# Validation of FD-TD Modeling of the Radar Cross Section of Three-Dimensional Structures Spanning Up to Nine Wavelengths

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Abstract—The first experimental validation is reported of the finite-difference time-domain (FD-TD) method for modeling the monostatic radar cross section (RCS) of three-dimensional conducting structures. The structures modeled and tested span up to nine free-space wavelengths ( $k_0s = 57$ ). This represents a thirty-fold increase in electrical size over the previous analytically validated case of FD-TD modeling of radar cross section. It appears that the cases studied represent the largest detailed three-dimensional numerical scattering models of any type ever verified wherein a uniformly fine spatial resolution and the ability to treat nonmetallic composition is incorporated in the model. It was found that FD-TD provided a high modeling accuracy of 1 dB (with respect to the measurements) over at least a 40-dB dynamic range of radar cross section values for the nine-wavelength size objects, which exhibited such scattering physics as edge and corner diffraction, corner reflection (double bounce), and cavity penetration.

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### I. INTRODUCTION

General electromagnetic scattering problems have been difficult to treat with either analytical or numerical methods because of the complicating effects of curvatures, corners, apertures, and dielectric loading of structures. In an attempt to gain insight into scattering mechanisms using analytical and numerical approaches, it has been necessary to use canonical structures, rather than realistic models. One potential alternate approach which permits more realistic modeling of scattering problems is the finite-difference time-domain (FD-TD) method [1]-[9]. This approach permits a detailed treatment of general threedimensional scattering problems in the resonant range and above.

FD-TD is a direct solution of Maxwell's time-dependent curl equations for the electric and magnetic fields at a regular lattice of points covering a volume of space that contains a scatterer. A fully explicit numerical algorithm is used to simulate realtime wave propagation and scattering. Field boundary conditions at adjacent dissimilar media are automatically satisfied by the curl equations analog. The radiation condition is not inherent, and must be formulated separately to work properly in the near field and in the time domain. Sinusoidal steady-state results can be obtained for a sinusoidal wave source in the limit as the number of time steps is made sufficiently large. The latter approach can be viewed as being an iterative solution to the time-harmonic Maxwell's equations.

This communication reports the first experimental validation of the FD-TD method for modeling the monostatic radar cross section (RCS) of three-dimensional conducting structures. The structures modeled and tested span up to nine free-space wavelengths ( $k_0 s = 57$ ). This represents a thirtyfold increase in electrical size over the previous analytically validated case of FD-TD modeling of radar cross section [9]. The results indicate that FD-TD provided a high modeling accuracy of 1 dB (with respect to the measurements) over at least a 40-dB dynamic range of radar cross section values for the nine-wavelength size objects, which exhibited such scattering physics as edge and corner diffraction, corner reflection (double bounce), and cavity penetration.

## II. MODELS AND MEASUREMENT PROCEDURE

Three canonical conducting structures were modeled and tested for radar cross section. The first was a flat, rectangular plate with the dimensions 30 cm X 10 cm X 0.65 cm. The second was a crossed-plate scatterer comprised of two flat plates electrically bonded together to form the shape of a "T." The main plate had the dimensions 30 cm X 10 cm X 0.33 cm, and the bisecting fin had the dimensions 10 cm X 10 cm X 0.33 cm. The third scatterer was a hollow square cylinder comprised of four flat plates, each having the dimensions 30 cm X 10 cm X 0.33 cm, and provided with mitered edges to permit easy electrical bonding. Thus, the overall cylinder was 30 cm X 10 cm X 10 cm, with 0.33-cm thick walls.

International, Menlo Park, CA. Over this frequency range, the of the incident wave. three scatterers spanned from one to nine free-space wavelengths.

The SRI measurements were quasimonostatic in that two horn antennas (one transmitting and one receiving) were placed

SRI has determined that this arrangement approximates the monostatic results to a high accuracy, and improves the measurement dynamic range substantially. It should be noted that the numerical models to be discussed incorporate the actual bistatic angles used by SRI.

At each look angle and microwave center frequency  $f_0$ , SRI performed separate measurements at the frequencies  $f_0$  – 40 MHz;  $f_0 - 20$  MHz;  $f_0$ ;  $f_0 + 20$  MHz; and  $f_0 + 40$  MHz by stepping a programmable oscillator. This was done to provide a range of measured data indicative of the uncertainty introduced by SRI's "software bridge" technique for nulling the anechoic chamber wall reflections. All experimental results in this communication will therefore show uncertainty bars which correspond to the range of SRI data at each look angle for the five closely spaced frequencies clustered about each microwave center frequency.

