

AD-A189 277

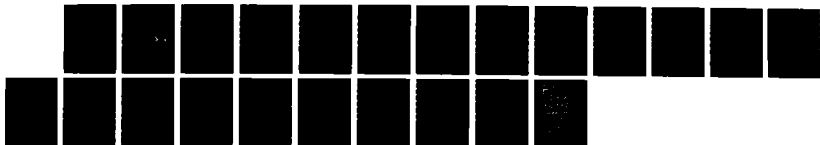
THEORY AND SIMULATION OF THE RAYLEIGH-TAYLOR
INSTABILITY IN THE LARGE LARMOR RADIUS LIMIT (U) NAVAL
RESEARCH LAB WASHINGTON DC J D HUBA ET AL. 29 DEC 87
NRL-MR-6070

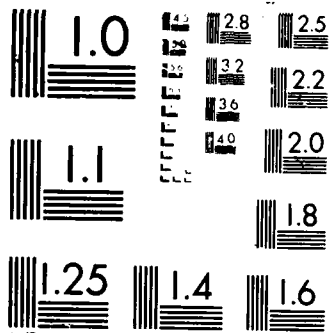
1/1

UNCLASSIFIED

F/G 20/9

ML





AD-A189 277

NRL Memorandum Report 6070

Theory and Simulation of the Rayleigh-Taylor Instability in the Large Larmor Radius Limit

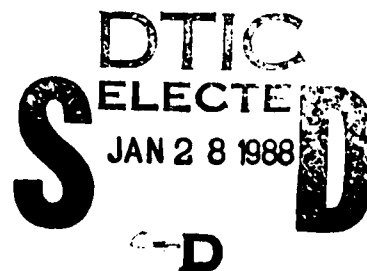
J.D. HUBA, J.G. LYON, AND A.B. HASSAM*

*Geophysical and Plasma Dynamics Branch
Plasma Physics Division*

**University of Maryland
College Park, MD 20742*

and

*SAIC
McLean, VA 22102*



December 29, 1987

This report was sponsored by DNA under "Weapons Phenomenology and Code Development,"
Work Unit Code and Title: RB RC/00158, Plasma Structure Evolution.

Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No 0704 0188	
1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION AVAILABILITY OF REPORT		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			Approved for public release; distribution is unlimited.		
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6070			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
6a NAME OF PERFORMING ORGANIZATION Naval Research Laboratory		6b OFFICE SYMBOL (if applicable) Code 4780	7a NAME OF MONITORING ORGANIZATION		
6c ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000			7b ADDRESS (City, State, and ZIP Code)		
8a NAME OF FUNDING/SPONSORING ORGANIZATION Defense Nuclear Agency		8b OFFICE SYMBOL (if applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20305			10 SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO 62715H	PROJECT NO S99QMXBC-	TASK NO 00102
			WORK UNIT ACCESSION NO DN580-072		
11 TITLE (Include Security Classification) Theory and Simulation of the Rayleigh-Taylor Instability in the Large Larmor Radius Limit					
12 PERSONAL AUTHOR(S) Huba, J.D., Lyon, J.G., and Hassam,* A.B.					
13a TYPE OF REPORT Interim		13b TIME COVERED FROM _____ TO _____		14 DATE OF REPORT (Year, Month, Day) 1987 December 29	15 PAGE COUNT 22
16 SUPPLEMENTARY NOTATION (See page ii)					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Rayleigh-Taylor instability		
			Early time structure		
			Large Larmor radius limit		
19 ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>The theory and first nonlinear simulations of the Rayleigh-Taylor instability in the large ion Larmor radius limit (i.e., $\rho_i/L \gg 1$) are presented. It is shown that in the large Larmor radius limit, the Rayleigh-Taylor instability evolves much faster and in a dramatically different manner than in the small Larmor radius limit.</p>					
20 DISTRIBUTION AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a NAME OF RESPONSIBLE INDIVIDUAL J.D. Huba		22b TELEPHONE (Include Area Code) (202) 767-3630		22c OFFICE SYMBOL Code 4780	

16. SUPPLEMENTARY NOTATION

This report was sponsored by DNA under "Weapons Phenomenology and Code Development," Work Unit Code and Title: RB RC/00158, Plasma Structure Evolution.

*University of Maryland, College Park, MD 20742 and SAIC, McLean, VA 22102

CONTENTS

I. INTRODUCTION.....	1
II. THEORY.....	2
III. CONCLUSION.....	6
ACKNOWLEDGMENTS.....	7
REFERENCES.....	8

Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution	
Availability Codes	
Dist	Avail and/or Special
A-1	

Theory and Simulation of the Rayleigh-Taylor Instability in the Large Larmor Radius Limit

I. INTRODUCTION

Interchange instabilities, such as the Rayleigh-Taylor instability, have been the subject of intense scientific interest for most of this century.¹ Generically, an interchange instability can occur when two fluids of different densities are accelerated. Although initially studied in the context of hydrodynamic theory,² this type of instability has also been shown to exist in magnetized plasmas.³ Subsequently, plasma interchange modes have become an important area of research in the plasma physics community, and a considerable amount of work (theoretical, experimental, and computational) has been done over the past two decades. The bulk of the research has been motivated by the fusion research program, especially in regard to the stability of magnetically confined plasmas⁴ and imploding laser target pellets.⁵ However, there is also evidence that this type of instability can occur in space plasmas.⁶ Thus, interchange modes are relevant to a broad spectrum of plasma regimes.

The study of the Rayleigh-Taylor instability in a magnetized plasma has largely been confined to the regime $\rho_i/L \ll 1$ and $\omega/\Omega_i \ll 1$ where ρ_i and Ω_i are the ion gyroradius and gyrofrequency, respectively, and ω and L are the frequency and length scales of interest, respectively. Standard MHD theory can be used when $k\rho_i \ll 1$ (where k is the wavenumber) while finite-Larmor-radius (FLR) MHD theory is used when $k\rho_i \lesssim 1$.⁷ [Of course, use of kinetic theory can remove all restrictions on the value of $k\rho_i$.^{8,9}] However, space¹⁰ and laboratory^{11,12} experiments have observed plasma structure, apparently caused by the rapid deceleration of a plasma expanding into a strong magnetic field, in the parameter regime $\rho_i/L \gg 1$ and $\omega/\Omega_i \gg 1$ but $\rho_e/L \ll 1$ and $\omega/\Omega_e \ll 1$. Similar structure has also been observed in earlier plasma expansion experiments^{13,14} and in theta pinch implosion experiments¹⁵ in the regime $\rho_i/L \lesssim 1$ and $\omega/\Omega_i \lesssim 1$. The purpose of this Letter is to investigate, both analytically and computationally, the development of the Rayleigh-Taylor instability in the large ion Larmor radius regime (i.e., $\rho_i/L \gg 1$ and $\omega/\Omega_i \gg 1$). We show that in this regime the Rayleigh-Taylor instability develops much faster and has a dramatically different nonlinear behavior than the conventional Rayleigh-Taylor instability.

