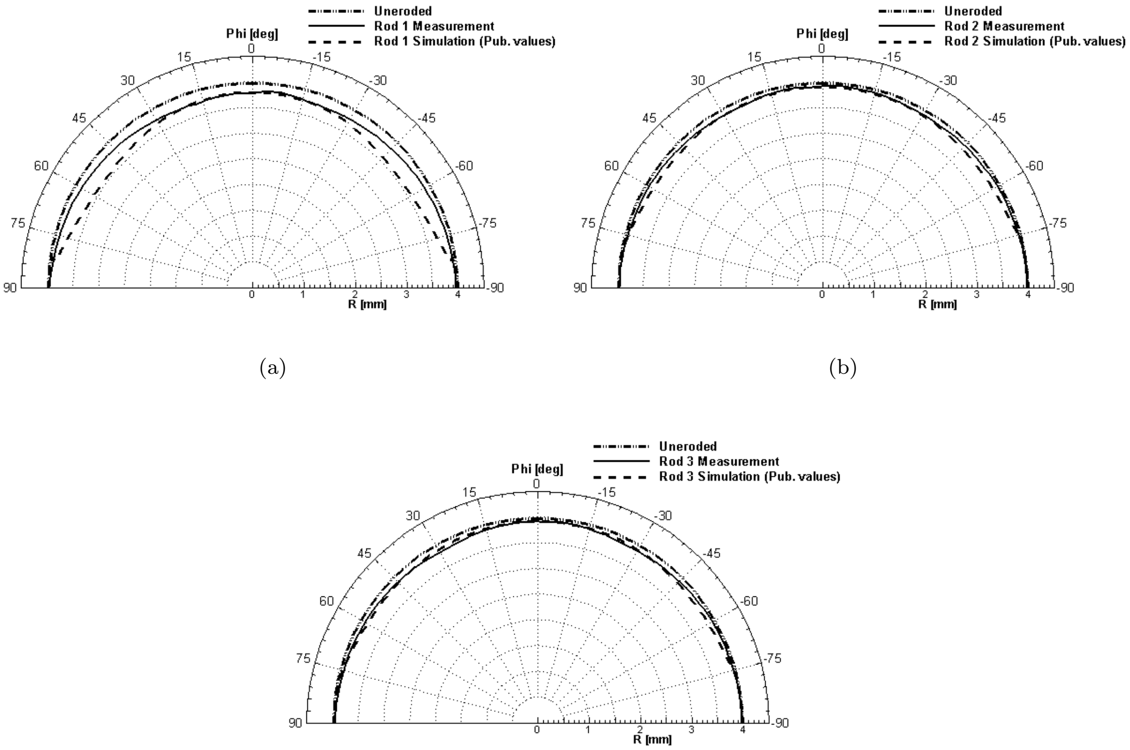
[1] Yamamura, Y., Y. Itikawa, and N. Itoh. IPPJ-AM-26, "Angular Dependence of Sputtering Yields on Monatomic Solids." Institute of Plasma Physics, Nagoya University, June 1983.

[2] Yalin, A. P., Williams, J. D., Surla, V., and Zoerb, K. A., "Differential Sputter Yield Profiles of Molybdenum due to Bombardment by Low Energy Xenon Ions at Normal and Oblique Incidence," Submitted to: *Journal of Physics D: Applied Physics*

[3] Barrie, A., Taylor, B., Ekholm, J., and Hargus, W., "Calculating Sputter Rate Angular Dependence Using Optical Profilometry," *30th International Electric Propulsion Conference*, IEPC-2007-001

[4] Cheng, S.,*Computational Modeling of a Hall Thruster Plasma Plume in a Vamccum Tank,* Masters Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2002.

[5] Yamamura, Y. and Tawara, H., "Energy Dependence of Ion Induced Sputtering Yields From Monatomic Solids at Normal Incidence," *Atomic Data and Nuclear Tables*, Vol. 62, 1996.



(a)

(b)

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Figure 6. Comparison between measured rod profiles and simulations using published fit parameter values

