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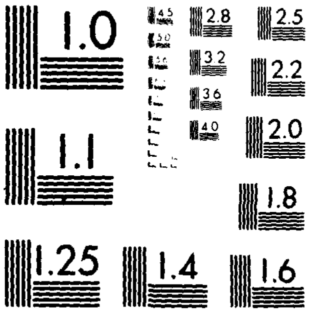

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THEORETICAL INVESTIGATION OF ABSORPTIVE PROCESSES

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With the ultimate goal of developing computer codes for obtaining the transmission and reflection properties of conductive particle clouds, progress is described in both the computation of electromagnetic cross sections of conductive fibers, and the radiative transfer effects governing the behavior of clouds of such fibers.

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1. SUMMARY

The ultimate goals of this program are to develop both theory and computer codes for (1) obtaining the electromagnetic cross sections of thin conductive fibers, and (2) for evaluating the reflection and transmission matrices appropriate to radiative transfer, and (3) to integrate this work into a single computer code capable of evaluating the reflection and transmission properties of a cloud of such fibers under a wide variety of conditions.

Significant progress has been made in the first two areas during the year just completed. For the electromagnetic scattering problem, the earlier computer code has been modified to use more accurate trial functions for the induced currents in the fibers, and also a complete expression for the surface impedance. In the radiative transfer work, the exact low of reflection for the eigenfields has been discovered, and this in turn leads to a closed-form solution for the reflection and transmission matrices which should be extremely useful in the program. These results are discussed in more detail below.

2. ELECTROMAGNETIC PROPERTIES OF CONDUCTIVE FIBERS

The purpose of this task is to develop the theory and computer codes for evaluating the electromagnetic cross sections of highly elongated conductive fibers. In April 1980, at the end of the previous program year, a technical report was submitted to the Chemical Systems Laboratory detailing the theoretical and computational situation as it stood at that point.[1] Below we will summarize the further progress that has been made, including a few representative computations, and point out the areas where additional work must be done in order that the computer codes may be employed with full confidence over the entire range of parameters desired. For more technical detail, the reader should consult the earlier report,[1] of which copies are enclosed.

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[1] Jeanne Pedersen and Norman Pedersen, "Electromagnetic Theory of Scattering and Absorption by Finite Conducting Fibers," Technical Report, Panametrics, Inc.

Figure 1 shows the results of a typical computation as it stood in April 1980. The electromagnetic cross sections are plotted (log-log scale, MKS units throughout) vs. wavelength over the range from 0.1 to 100 microns, for a specified radius, length, and conductivity of the target fiber. Results of the 1965 (Rayleigh) theory are included, in this and the following figures, purely for comparative purposes.

The main feature to note in this figure is the oscillatory behavior of the cross sections at the shorter wave lengths, which was regarded at the time as probably incorrect. In addition, one observes that the absorption cross section (solid curve) exceeds the extinction cross section (single dash broken line) in this region, a clear violation of energy conservation requirements.

These difficulties were attributed to the fact that a fixed trigonometric representation was being used for the current in the fiber, and such a representation was not adequate to describe the situation for fibers too long compared to wavelength (although one should note that no difficulties arise in the example shown, provided $k\ell \lesssim 3.5$). It was thus decided to use a series of functions to represent current. The corresponding theory has been described earlier,[1] and leads to a set of non-linear algebraic equations to be solved.

As our first approximation to solving the latter, only that function was selected which was expected to most nearly represent the current. This function involves trigonometric functions of argument nkz, where z represents position of the fiber, and is dependent upon total length ℓ of the fiber, in that n is chosen as