II. THEORY

A set of one-fluid, modified MHD equations has been derived which describes a plasma for arbitrary ρ_i/L or ω/Ω_i :^{16,17}

$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{u} = 0 \quad (1)$$

$$nM \frac{d\mathbf{u}}{dt} = -T\nabla n - \nabla B^2/8\pi + \mathbf{B} \cdot \nabla \mathbf{B}/4\pi + nM\mathbf{g} \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{Mc}{e} \nabla \times \frac{d\mathbf{u}}{dt} \quad (3)$$

where \mathbf{u} is the center of mass velocity, n is the density, \mathbf{B} is the magnetic field, M is the ion mass, and \mathbf{g} is the gravitational force. [With regard to plasma expansion experiments, we can identify the plasma acceleration with an effective gravitational acceleration, i.e., $d\mathbf{u}_0/dt = -\mathbf{g}_{\text{eff}}$]. Equations (1) - (3) are derived directly from the ion and electron Vlasov equations under the following assumptions. We assume (1) $\rho_e/L \ll 1$ and $\omega/\Omega_e \ll 1$ (i.e., the electrons are strongly magnetized), (2) the electron and ion pressure tensors are isotropic, (3) the electron and ion fluids are isothermal with $T = T_e + T_i$, and (4) the Debye length is very small. We mention that (1) - (3) are similar to a set of one-fluid MHD equations derived in Ref. 18 in the limit $T_i = 0$.

The final term in (3) is what makes these equations different from the conventional ideal MHD equations. In this representation it is clear that ion inertia is the origin of this term and that it is potentially important when $\omega/\Omega_i \gg 1$ (or $\rho_i/L \gg 1$). We also point out that (3) can be rewritten as

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times (\mathbf{j} \times \mathbf{B})/ne \quad (4)$$

so that the new term can be identified as the Hall term.

To study the linear evolution of the Rayleigh-Taylor instability in both the small and large Larmor radius limits, we consider the following slab geometry and plasma configuration. We assume $\underline{B} = B_0(x) \hat{e}_z$, $n = n_0(x)$, and $\underline{g} = g \hat{e}_x$. The equilibrium is given by $\partial/\partial x (n_0 T + B_0^2/8\pi) = n_0 M g$. We perturb (1) - (3) about this equilibrium and assume perturbations are proportional to $\exp [i(k_y y - \omega t)]$. We consider the "local" limit and require $k_y L_n \gg 1$ where $L_n = (\partial \ln n_0 / \partial x)^{-1}$ is the scale length of the density gradient. The dispersion equation is given by¹⁶

$$-\omega^4 / k_y^2 V_A^2 + (1 + \beta) \omega^2 - \left(\frac{g}{L_n} \right) \left(1 - \frac{\partial \ln B_0}{\partial \ln n_0} \right) + \frac{\rho_i}{L_n} \frac{1}{k_y C_S} \left(\omega^2 - k_y^2 g L_n \right) \omega = 0 \quad (5)$$

where $V_A = B/(4\pi n M)^{1/2}$ is the Alfvén velocity, $C_S = (2T/M)^{1/2}$ is the sound speed, $\rho_i = C_S/\Omega_i$, and $\beta = 8\pi n T/B^2$.

In the limit $\rho_i/L_n \rightarrow 0$ (i.e., conventional MHD theory) we recover from (5) the magnetosonic modes [$\omega^2 = k_y^2 V_A^2 (1 + \beta)$] and the usual Rayleigh-Taylor instability [$\omega^2 = g/L_n (1 - \partial \ln B_0 / \partial \ln n_0)$]. Instability can occur when $g/L_n < 0$ with the growth rate $\gamma_0 = (g/L_n)^{1/2}$. However, when $\rho_i/L_n \gg 1$, a faster growing mode can occur which has a growth rate determined by $\omega^2 = k_y^2 g L_n$.^{11,16} Again, instability can occur when $g L_n < 0$ but the growth rate is $\gamma = k_y (g L_n)^{1/2} = k_y L_n \gamma_0$; the turn-on condition for this mode is $(g/L_n) > \Omega_i^2/4$. Interestingly, for a magnetically confined plasma expansion in a low β plasma, the turn-on condition is independent of the magnetic field which is consistent with experimental observations.¹² Of further interest is the eigenmode structure. We note that when $\rho_i/L_n \gg 1$ and $\omega \sim k_y C_S$, then $\omega/\Omega_i \gg 1$ and the final term in (3) will be large unless $\hat{e}_z \cdot \nabla \times \underline{u} \rightarrow 0$. We use this fact in the equation obtained by taking the z component of the curl of (2) to get $-i\omega(\partial n_0/\partial x) \tilde{u}_y = ik_y g \tilde{n}$. From (1) we obtain $-i\omega \tilde{n} + in_0 k_y \tilde{u}_y + (\partial n_0/\partial x) \tilde{u}_x = 0$. But since $\hat{z} \cdot \nabla \times \underline{u} = 0$ we note that $ik_y \tilde{u}_x = 0$ so that $-i\omega \tilde{n} + in_0 k_y \tilde{u}_y = 0$. Thus, eliminating \tilde{n} and \tilde{u}_y from these equations we get $\omega^2 = k_y^2 g L_n$. The crucial point is that the fluid motion is primarily curl-free and not divergence-free (i.e., $\nabla \times \tilde{\underline{u}} = 0$ and $\nabla \cdot \tilde{\underline{u}} = ik_y \tilde{u}_y \neq 0$). This represents a behavior quite different from the conventional MHD Rayleigh-Taylor instability which is primarily divergence-free and not curl-free ($\nabla \cdot \tilde{\underline{u}} = 0$ and $\nabla \times \tilde{\underline{u}} \neq 0$).

This contrasting fluid behavior can also be seen by considering the following, simplified ion momentum equation in the limit $T \rightarrow 0$: $nM d\tilde{v}_i/dt = e(\tilde{E} + \tilde{v}_i \times \tilde{B}/c)$. In the latter case, when $\omega/\Omega_i \ll 1$, the dominant perturbed ion velocity is $\tilde{v}_i = -c\tilde{E} \times \tilde{B}/c$ which is divergence-free. In the former case, when $\omega/\Omega_i \gg 1$, the dominant perturbed ion velocity is $\tilde{v}_i = ie\tilde{E}/nM\omega$ which is curl-free. Thus, based upon this linear eigenfunction we anticipate that the nonlinear behavior of the unmagnetized and magnetized ion Rayleigh-Taylor instabilities will be quite different.