The SRI look angle variation was not performed continuously. Instead, measurements of radar cross section were made only for discrete angular steps of the azimuth. The step size was selected prior to an experimental run to provide adequate detail of the principal expected features of the scattering pattern.

#### III. THE FLAT-PLATE SCATTERER

Fig. 1 depicts the geometry of the flat-plate scatterer and illumination, which is a plane wave at 0° elevation angle and TM polarization. For the 9-GHz FD-TD model, a FD-TD lattice cell size of 0.3125 cm was selected. This is approximately equal to 1/11 free-space wavelength. The flat plate was modeled by 96 X 32 X 2 cells embedded in an overall lattice of 112 X 48 X 18 cells (580 608 unknown field components). Six hundred and sixty one time steps, equivalent to 31 cycles of the incident wave at 9 GHz, were used.

Fig. 2 compares the FD-TD predictions with the SRI experimental results for the radar cross section versus the azimuth of the look angle. It is seen that the agreement is within about 1 dB over a 24-dB dynamic range (ratio of the maximum RCS feature to the minimum RCS feature as the look angle is varied). The azimuths of the peaks and nulls of the RCS pattern are accurately predicted to within 1°.

#### IV. THE CROSSED-PLATE SCATTERER

Fig. 3 depicts the geometry of the crossed-plate scatterer and illumination, which is a plane wave at 0° elevation angle and TE polarization relative to the main plate. Note that look angle azimuths between 90° and 180° provide substantial corner reflector physics, in addition to the edge diffraction, corner diffraction, and other effects found for the flat plate.

For the 9-GHz FD-TD model, a FD-TD lattice cell size of 0.3125 cm was again selected, approximately 1/11 free-space wavelength. The main plate was formed by 32 X 96 X 1 cells the bisecting fin was formed by 32 X 32 X 1 cells; and the overall lattice was comprised of 48 X 112 X 48 cells (1 548 288 unknown Measurements of the quasimonostatic radar cross section field components). The slightly eccentric positioning of the biversus look angle azimuth were performed in a calibrated anechoic secting fin was accounted for in the FD-TD model. Six hundred chamber at the center frequencies 1, 3, and 9 GHz by SRI and sixty one time steps were again used, equivalent to 31 cycles

Fig. 4 compares the FD-TD predictions with the SRI experimental results at 9 GHz for the radar cross section versus the azimuth of the look angle. It is seen that the agreement is within about 1 dB over a total RCS-pattern dynamic range of 40 dB. at symmetric ±5° bistatic angles with respect to the azimuth. Locations of peaks and nulls of the pattern are accurately pre-