$$n = \text{Nearest integer to } (k\ell + 1). \qquad (1)$$

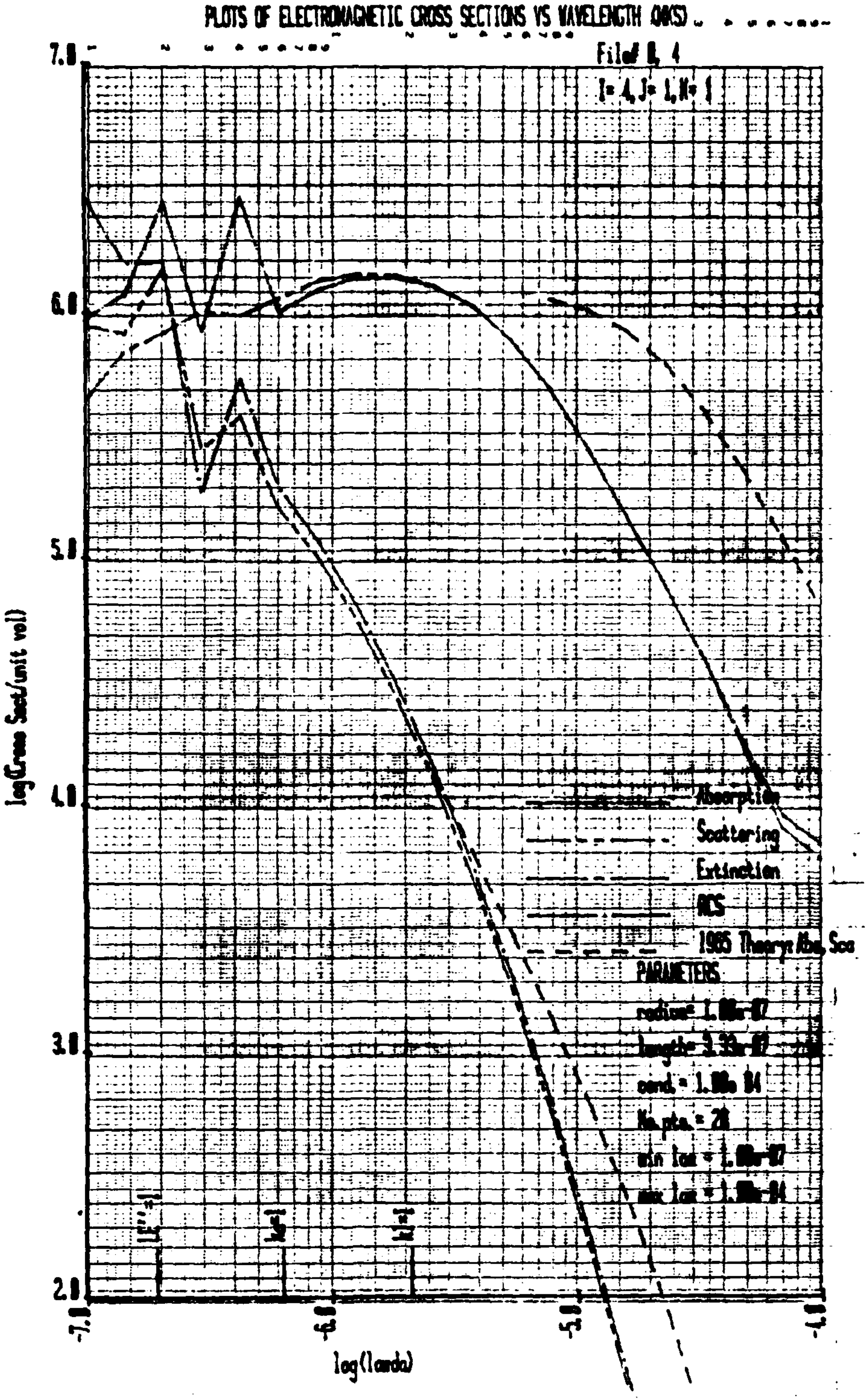

Figure 1. The electromagnetic cross sections as computed vs. wavelength (MKS units) for an elongated conductive fiber with dimensions and conductivity as indicated. These early results show spurious oscillations and failure to satisfy energy balance at the shorter wavelengths.

Specifically, we take

$$I(z) = Af_{cn}(z) + Bf_{sn}(z), \tag{2a}$$

where

$$f_{cn}(z) = \cos nkz \cos nqk\ell - \cos nk\ell \cos nqkz,$$

$$f_{sn}(z) = \sin nkz \sin nqk\ell - \sin nk\ell \sin nqkz, \tag{2b}$$

with $q = \cos\theta_i$ (θ_i is the angle of incidence on the fiber, measured from end-on aspect). The constants A and B are then determined from the variational computation.