We now confirm this suspicion by presenting results of 2D numerical simulations of the Rayleigh-Taylor instability in both the small Larmor radius limit (i.e., magnetized ions) and the large Larmor radius limit (i.e., unmagnetized ions). We solve (1), (2), and (4) numerically on a cartesian grid with resolution 125×100 (x,y). We consider plasma motion only in the plane transverse to the magnetic field ($\tilde{B} = -B\hat{e}_z$). Hard wall boundary conditions were used in the x direction, while periodic boundary conditions were used in the y-direction. The algorithm used solves (1), (2), and (4) in conservation form using a Total Variation Decreasing (TVD) non-linear switch between a first order transport scheme and an Adams-Bashforth, centered 8th order spatial scheme.¹⁹ The following density profile was chosen $n_0(x) = 0.55 + 0.45 \tanh(x/L_2)$ for $x < 0$, and $n_0(x) = [0.55 + 0.45 \tanh(x/L_2)] \exp(-x/L_1)$ for $x > 0$, with $\tilde{g} = -g\hat{e}_x$ and $\tilde{B}(x)$ determined from equilibrium force balance. We choose $L_1 = 1.0$, $L_2 = 0.2$, $C_s = 1.0$, and $g = 1.0$. The length scale is normalized to $L_1 = 1.0$, the velocity is normalized to $C_s = 1.0$, and the time scale is normalized to $L_1/C_s = 1.0$. The boundaries used in the simulations are $x = -2.5$ and 2.5 , and $y = 0.0$ and 4.0 .

We benchmarked the code in the linear regime by initializing the grid with a single mode and calculating the eigenfunction and eigenvalue. For $\rho_i/L_2 = 0$ and $\lambda_x = .8$ we calculate the linear growth rate to be $\gamma \sim 1.70$ which agrees well with the theoretical value of $\gamma \sim 1.81$. In the nonlinear regime it is difficult to benchmark the code with previous results because the code is compressible and we treat a diffuse density profile (as opposed to a sharp boundary model). Nevertheless, we estimate the Froude number to be $F \sim 0.27$ which is in reasonable agreement with experimental²⁰ ($F \sim 0.2 - 0.3$) and numerical²¹ ($F \sim 0.23$) results. The initial conditions for the simulations discussed in the remainder of the Letter is a 1% random density fluctuation throughout the grid.

In Fig. 1 we show the density contours (Fig. 1a) and velocity vector field (Fig. 1b) for the Rayleigh-Taylor instability in the small Larmor radius limit (i.e., we use $\rho_i/L_2 = 0$) at $t = 5.5$. We show these results primarily for comparison with the Rayleigh-Taylor instability in the large Larmor radius limit. The following points should be noted. First, the instability initially develops in the region $x < 0.2$. The peak of the density at $t = 0$ is at $x = 0.2$ so that the linearly unstable regime is $x < 0.2$ where $g\partial \ln n_0/\partial x < 0$. As the instability evolves nonlinearly, we find that the usual 'spike' and 'bubble' morphology develops (see Fig. 1a).²² The 'heavy' material falls (i.e., the 'spike') while the 'light' material rises (i.e., the 'bubble'). In each case, a mushroom-like structure develops. Second, associated with the development of the mushroom-like heads is the development of counter-rotating vortices. This is evident in Fig. 2a. The fluid motion in the 'spikes' is such that the fluid falls downward in the center of the spikes, but at the edges is deflected horizontally, and eventually turns upwards creating a swirling pattern. The 'bubbles' display the same behavior but the upward flowing fluid is eventually turned around to go downward. Thus, the fluid has a significant curl as expected. And third, the bulk of the 'action' takes place in the linearly unstable region (i.e., $x < 0.2$). We see that disturbed fluid motion occurs between $x \approx -1.0$ and $x \approx 0.7$ so by this time there is relatively little disruption of the 'stable' side of the density profile (i.e., where $g\partial \ln n_0/\partial x > 0$).

In Fig. 2 we show the density contours (Fig. 2a) and velocity vector field (Fig. 2b) for the Rayleigh-Taylor instability in the large Larmor radius limit (i.e., we use $\rho_i/L_2 = 5.0$) at $t = 1.0$. The following points should be noted. First, it is clear that the unmagnetized Rayleigh-Taylor instability develops much faster than the magnetized Rayleigh-Taylor instability, consistent with linear theory. Second, although not evident in Fig. 2, we find that during the linear evolution of the unmagnetized instability, the fastest growing modes are the shortest wavelength modes. This is consistent with the theoretical analysis which indicated that $\gamma \propto k_y$. However, longer wavelength structures seem to dominate as the instability progresses, i.e., those that are comparable to the initial density gradient scale length. Third, the instability initially develops on the 'unstable' side of the density profile (i.e., $g\partial \ln n_0/\partial x < 0$), but unlike the magnetized instability, it disrupts more of the density profile

(see Fig. 2a). The extent of the disruption is between $x \approx -1.1$ to $x \approx 1.6$, a significantly larger region than the previous case. It appears that narrow channels develop which allow the magnetic field to penetrate into the 'stable' topside of the density profile. Fourth, a secondary instability appears to develop on one side of the largest density enhancements, i.e., the 'fishbone-like' structure in Fig. 2a. It is not entirely clear what cause this finer scale structure; it may be an eigenmode structure or a secondary instability. Fifth, the velocity vector field is completely different from the magnetized ion case. The flow is clearly not divergence-free (see Fig. 2b) and large-scale flows seem to form fluid 'sheets'. The maximum velocity reached in this case is $u_m = 1.9$ which is somewhat larger than the 'free-fall' velocity $u = 1.5$. And finally, we add that we have also performed simulations for $\rho_i/L_2 \sim 0(1)$; the linear growth rate of the instability is smaller than either of two examples presented above in accordance with linear theory.¹⁶

III. CONCLUSION

In conclusion, we have presented the theory and first nonlinear fluid simulations of the Rayleigh-Taylor instability in the large ion Larmor radius limit (i.e., $\rho_i/L \gg 1$). These results are based upon a modified set of one-fluid MHD equations which is valid for arbitrary values of ρ_i/L or ω/Ω_i (but requires $\rho_e/L \ll 1$ and $\omega/\Omega_e \ll 1$). We have demonstrated that in this limit the Rayleigh-Taylor instability evolves in a dramatically different manner from the conventional, small Larmor radius Rayleigh-Taylor instability. Besides developing much faster, the unmagnetized instability appears to be more disruptive of an accelerating plasma density shell, and generates compressible ion flows. Moreover, although the fastest growing modes have the shortest wavelength, longer wavelength modes seem to dominate in the nonlinear regime. Finally, these results are consistent with the observed structuring of the AMPTE barium release in the magnetotail,¹⁰ and recent laboratory observations of plasma structure.¹² In both cases, plasma shells rapidly decelerate as they expand into a strong magnetic field, develop structure on time scales much faster than the ion cyclotron period, and are dominated by structure sizes comparable to the density gradient scale length.

ACKNOWLEDGMENTS

We thank Dr. B. Ripin for helpful discussions regarding the NRL laser experiment and pointing out the experimental observation that the onset of instability is independent of magnetic field strength above a critical value. We also thank Dr. P. Bernhardt for discussions regarding the AMPTE data and Dr. H. Rowland for assistance in benchmarking the code. This research has been supported by the Defense Nuclear Agency.