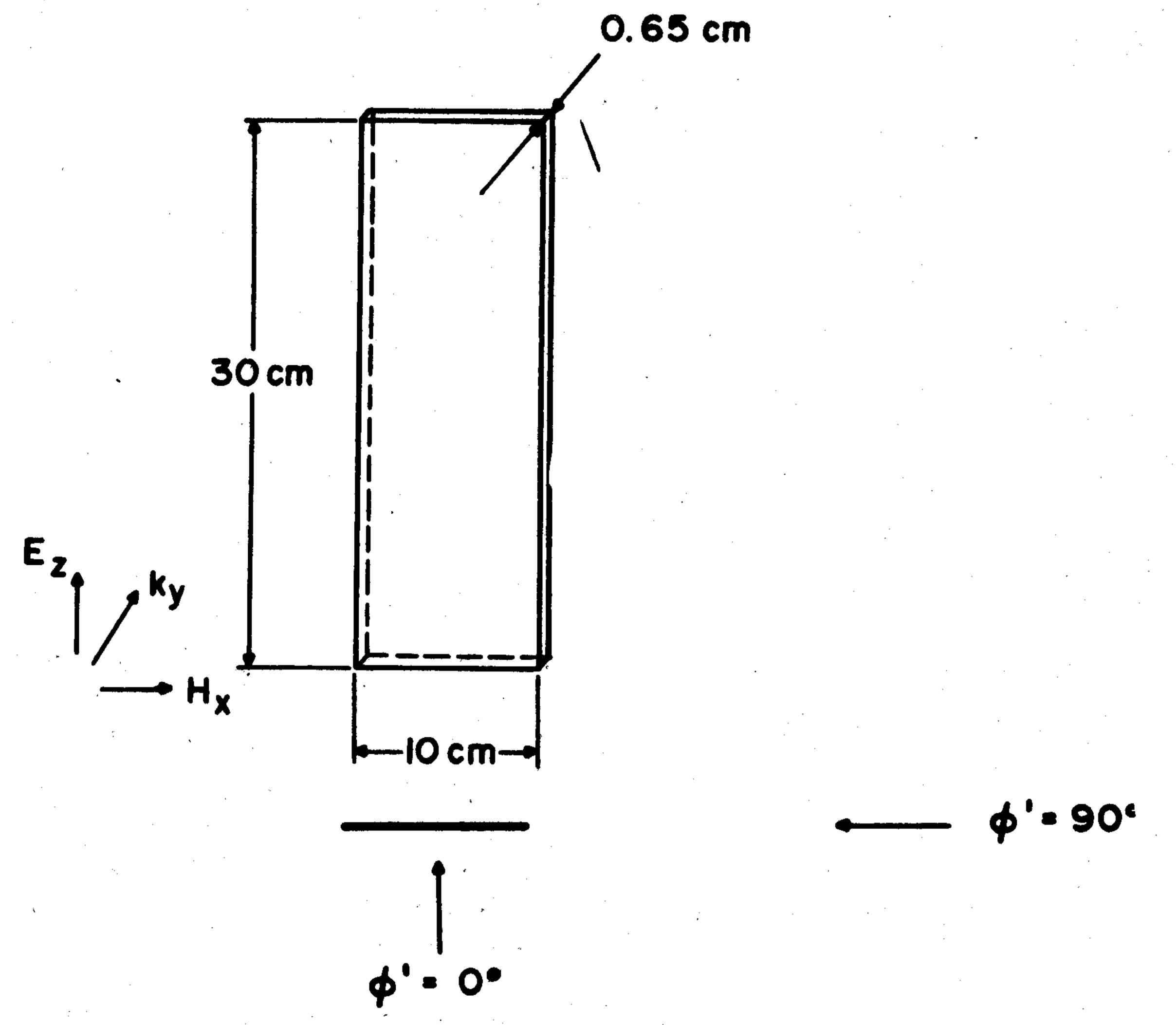


Fig. 1. Geometry of flat-plate scatterer and illumination.