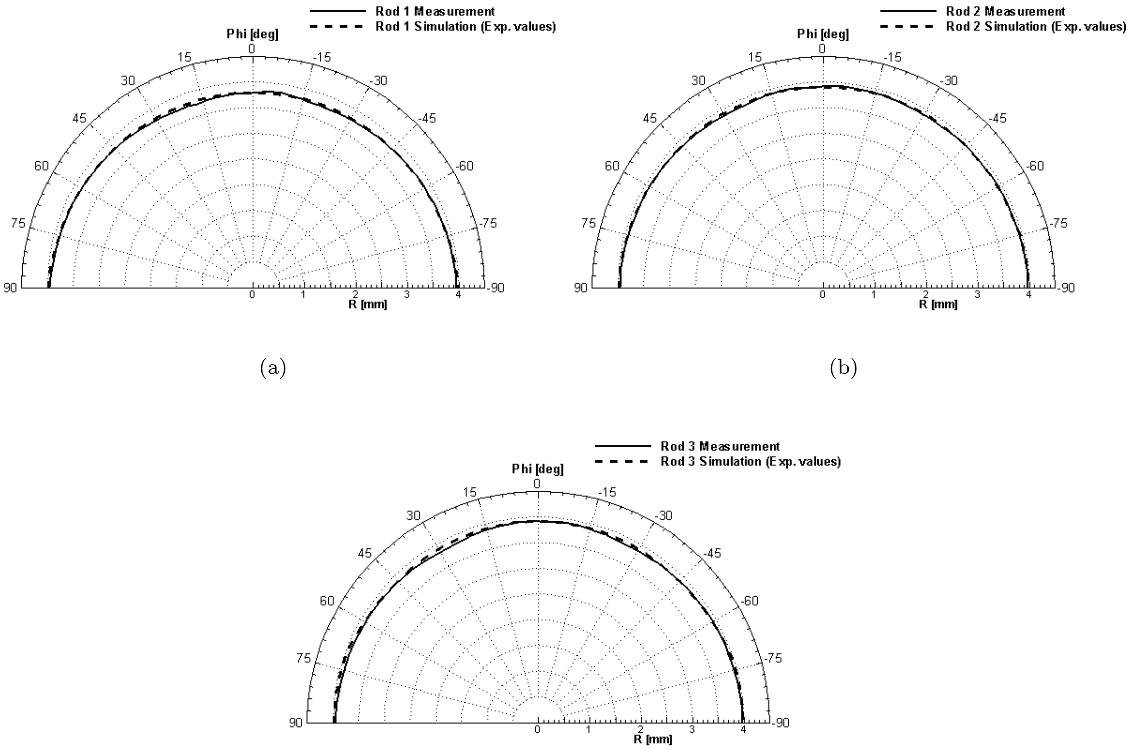

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Figure 7. Comparison between measured rod profiles and simulations using extracted f and Σ values

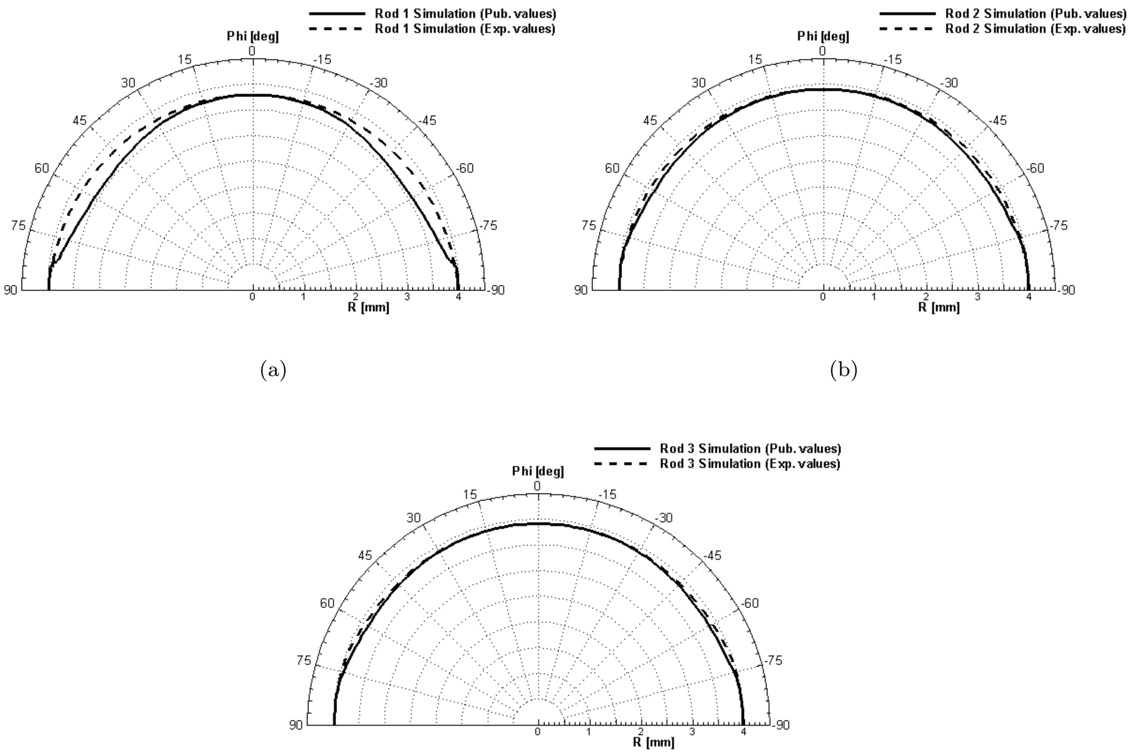

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Figure 8. Comparison between simulations using published and extracted f and Σ values