REFERENCES

1. S. Chandrasekhar, Hydrodynamic and Hydromagnetic Stability, (Dover Publications, Inc., New York, 1961), p. 428.
2. Lord Rayleigh, Scientific Papers, ii, 200 (1900).
3. M. Kruskal and M. Schwarzschild, Proc. Roy. Soc. (London) A, 223, 348 (1954).
4. C.L. Longmire and M.N. Rosenbluth, Ann. Phys., 1, 120 (1957).
5. S.E. Bodner, Phys. Rev. Lett., 33, 761 (1974).
6. G.L. Siscoe, in Solar-Terrestrial Physics, ed. R.L. Carovillano and J.M. Forbes, (De. Reidel Publishing Co., Boston, 1983), p. 11.
7. K.V. Roberts and J.B. Taylor, Phys. Rev. Lett., 8, 197 (1962).
8. M.N. Rosenbluth, N.A. Krall, and N. Rostoker, Nucl. Fusion, Suppl., 1, 143 (1962).
9. S.P. Gary and M.F. Thomsen, J. Plasma Phys., 28, 551, 1982.
10. P. A. Bernhardt, R. Roussel-Dupré, M.B. Pongratz, G. Haerendel, A. Valenzuela, D.A. Gurnett, and R.R. Anderson, to be published in J. Geophys. Res. (1987).
11. S. Okada, K. Sato, and T. Sekiguchi, Jap. J. Appl. Phys., 20, 157 (1981).
12. B.H. Ripin, E.A. McLean, C.K. Manka, C. Pawley, J.A. Stamper, T.A. Peyser, A.N. Mostovych, J. Grun, A.B. Hassam, and J.D. Huba, submitted to Phys. Rev. Lett. (1987).
13. H. Dickinson, W.H. Bostick, J.N. DiMarco, and S. Koslov, Phys. Fluids, 5, 1048 (1962).
14. G. Jellison and C. Parsons, Phys. Fluids, 24, 1787 (1981).
15. M. Keilhacker, M. Kornherr, H. Niedemeyer, F. Soldner, and K.-H. Stever, Phys. Rev. Lett., 32, 1044 (1974);: K.F. McKenna, R. Kristal, and E.L. Zimmerman, Phys. Fluids, 18, 1371 (1975).
16. A.B. Hassam and J.D. Huba, Geophys. Res. Lett., 14, 60 (1987).
17. A.B. Hassam and J.D. Huba, submitted to Phys. Fluids (1987).
18. A.B. Hassam and Y.C. Lee, Phys. Fluids, 27, 438 (1984).
19. A. Harten, J. Comp. Phys., 49, 357 (1983).
20. H.W. Emmons, C.T. Chang and B.C. Watson, J. Fluid Mech., 7, 177 (1959).
21. G.R. Baker, D.I. Meiron, and S.A. Orszag, Phys. Fluids, 23, 1485 (1980).
22. M.H. Emery, J.H. Gardner, and J.P. Boris, Phys. Rev. Lett., 48, 677 (1982).

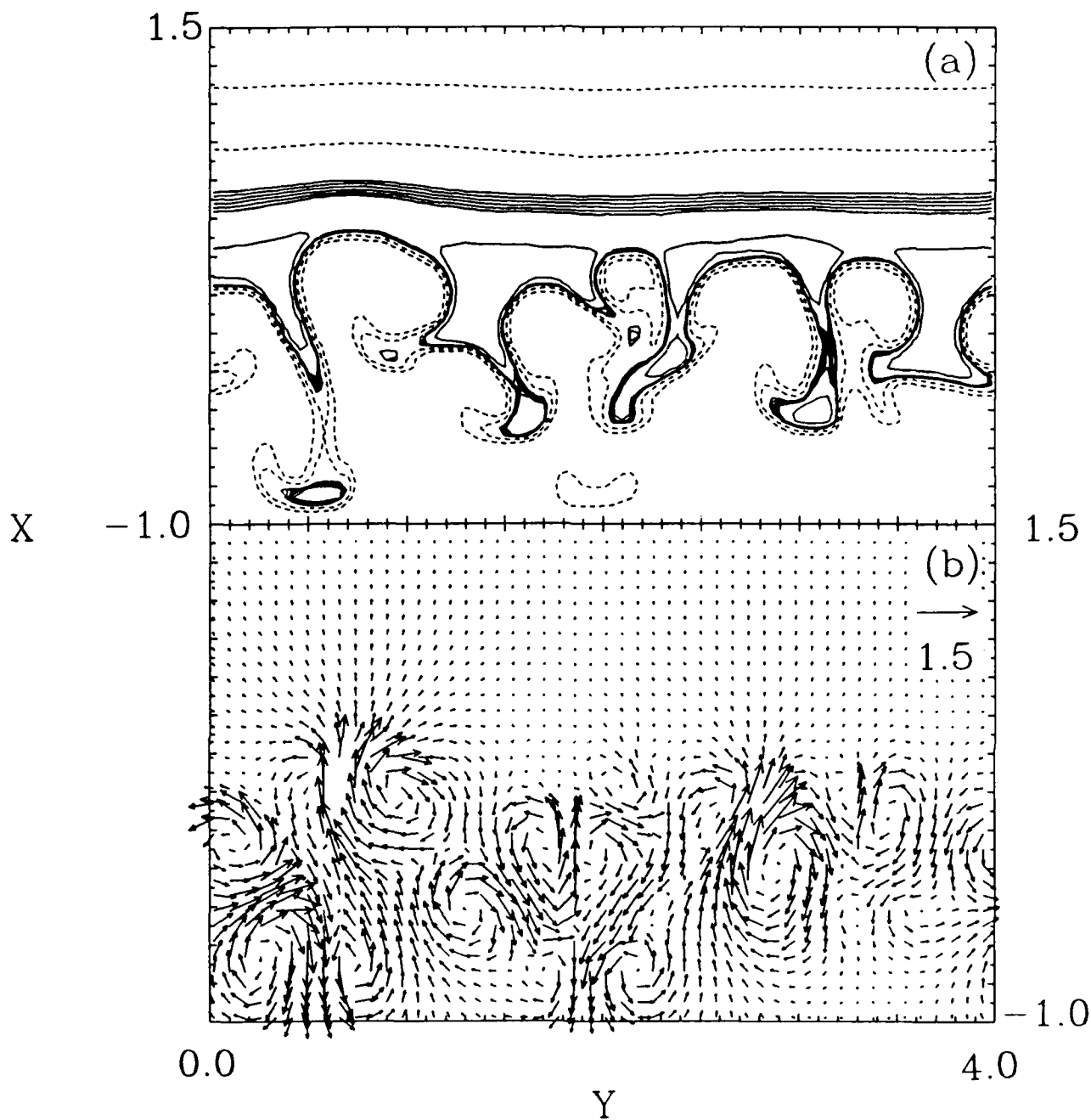


Fig. 1) Simulation results for the Rayleigh-Taylor instability in the small Larmor radius limit ($\rho_1/L_2 = 0$) at time $t = 5.5$. The magnetic field is in the $-z$ direction (out of the page). (a) Density contours. The contour levels are as follows: dashed (0.30 and 0.43), heavy solid (0.55), light solid (0.68 and 0.80). (b) Velocity vector field. The 'unit' velocity vector of 1.5 is shown for comparison.