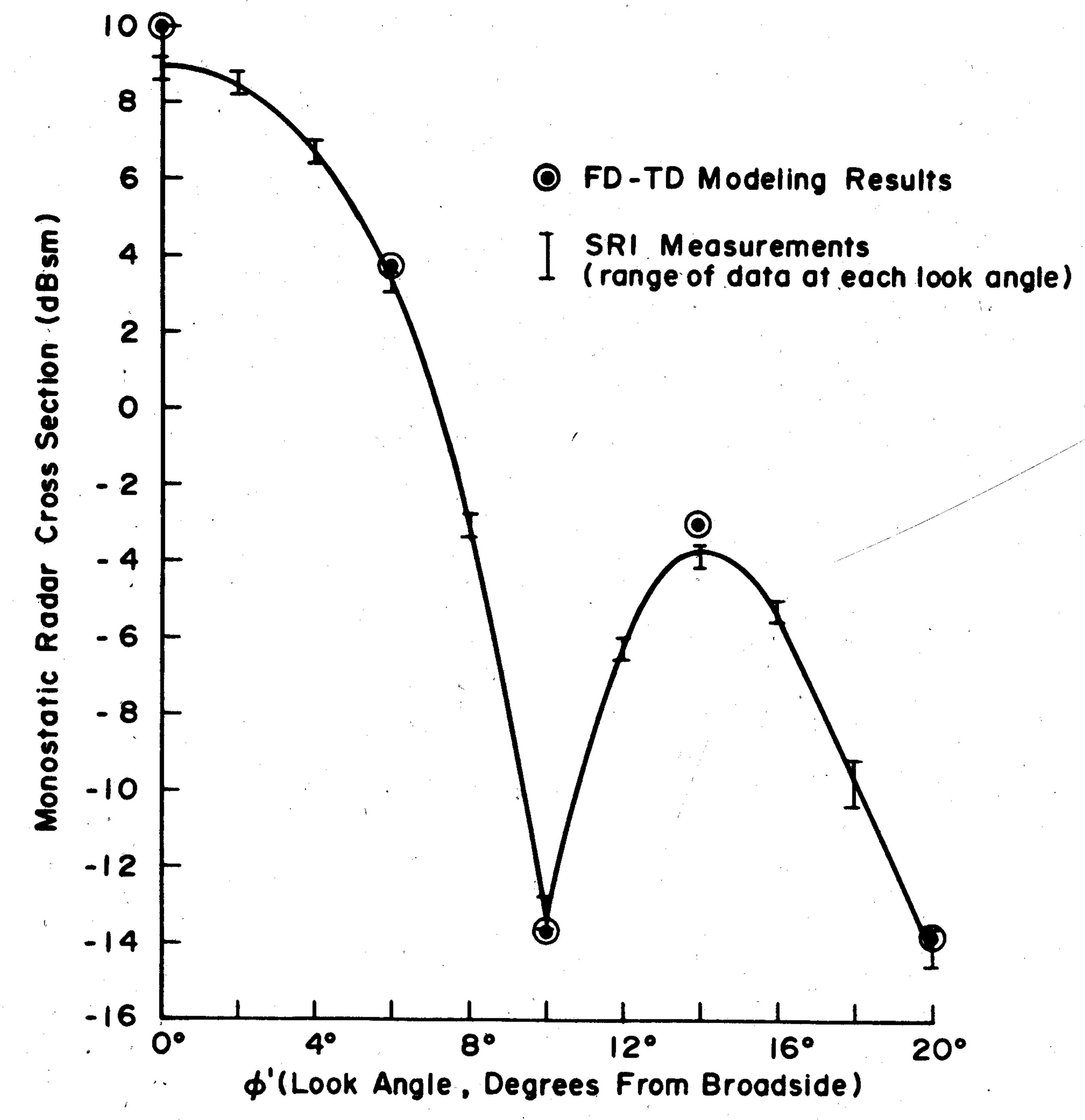


Fig. 2. Comparison of FD-TD modeling predictions with SRI measurements for the flat-plate scatterer at 9 GHz (scatterer size =  $9 \lambda_0$ ).