Results from this modification are shown in Fig. 2. There is of course no change from Fig. 1 at the longer wavelengths, because Eq. (1) has not yet introduced any changes. At the shorter wavelengths, however, we see that the oscillations are greatly reduced, and the energy balance requirement

$$\sigma_{ex} = \sigma_{abs} + \sigma_{scat} \tag{3}$$

is now fairly well met.

One further refinement has been introduced, by taking into account a more complete expression for the surface impedance of the fiber. The appropriate equations to employ were discussed in the earlier report,[1] and are as follows: for the impedance, one takes

$$Z = \frac{\omega}{\hat{\sigma}} \frac{I_1(wa)}{I'_1(wa)} \tag{4a}$$

where

$$\hat{\sigma} \equiv \sigma + i\omega\epsilon,$$

$$w = (k^2 \cos^2\theta_i + i\sigma\mu\omega)^{1/2}. \tag{4b}$$

Here I_1 and I'_1 are the modified Bessel function and its derivative with respect to argument wa, and σ, ω, a are conductivity, dielectric constant, and radius of the fiber, respectively.

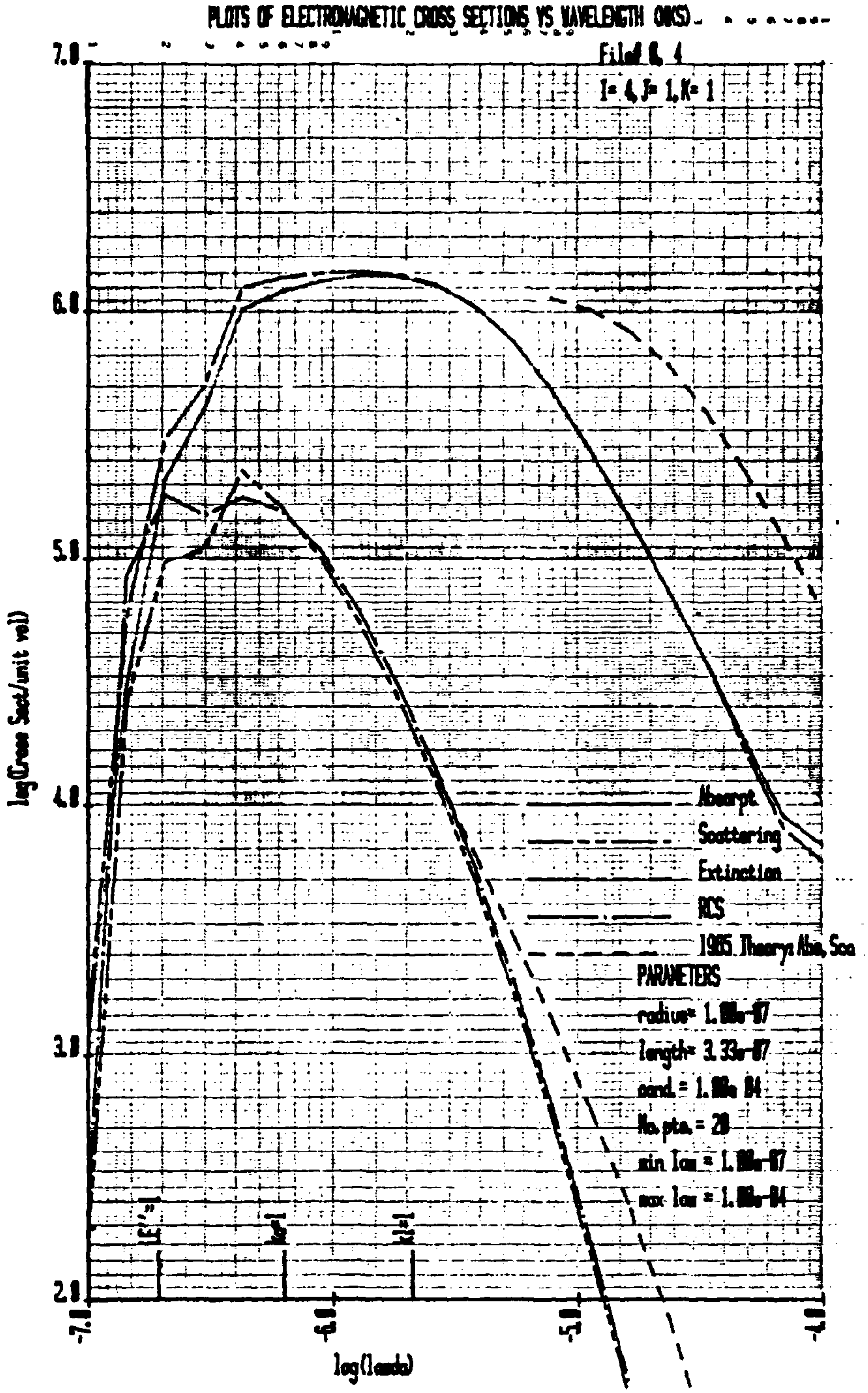

Figure 2. The electromagnetic cross sections of Fig. 1 are recomputed using an improved trial function for the induced currents (see text). Oscillations at the shorter wavelengths have almost disappeared, and energy balance requirements are now being met.

With this change, the computation yields results as shown in Fig. 3. As one can see, the oscillations have now vanished completely in all cross sections, and the energy constraints of Eq.