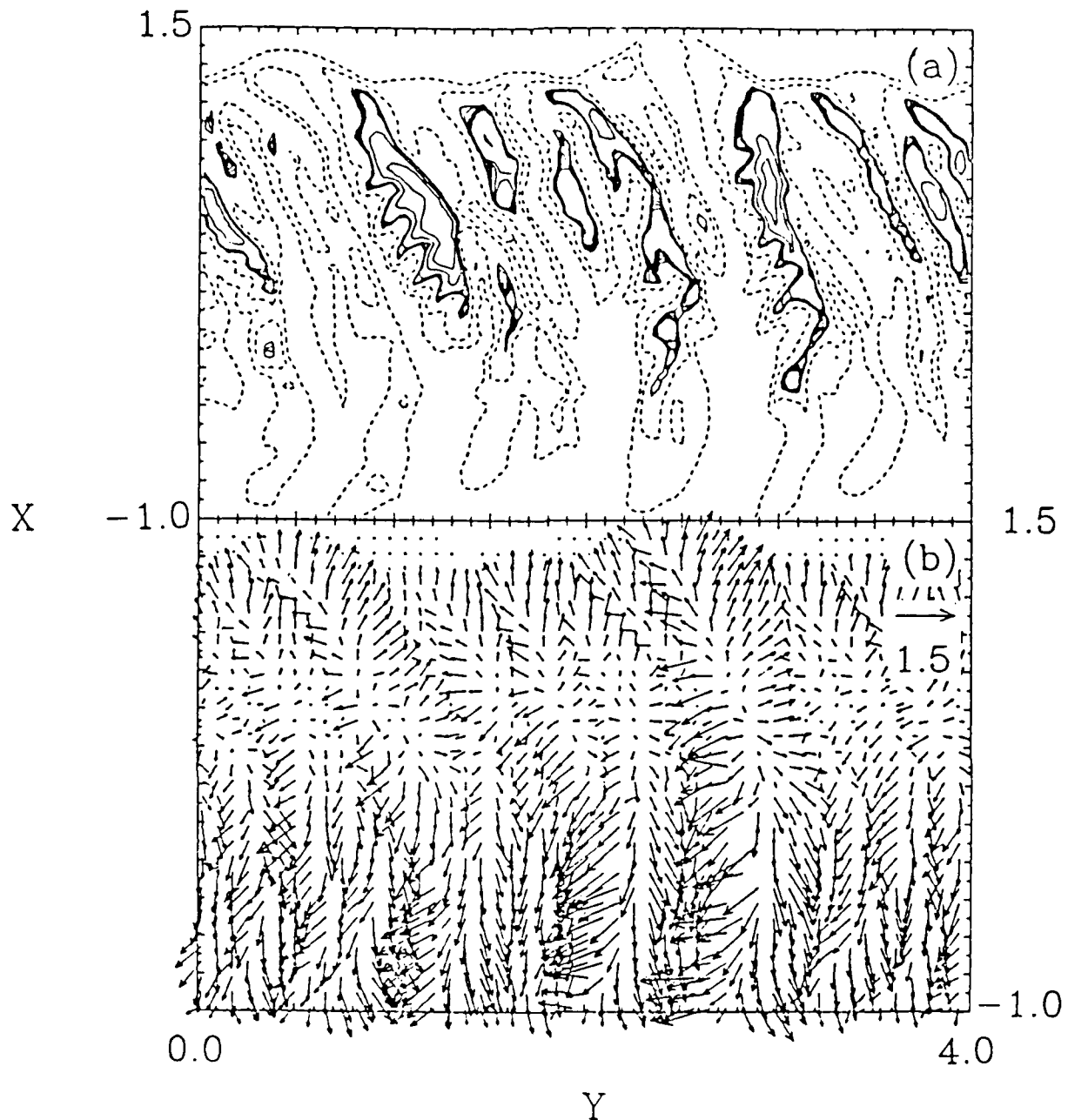


Fig. 2) Simulation results for the Rayleigh-Taylor instability in the large Larmor radius limit ($\rho_1/L_2 = 5$) at time $t = 1.0$. The magnetic field is in the $-z$ direction (out of the page). (a) Density contours. The contour levels are the same as in Fig. 1a. (b) Velocity vector field. The 'unit' velocity vector of 1.5 is shown for comparison.

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

ASSISTANT SECRETARY OF DEFENSE
COMM, CMD, CONT 7 INTELL
WASHINGTON, DC 20301

DIRECTOR
COMMAND CONTROL TECHNICAL CENTER
PENTAGON RM BE 685
WASHINGTON, DC 20301
01CY ATTN C-650
01CY ATTN C-312 R. MASON

DIRECTOR
DEFENSE ADVANCED RSCH PROJ AGENCY
ARCHITECT BUILDING
1400 WILSON BLVD.
ARLINGTON, VA 22209
01CY ATTN NUCLEAR
MONITORING RESEARCH
01CY ATTN STRATEGIC TECH OFFICE

DEFENSE COMMUNICATION ENGINEER CENTER
1860 WIEHLE AVENUE
RESTON, VA 22090
01CY ATTN CODE R410
01CY ATTN CODE R812

DIRECTOR
DEFENSE NUCLEAR AGENCY
WASHINGTON, DC 20305
01CY ATTN STVL
04CY ATTN TITL
01CY ATTN DDST
03CY ATTN RAAE

COMMANDER
FIELD COMMAND
DEFENSE NUCLEAR AGENCY
KIRTLAND, AFB, NM 87115
01CY ATTN FCPR

DEFENSE NUCLEAR AGENCY
SAO/DNA
BUILDING 20676
KIRTLAND AFB, NM 87115
01CY D.C. THORNBURG

DIRECTOR
INTERSERVICE NUCLEAR WEAPONS SCHOOL
KIRTLAND AFB, NM 87115
01CY ATTN DOCUMENT CONTROL

JOINT PROGRAM MANAGEMENT OFFICE
WASHINGTON, DC 20330
01CY ATTN J-3 WWMCCS EVALUATION
OFFICE

DIRECTOR
JOINT STRAT TGT PLANNING STAFF
OFFUTT AFB
OMAHA, NB 68113
01CY ATTN JSTPS/JLKS
01CY ATTN JPST G. GOETZ

CHIEF
LIVERMORE DIVISION FLD COMMAND DNA
DEPARTMENT OF DEFENSE
LAWRENCE LIVERMORE LABORATORY
P.O. BOX 808
LIVERMORE, CA 94550
01CY ATTN FCPRL