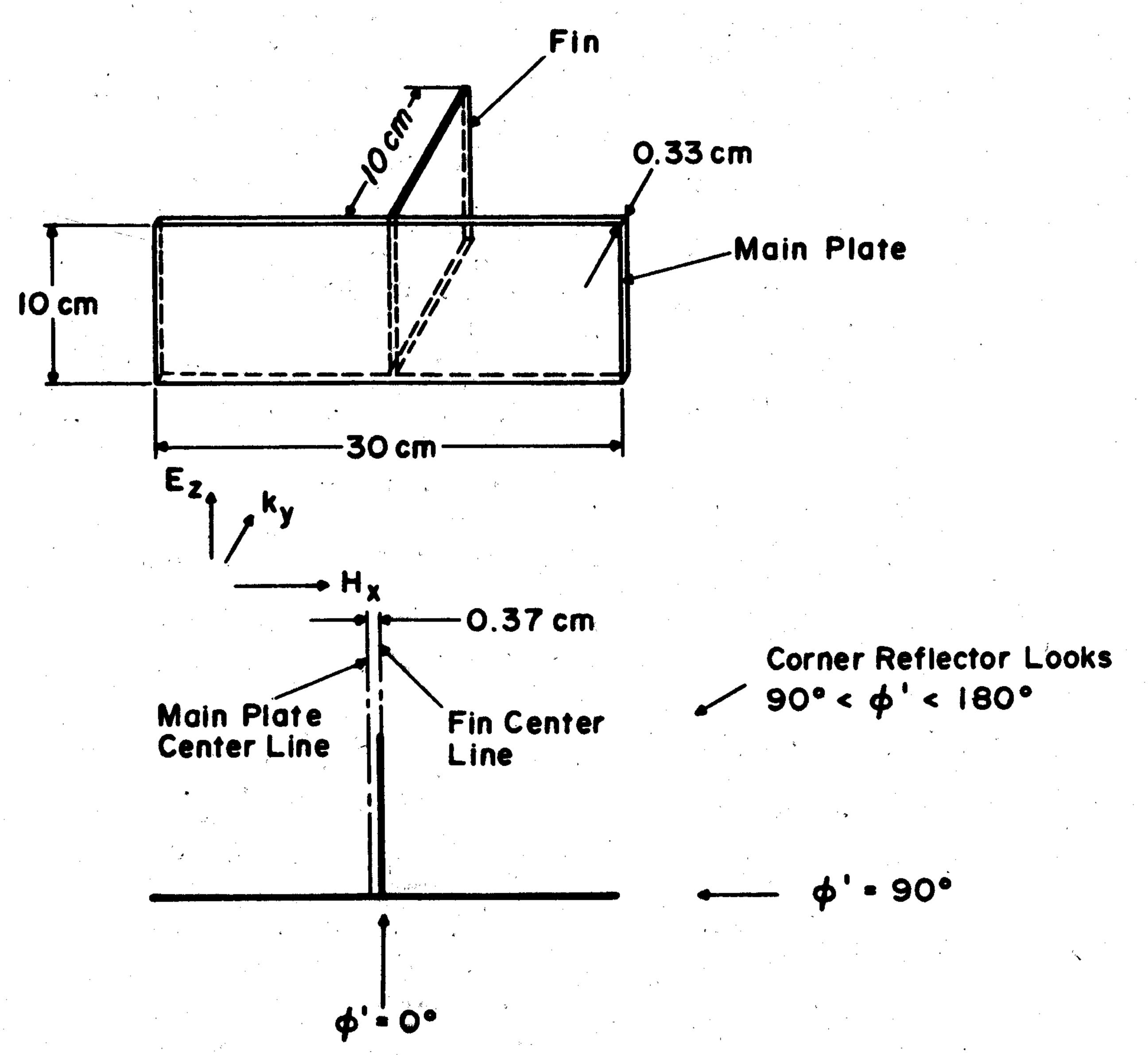


Fig. 3. Geometry of crossed-plate (T) scatterer and illumination.

dicted to within 1°. Note especially the excellent agreement for the look angle azimuths greater than 90°, where there is a pronounced corner-reflector effect. The observed accuracy of 1 dB here is comparable to that of the flat-plate model of Figs. 1 and 2.

#### IV. THE HOLLOW SQUARE CYLINDER SCATTERER

Fig. 5 depicts the geometry of the hollow square cylinder scatterer and illumination, which is a plane wave at 0° elevation angle and TM polarization relative to the cylinder. Note that this geometry provides substantial cavity-penetration physics and corner-diffraction physics in addition to edge diffraction and other effects.

For the 9-GHz FD-TD model, a FD-TD lattice cell size of 0.3125 cm was again selected, approximately 1/11 free-space wavelength. Each cylinder wall was formed by 96 × 32 × 1 cells, and the overall lattice size was 112 × 48 × 48 cells (1 548 288 unknown field components). Six hundred and sixty one time steps were again used, equivalent to 31 cycles of the incident wave.

Fig. 6 compares the FD-TD predictions with the SRI experimental results at 9 GHz for the radar cross section versus the azimuth of the look angle. Overall agreement is within about 1 dB at each look angle modeled, an accuracy level comparable to that of the flat-plate and crossed-plate models discussed previously.

#### V. DISCUSSION

Benchmark runs of FD-TD for the crossed-plate and hollow-cylinder scatterers presented above show that the required computer time per look angle for the 9-GHz (nine-wavelength) models is as shown in Table I.

Note that the range of computation time per look angle (circa 1984) varies over a 4800 to 1 range, depending upon the type of computer used and the degree of optimization of the FD-TD code. It is clear that present FD-TD software requires the use of a supercomputer to permit modeling multiple looks at a nine-wavelength scatterer with acceptably small turn-around times. Yet, because computing capabilities are expanding, it is clear that present FD-TD codes will become eminently practical for this size object by 1990. Equivalently, modeling larger three-dimensional scatterers spanning up to about 50 wavelengths will be feasible by 1990 (execution times of 1 h or less, using present FD-TD codes).

Computer storage requirements of FD-TD can be compared to those of the well-known method of moments (MM) triangular surface-patching approach [10]. A detailed convergence study of this MM technique for the case of the flat-plate scatterer is reported in [11]. There, it was determined that the spatial resolution of each triangular patch should be less than 0.25 wavelength for proper convergence of the radar cross section for the case of the electrically large scatterer. Consider the case of the hollow square cylinder at 9 GHz. Assuming that the cylinder wall thickness of 0.33 cm (0.1 wavelength) necessitates a thick-plate MM model, it can be shown that 0.25-wavelength resolution of the triangular patches implies a total of 7104 patches needed to specify the cylinder geometry. Consequently, a complex-valued MM system matrix of order  $1.5 \cdot 7104 = 10656$ must be filled and inverted. This matrix would have 1.14.108 complex numbers as elements, a factor of 150 times more storage than the FD-TD requirement of 1.5·10<sup>6</sup> real numbers. If the cylinder is not empty, but in fact filled with arbitrary media,