(2) appear to be accurately met. Note also that the scattering and radar cross sections have developed peaks in the vicinity of 0.4 microns. In order to confirm that this peaked behavior, as well as the sharp drop-off in all cross sections at shorter wavelengths, are real effects, further study will be made of effects of keeping additional terms in the non-linear equations.[1] Independent confirmation of the computer code will also be sought, by examining alternative theoretical procedures and, if applicable, any existing experimental measurements.

Finally, we note that during the program year Dr. Galen Daum of the Chemical Systems Laboratory employed results of one of our computer codes to compare with experimental data, and found good agreement in those cases for which measurements were available.

3. RADIATIVE TRANSFER IN PARTICLE CLOUDS

The purpose of this task is to develop both theory and computer codes for treating the problem of radiative transfer through a cloud of elongated conductive fibers, in order to obtain the transmission and reflection properties of such a medium. The theoretical approach employs the matrix-exponential operator to obtain results in either analytical or numerical form.

The basic theory was completed and submitted to the Journal of the Optical Society of America in August of 1980, with copies sent to the Chemical Systems Laboratory. This work was then further revised.[2] One aspect of the revision, copies of which are enclosed, dealt with showing

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[2] P. C. Waterman, "Matrix Exponential Description of Radiative Transfer," Technical Report, Panametrics, Inc. Also J. Opt. Soc. Am. 71, 410-422 (1981).