COMMANDANT
NATO SCHOOL (SHAPE)
APO NEW YORK 09172
01CY ATTN U.S. DOCUMENTS OFFICER

UNDER SECY OF DEF FOR RSCH & ENGRG
DEPARTMENT OF DEFENSE
WASHINGTON, DC 20301
01CY ATTN STRATEGIC & SPACE
SYSTEMS (OS)

COMMANDER/DIRECTOR
ATMOSPHERIC SCIENCES LABORATORY
U.S. ARMY ELECTRONICS COMMAND
WHITE SANDS MISSILE RANGE, NM 88002
01CY ATTN DELAS-EO, F. NILES

DIRECTOR
BMD ADVANCED TECH CTR
HUNTSVILLE OFFICE
P.O. BOX 1500
HUNTSVILLE, AL 35807
01CY ATTN ATC-T MELVIN T. CAPPS
01CY ATTN ATC-O W. DAVIES
01CY ATTN ATC-R DON RUSS

PROGRAM MANAGER
BMD PROGRAM OFFICE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
O1CY ATTN DACS-BMT J. SHEA

CHIEF C-E- SERVICES DIVISION
U.S. ARMY COMMUNICATIONS CMD
PENTAGON RM 1B269
WASHINGTON, DC 20310
O1CY ATTN C- E-SERVICES DIVISION

COMMANDER
U.S. ARMY COMM-ELEC ENGRG INSTAL AGY
FT. HUACHUCA, AZ 85613
O1CY ATTN CCC-EMEO GEORGE LANE

COMMANDER
U.S. ARMY FOREIGN SCIENCE & TECH CTR
220 7TH STREET, NE
CHARLOTTESVILLE, VA 22901
O1CY ATTN DRXST-SD

COMMANDER
U.S. ARMY MATERIAL DEV & READINESS CMD
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
O1CY ATTN DRCLDC J.A. BENDER

COMMANDER
U.S. ARMY NUCLEAR AND CHEMICAL AGENCY
7500 BACKLICK ROAD
BLDG 2073
SPRINGFIELD, VA 22150
O1CY ATTN LIBRARY

DIRECTOR
U.S. ARMY BALLISTIC RESEARCH
LABORATORY
ABERDEEN PROVING GROUND, MD 21005
O1CY ATTN TECH LIBRARY,
EDWARD BAICY

COMMANDER
U.S. ARMY SATCOM AGENCY
FT. MONMOUTH, NJ 07703
O1CY ATTN DOCUMENT CONTROL

COMMANDER
U.S. ARMY MISSILE INTELLIGENCE AGENCY
REDSTONE ARSENAL, AL 35809
O1CY ATTN JIM GAMBLE

DIRECTOR
U.S. ARMY TRADOC SYSTEMS ANALYSIS
ACTIVITY
WHITE SANDS MISSILE RANGE, NM 89007
O1CY ATTN ATAA-SA
O1CY ATTN TCC/F. PAYAN JR.
O1CY ATTN ATTA-TAC LTC J. HESSE

COMMANDER
NAVAL ELECTRONIC SYSTEMS COMMAND
WASHINGTON, DC 20360
O1CY ATTN NAVALEX 034 T. HUGHES
O1CY ATTN PME 117
O1CY ATTN PME 117-T
O1CY ATTN CODE 5011

COMMANDING OFFICER
NAVAL INTELLIGENCE SUPPORT CTR
4301 SUITLAND ROAD, BLDG. 5
WASHINGTON, DC 20390
O1CY ATTN MR. DUBBIN STIC 12
O1CY ATTN NISC-50
O1CY ATTN CODE 5404 J. CALET

COMMANDER
NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CA 92152
O1CY ATTN J. FERGUSON

NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375
O1CY ATTN CODE 4700 S.L. Ossakow,
26 CYS IF UNCLASS
(O1CY IF CLASS)
ATTN CODE 4780 J.D. HUBA, 50
CYS IF UNCLASS, O1CY IF CLASS
O1CY ATTN CODE 4701 I. VITKOVITSKY
O1CY ATTN CODE 7500
O1CY ATTN CODE 7550
O1CY ATTN CODE 7580
O1CY ATTN CODE 7551
O1CY ATTN CODE 7555
O1CY ATTN CODE 4730 E. MCLEAN
O1CY ATTN CODE 4752
O1CY ATTN CODE 4730 B. RIPIN
20CY ATTN CODE 2628

COMMANDER
NAVAL SPACE SURVEILLANCE SYSTEM
DAHLGREN, VA 22448
O1CY ATTN CAPT J.H. BURTON

OFFICER-IN-CHARGE
NAVAL SURFACE WEAPONS CENTER
WHITE OAK, SILVER SPRING, MD 20910
01CY ATTN CODE F31

DIRECTOR
STRATEGIC SYSTEMS PROJECT OFFICE
DEPARTMENT OF THE NAVY
WASHINGTON, DC 20376
01CY ATTN NSP-2141
01CY ATTN NSSP-2722 FRED WIMBERLY

COMMANDER
NAVAL SURFACE WEAPONS CENTER
DAHLGREN LABORATORY
DAHLGREN, VA 22448
01CY ATTN CODE DF-14 R. BUTLER

OFFICER OF NAVAL RESEARCH
ARLINGTON, VA 22217
01CY ATTN CODE 465
01CY ATTN CODE 461
01CY ATTN CODE 402
01CY ATTN CODE 420
01CY ATTN CODE 421

COMMANDER
AEROSPACE DEFENSE COMMAND/XPD
DEPARTMENT OF THE AIR FORCE
ENT AFB, CO 80912
01CY ATTN XPDQQ
01CY ATTN XP

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731
01CY ATTN OPR HAROLD GARDNER
01CY ATTN LKB
KENNETH S.W. CHAMPION
01CY ATTN OPR ALVA T. STAIR
01CY ATTN PHD JURGEN BUCHAU
01CY ATTN PHD JOHN P. MULLEN

AF WEAPONS LABORATORY
KIRTLAND AFT, NM 87117
01CY ATTN SUL
01CY ATTN CA ARTHUR H. GUENTHER

AFTAC
PATRICK AFB, FL 32925
01CY ATTN TN

AIR FORCE AVIONICS LABORATORY
WRIGHT-PATTERSON AFB, OH 45433
01CY ATTN AAD WADE HUNT
01CY ATTN AAD ALLEN JOHNSON

DEPUTY CHIEF OF STAFF
RESEARCH, DEVELOPMENT, & ACQ
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
01CY ATTN AFRDQ

HEADQUARTERS
ELECTRONIC SYSTEMS DIVISION
DEPARTMENT OF THE AIR FORCE
HANSCOM AFB, MA 01731-5000
01CY ATTN J. DEAS
ESD/SCD-4

COMMANDER
FOREIGN TECHNOLOGY DIVISION, AFSC
WRIGHT-PATTERSON AFB, OH 45433
01CY ATTN NICD LIBRARY
01CY ATTN ETD P. B. EALLARD