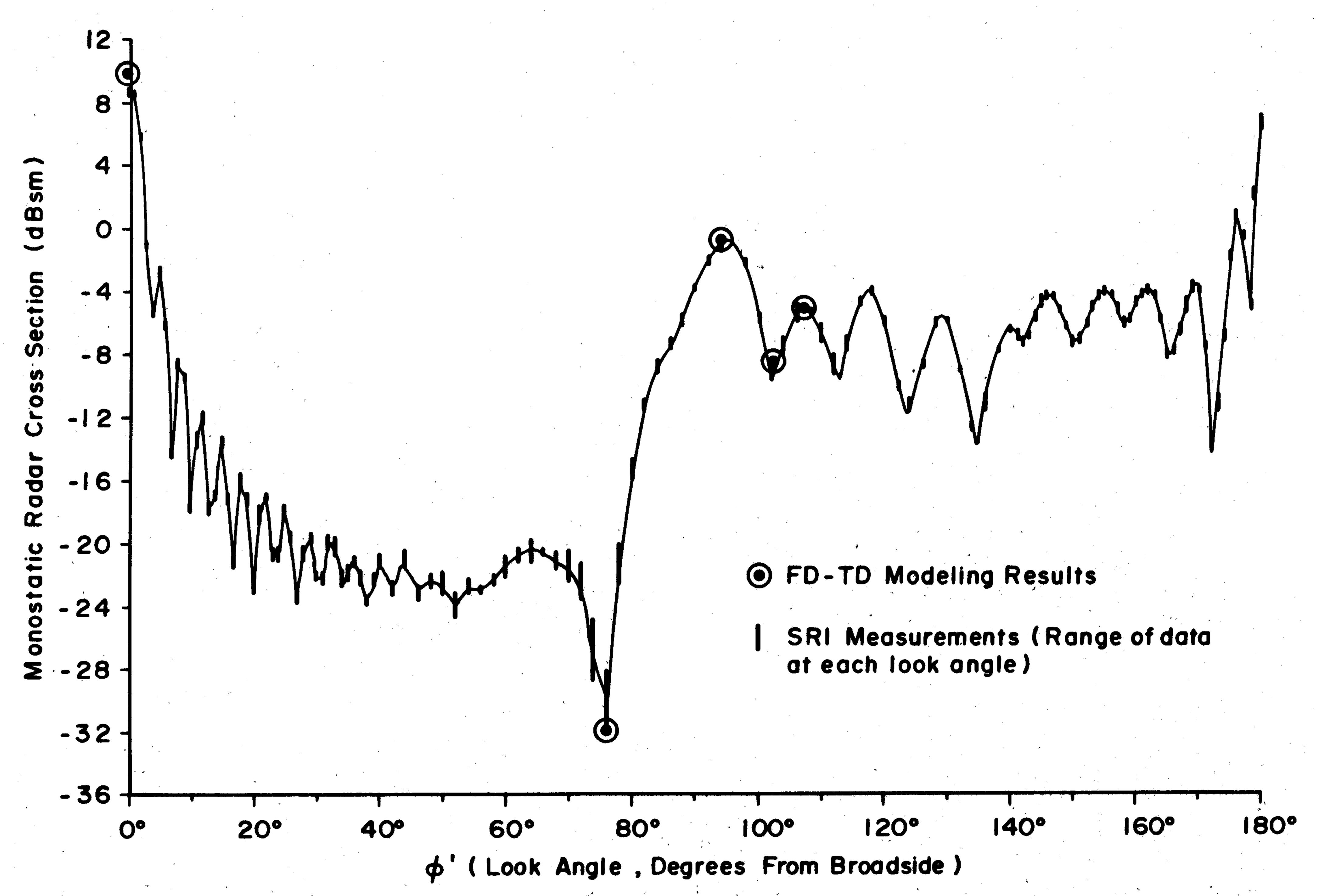


Fig. 4. Comparison of FD-TD modeling predictions with SRI measurements for the crossed-plate scatterer at 9 GHz (maximum scatterer size =  $9 \lambda_0$ ).