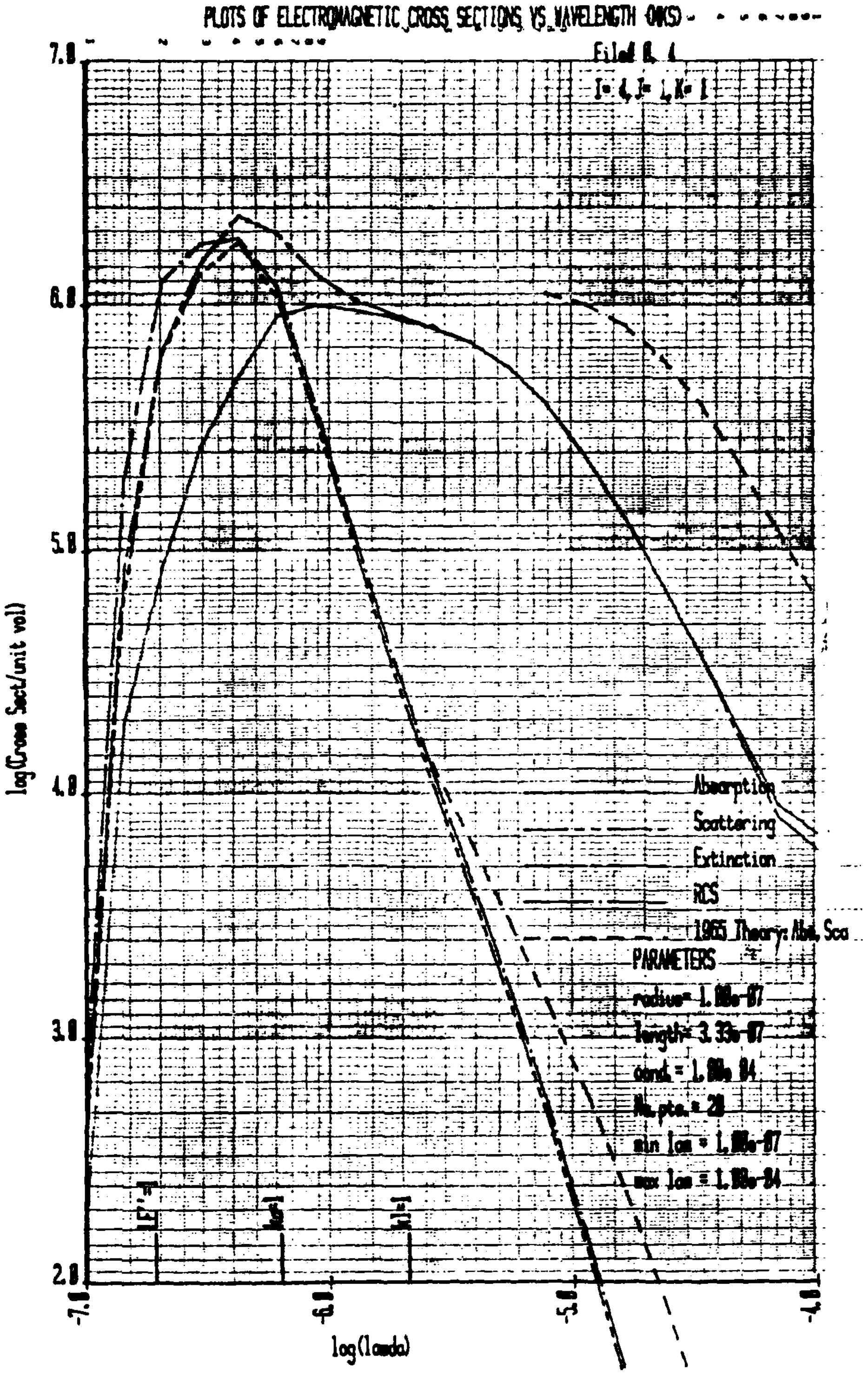

Figure 3. The electromagnetic cross sections as obtained with the latest form of the computer code, which utilizes the complete form of the expression for surface impedance. Note that energy balance requirements are met, and the spurious oscillations evident in Figs. 1 and 2 have now completely disappeared.

the relationship between this method and the non-linear matrix differential equations that result using invariant imbedding techniques.[3] More important was the discovery of the exact law of reflection for the Chandrasekhar eigenfields at a free space interface. This law enables one to give a simple physical interpretation of the iterative solutions for the transmission and reflection matrices. Reprints of the April 1981 journal article will be enclosed if available in time.

One further aspect of the basic work is being explored. It has been found that, using the law of reflection, closed-form expressions for transmission and reflection can be derived and the relationship to the iterative solutions demonstrated. A preliminary report on this aspect of the work will be given at the June 1981 C.S.L. Conference, and a technical report completed shortly thereafter.

The iterative and closed-form solutions will be employed to check the validity and accuracy of the numerical solution, computer codes for which will be developed during the next program year. As discussed earlier,[2] the computer computation will proceed by first performing a numerical evaluation of the matrix exponential. The results will then be used as starting values for the transmission and reflection matrices, and the doubling method employed to extend the results to any desired optical depth. This method appears to be extremely efficient, and should also integrate well with the computer codes for electromagnetic cross sections of fibers.

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[3] R. Bellman, R. Kalaba and G. M. Wing, Invariant imbedding and mathematical physics. I. Particle processes. J. Math. Phys. 1, 280-308 (1960).