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
GRIFFISS AFB, NY 13441
01CY ATTN DOC LIBRARY/TSLD
01CY ATTN OCSE V. COYNE

STRATEGIC AIR COMMAND/XPFS
OFFUTT AFB, NB 68113
01CY ATTN XPFS

SAMSO/MN
NORTON AFB, CA 92409
(MINUTEMAN)
01CY ATTN MNLL

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
HANSCOM AFB, MA 01731
01CY ATTN EEP A. LORENTZEN

DEPARTMENT OF ENERGY
LIBRARY ROOM G-042
WASHINGTON, DC 20545
01CY ATTN DOC CON FOR A. LABOWITZ

DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
P.O. BOX 5400
ALBUQUERQUE, NM 87114
01CY ATTN DOC CON FOR D. SHERWOOD

EG&G, INC.
LOS ALAMOS DIVISION
P.O. BOX 809
LOS ALAMOS, NM 85544
01CY ATTN DOC CON FOR J. BREEDLOVE

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
P.O. BOX 808
LIVERMORE, CA 94550
01CY ATTN DOC CON FOR TECH INFO
DEPT
01CY ATTN DOC CON FOR L-389 R. OTT
01CY ATTN DOC CON FOR L-31 R. HAGER

LOS ALAMOS NATIONAL LABORATORY
P.O. BOX 1663
LOS ALAMOS, NM 87545
01CY ATTN DOC CON FOR J. WOLCOTT
01CY ATTN DOC CON FOR R.F. TASCHEK
01CY ATTN DOC CON FOR E. JONES
01CY ATTN DOC CON FOR J. MALIK
01CY ATTN DOC CON FOR R. JEFFRIES
01CY ATTN DOC CON FOR J. ZINN
01CY ATTN DOC CON FOR D. WESTERVELT
01CY ATTN D. SAPPENFIELD

LOS ALAMOS NATIONAL LABORATORY
MS D438
LOS ALAMOS, NM 87545
01CY ATTN S.P. GARY
01CY ATTN J. BOROVSKY

SANDIA LABORATORIES
P.O. BOX 5800
ALBUQUERQUE, NM 87115
01CY ATTN DOC CON FOR W. BROWN
01CY ATTN DOC CON FOR A.
THORNBROUGH
01CY ATTN DOC CON FOR T. WRIGHT
01CY ATTN DOC CON FOR D. DAHLGREN
01CY ATTN DOC CON FOR 3141
01CY ATTN DOC CON FOR SPACE PROJECT
DIV

SANDIA LABORATORIES
LIVERMORE LABORATORY
P.O. BOX 959
LIVERMORE, CA 94550
01CY ATTN DOC CON FOR B. MURPHEY
01CY ATTN DOC CON FOR T. COOK

OFFICE OF MILITARY APPLICATION
DEPARTMENT OF ENERGY
WASHINGTON, DC 20545
01CY ATTN DOC CON DR. YO SONG

NATIONAL OCEANIC & ATMOSPHERIC ADMIN
ENVIRONMENTAL RESEARCH LABORATORIES
DEPARTMENT OF COMMERCE
BOULDER, CO 80302
01CY ATTN R. GRUBB

DEPARTMENT OF DEFENSE CONTRACTORS

AEROSPACE CORPORATION
P.O. BOX 92957
LOS ANGELES, CA 90009
01CY ATTN I. GARFUNKEL
01CY ATTN T. GALMI
01CY ATTN V. JOSEPHSON
01CY ATTN S. BOWER
01CY ATTN D. OLSEN

ANALYTICAL SYSTEMS ENGINEERING CORP
5 OLD CONCORD ROAD
BURLINGTON, MA 01803
01CY ATTN RADIO SCIENCES

AUSTIN RESEARCH ASSOC., INC.
1901 RUTLAND DRIVE
AUSTIN, TX 78758
01CY ATTN L. SLOAN
01CY ATTN R. THOMPSON

BERKELEY RESEARCH ASSOCIATES, INC.
P.O. BOX 983
BERKELEY, CA 94701
01CY ATTN J. WORKMAN
01CY ATTN C. PRETTIE
01CY ATTN S. BRECHT

BOEING COMPANY, THE
P.O. BOX 3707
SEATTLE, WA 98124
01CY ATTN G. KEISTER
01CY ATTN D. MURRAY
01CY ATTN G. HALL
01CY ATTN J. KENNEY

CHARLES STARK DRAPER LABORATORY, INC
555 TECHNOLOGY SQUARE
CAMBRIDGE, MA 02139
01CY ATTN D.B. BOY
01CY ATTN J.P. GILMORE

COMSAT LABORATORIES
22300 COMSAT DRIVE
CLARKSBURG, MD 20871
01CY ATTN G. HYDE

CORNELL UNIVERSITY
DEPARTMENT OF ELECTRICAL ENGINEERING
ITHACA, NY 14850
01CY ATTN D.T. FARLEY, JR.

ELECTROSPACE SYSTEMS, INC.
BOX 1359
RICHARDSON, TX 75080
01CY ATTN H. LOGSTON
01CY ATTN SECURITY (PAUL PHILLIPS)

EOS TECHNOLOGIES, INC.
606 Wilshire Blvd.
Santa Monica, CA 90401
01CY ATTN C.B. GABBARD
01CY ATTN R. LELEVIER

GENERAL ELECTRIC COMPANY
SPACE DIVISION
VALLEY FORGE SPACE CENTER
GODDARD BLVD KING OF PRUSSIA
P.O. BOX 8555
PHILADELPHIA, PA 19101
01CY ATTN M.H. BORTNER
SPACE SCI LAB

GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701
(ALL CLASS ATTN: SECURITY OFFICER)
01CY ATTN T.N. DAVIS (UNCLASS ONLY)
01CY ATTN NEAL BROWN (UNCLASS ONLY)

GTE SYLVANIA, INC.
ELECTRONICS SYSTEMS GRP-EASTERN DIV
77 A STREET
NEEDHAM, MA 02194
01CY ATTN DICK STEINHOF

HSS, INC.
2 ALFRED CIRCLE
BEDFORD, MA 01730
01CY ATTN DONALD HANSEN

ILLINOIS, UNIVERSITY OF
107 COBLE HALL
150 DAVENPORT HOUSE
CHAMPAIGN, IL 61820
(ALL CORRES ATTN DAN MCCLELLAND)
01CY ATTN K. YEH

INSTITUTE FOR DEFENSE ANALYSES
1801 NO. BEAUREGARD STREET
ALEXANDRIA, VA 22311
01CY ATTN J.M. AEIN
01CY ATTN ERNEST BAUER
01CY ATTN HANS WOLFARD
01CY ATTN JOEL BENGSTON

INTL TEL & TELEGRAPH CORPORATION
500 WASHINGTON AVENUE
NUTLEY, NJ 07110
01CY ATTN TECHNICAL LIBRARY

JAYCOR
11011 TORREYANA ROAD
P.O. BOX 85154
SAN DIEGO, CA 92138
01CY ATTN J.L. SPERLING

JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
JOHNS HOPKINS ROAD
LAUREL, MD 20810
01CY ATTN DOCUMENT LIBRARIAN
01CY ATTN THOMAS POTEIRA
01CY ATTN JOHN DASSOULAS