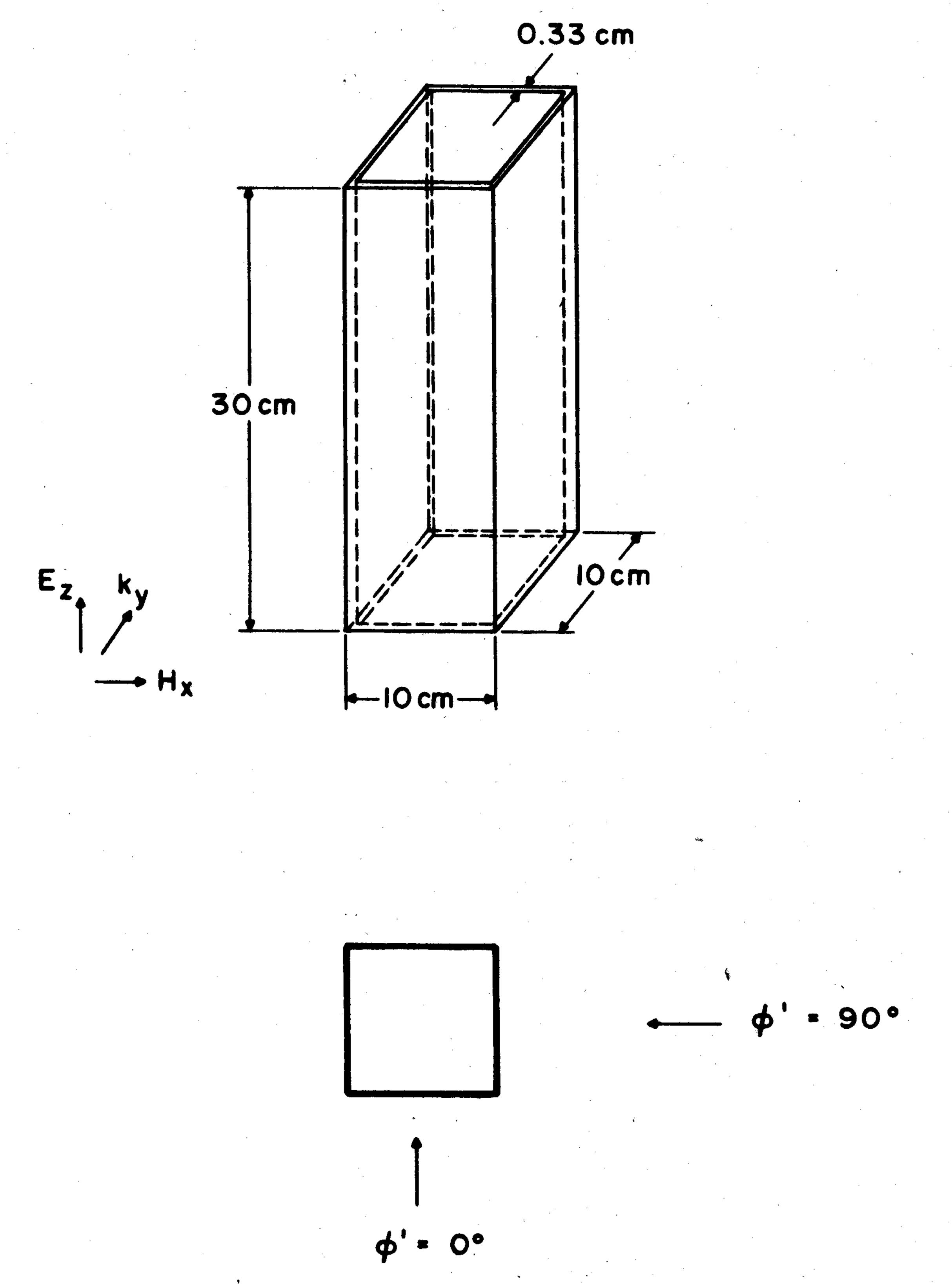


Fig. 5. Geometry of hollow square cylinder and illumination.