KAMAN SCIENCES CORP
P.O. BOX 7463
COLORADO SPRINGS, CO 80933
01CY ATTN T. MEAGHER

KAMAN TEMPO-CENTER FOR ADVANCED
STUDIES
816 STATE STREET (P.O DRAWER QQ)
SANTA BARBARA, CA 93102
01CY ATTN DASIAC
01CY ATTN WARREN S. KNAPP
01CY ATTN WILLIAM MCNAMARA
01CY ATTN B. GAMBILL

LINKABIT CORP
10453 ROSELLE
SAN DIEGO, CA 92121
01CY ATTN IRWIN JACOBS

LOCKHEED MISSILES & SPACE CO., INC
P.O. BOX 504
SUNNYVALE, CA 94088
01CY ATTN DEPT 60-12
01CY ATTN D.R. CHURCHILL

LOCKHEED MISSILES & SPACE CO., INC.
3251 HANOVER STREET
PALO ALTO, CA 94304
01CY ATTN MARTIN WALT DEPT 52-12
01CY ATTN W.L. IMHOF DEPT 52-12
01CY ATTN RICHARD G. JOHNSON
DEPT 52-12
01CY ATTN J.B. CLADIS DEPT 52-12

MARTIN MARIETTA CORP
ORLANDO DIVISION
P.O. BOX 5837
ORLANDO, FL 32805
01CY ATTN R. HEFFNER

MCDONNELL DOUGLAS CORPORATION
5301 BOLSA AVENUE
HUNTINGTON BEACH, CA 92647
01CY ATTN N. HARRIS
01CY ATTN J. MOULE
01CY ATTN GEORGE MROZ
01CY ATTN W. OLSON
01CY ATTN R.W. HALPRIN
01CY ATTN TECHNICAL
LIBRARY SERVICES

MISSION RESEARCH CORPORATION
735 STATE STREET
SANTA BARBARA, CA 93101
01CY ATTN P. FISCHER
01CY ATTN W.F. CREVIER
01CY ATTN STEVEN I. GUTSCHE
01CY ATTN R. BOGUSCH
01CY ATTN R. HENDRICK
01CY ATTN RALPH KILB
01CY ATTN DAVE SOWLE
01CY ATTN F. FAJEN
01CY ATTN M. SCHEIBE
01CY ATTN CONRAD L. LONGMIRE
01CY ATTN B. WHITE
01CY ATTN R. STAGAT

MISSION RESEARCH CORP.
1720 RANDOLPH ROAD, S.E.
ALBUQUERQUE, NM 87106
01CY R. STELLINGWERF
01CY M. ALME
01CY L. WRIGHT

MITRE CORP
WESTGATE RESEARCH PARK
1820 DOLLY MADISON BLVD
MCLEAN, VA 22101
01CY ATTN W. HALL
01CY ATTN W. FOSTER

PACIFIC-SIERRA RESEARCH CORP
12340 SANTA MONICA BLVD.
LOS ANGELES, CA 90025
01CY ATTN H.C. FIELD, JR.

PENNSYLVANIA STATE UNIVERSITY
IONOSPHERE RESEARCH LAB
318 ELECTRICAL ENGINEERING EAST
UNIVERSITY PARK, PA 16802
(NO CLASS TO THIS ADDRESS)
01CY ATTN IONOSPHERIC RESEARCH LAB

PHOTOMETRICS, INC.
4 ARROW DRIVE
WOBURN, MA 01801
01CY ATTN IRVING L. KOFSKY

PHYSICAL DYNAMICS, INC.
P.O. BOX 3027
BELLEVUE, WA 98009
01CY ATTN E.J. FREMOUW

PHYSICAL DYNAMICS, INC.
P.O. BOX 10367
OAKLAND, CA 94610
ATTN A. THOMSON

R & D ASSOCIATES
P.O. BOX 9695
MARINA DEL REY, CA 90291
01CY ATTN FORREST GILMORE
01CY ATTN WILLIAM B. WRIGHT, JR.
01CY ATTN WILLIAM J. KARZAS
01CY ATTN H. ORY
01CY ATTN C. MACDONALD
01CY ATTN BRIAN LAMB
01CY ATTN MORGAN GROVER

RAYTHEON CO.
528 BOSTON POST ROAD
SUDBURY, MA 01776
01CY ATTN BARBARA ADAMS

RIVERSIDE RESEARCH INSTITUTE
330 WEST 42nd STREET
NEW YORK, NY 10036
01CY ATTN VINCE TRAPANI

SCIENCE APPLICATIONS
INTERNATIONAL INCORPORATED
1150 PROSPECT PLAZA
LA JOLLA, CA 92037
01CY ATTN LEWIS M. LINSON
01CY ATTN DANIEL A. HAMLIN
01CY ATTN E. FRIEMAN
01CY ATTN E.A. STRAKER
01CY ATTN CURTIS A. SMITH

SCIENCE APPLICATIONS
INTERNATIONAL CORPORATION
1710 GOODRIDGE DR.
MCLEAN, VA 22102
01CY J. COCKAYNE
01CY E. HYMAN

SRI INTERNATIONAL
333 RAVENSWOOD AVENUE
MENLO PARK, CA 94025
01CY ATTN J. CASPER
01CY ATTN DONALD NEILSON
01CY ATTN ALAN BURNS
01CY ATTN G. SMITH
01CY ATTN R. TSUNOLA
01CY ATTN DAVID A. JOHNSON
01CY ATTN WALTER G. CHESNUT
01CY ATTN CHARLES L. RINO
01CY ATTN WALTER JAYE
01CY ATTN J. VICKREY
01CY ATTN RAY L. LEADABRAND
01CY ATTN G. CARPENTER
01CY ATTN G. PRICE
01CY ATTN R. LIVINGSTON
01CY ATTN V. GONZALES
01CY ATTN D. MCDANIEL

TECHNOLOGY INTERNATIONAL CORP
75 WIGGINS AVENUE
BEDFORD, MA 01730
01CY ATTN W.P. BOQUIST

TRW DEFENSE & SPACE SYS GROUP
ONE SPACE PARK
REDONDO BEACH, CA 90278
01CY ATTN R. K. PLEBUCH
01CY ATTN S. ALTSCHULER
01CY ATTN D. DEE
01CY ATTN D/ STOCKWELL
SNTF/1575

VISIDYNE
SOUTH BEDFORD STREET
BURLINGTON, MA 01803
01CY ATTN W. REIDY
01CY ATTN J. CARPENTER
01CY ATTN C. HUMPHREY

UNIVERSITY OF PITTSBURGH
PITTSBURGH, PA 15213
01CY ATTN: N. ZABUSKY

END

DATE

FILMED

MARCH

1988

DTIC