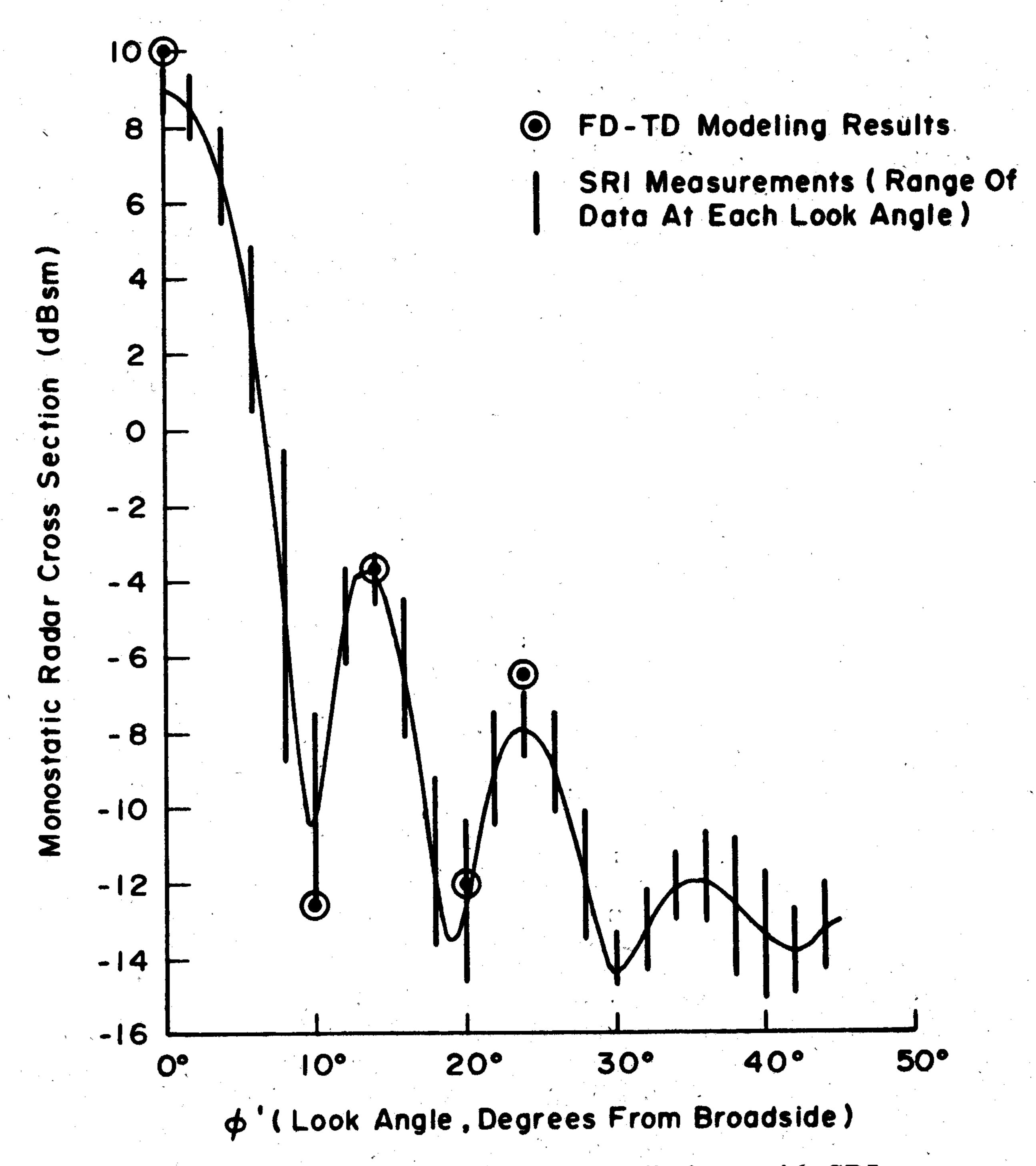


Fig. 6. Comparison of FD-TD modeling predictions with SRI measurements for the hollow square cylinder at 9 GHz (maximum scatterer size =  $9 \lambda_0$ ).

# TABLE I COMPUTATION TIMES

Machine	9-Wavelength Model Present FD-TD Code
VAX 11/780 (no floating point accelerator)	40.0 h
Cray-1S (using the VAX Fortran	24.0 min
Cray-1S (optimized code)	6.0 min
Cray X-MP (2 processors, optim	ized code) 2.0 min
Cray-2* (4 processors, optimiz	ed code) 0.5 min
True 10 GFlop ** (optimized cod	e) 2.0 s

Available late 1984; benchmark is estimated.

the number of MM patches would increase, whereas FD-TD storage would be *unchanged* if the interior cylinder loading could be specified without having to reduce the lattice cell size of 0.3125 cm.

#### VI. CONCLUSION

The FD-TD computational modeling approach has been shown to yield highly accurate predictions of radar cross section for three-dimensional conducting structures spanning up to nine free-space wavelengths, and exhibiting such scattering physics as edge and corner diffraction, corner reflection, and cavity penetration. FD-TD has demonstrated 1 dB accuracy over at least a 40 dB dynamic range relative to reliable anechoic chamber measurements. It appears that the cases studied represent the largest detailed three-dimensional numerical scattering models of any type ever verified wherein a uniformly fine spatial resolution and the ability to treat nonmetallic composition is incorporated in the model.

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<sup>\*\*</sup>Available 1990; benchmark is estimated.