FINAL REPORT

NASA GRANT NAGW-925

EARTH OBSERVATIONAL RESEARCH USING MULTISTAGE EOS-LIKE DATA

Principal Investigators

C. J. Johannsen
LARS/ Entomology Hall
Purdue University
West Lafayette, Indiana 47907-1158
Phone 317-494-6305
FAX 317-494-0535
Internet: johannsn@ecn.purdue.edu

D. A. Landgrebe
School of Electrical Engineering
Purdue University
West Lafayette, Indiana 47907-1285
Phone 317-494-3486
FAX 317-494-6440
Internet: landgreb@ecn.purdue.edu

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Introduction.

This grant was funded as a part of a program in which both research and educational impact were intended. Research work under this grant is directed at the understanding and use of future hyperspectral[1] data such as that from imaging spectrometers. Specifically, the objectives of the work were (a) to prepare suitable means for analyzing data from sensors which have large numbers of spectral bands, (b) to advance the fundamental understanding of the manner in which soils and vegetative materials reflect high spectral resolution optical wavelength radiation, and (c) to maximize the impact of the results on the educational community. Over the life of the grant, the work has thus involved basic Earth science research and information system technique understanding and development in a mutually supportive way. However, during the later years it became necessary to focus the work primarily on areas (a) and (c), due to a steadily decreasing level of effort.

Research Directions.

Some key factors influencing remote sensing information extraction in the new context of hyperspectral data are

(a) there will be a much larger number of spectral bands available than in the past ($n > 200$),

(b) this should lead to the possibility of discriminating between a larger number of more detailed ground classes,

(c) there is, in remote sensing, inherently a paucity of information about ground classes available by which to quantitatively define the classes to be discriminated between, and

(d) there is also an inherent impreciseness in the knowledge of values of some of the analysis parameters (e.g. class prior probabilities, class statistics, loss functions, atmospheric parameters, etc.).

Thus, in the new era, one may expect at least an order of magnitude increase in signal dimensionality, and nearly that much in the information to be produced. However, the limitations imposed by the remote sensing context, e.g., limitations on the prior specific knowledge about the subject matter, the observational parameters, etc. may be expected to improve only marginally. In the face of these factors, simple extensions to previous methods of data analysis are not likely to provide the ultimate in analysis results which the data are capable of delivering, and fundamentally new approaches

[1] In this report the term *Hyperspectral* is used in the sense of multispectral but for the case where there are many spectral bands (≥ 100) involved, such that traditional techniques for dealing with multispectral data may not be as well suited.

and techniques must be sought. One must seek to apply the most fundamental principles of both Earth science together with those of signal processing and information system theory. Thus the work begin by studying the problem of analysis of hyperspectral data from a quite fundamental point of view. Work was divided into the following thrust areas:

- **Feature Design or Selection**. Create a calculation procedure which would allow one to determine the best problem-specific spectral feature set for discriminating between a given set of Earth surface materials, given the location, time of season, and raw high resolution spectral samples to be available from a given sensor. The feature set may be realized either in terms of a (usually linear) combination of the original sensor bands or by selecting an optimal subset of them. [2, 4, 6, 8, 19, 20, 30, 47, 49, 56, 64, 65, 68, 70, 71][2]

- **Analysis Algorithm Design.** Determine a set of analysis algorithms which are well matched to high dimensional hyperspectral data and a list of classes presumably larger in number and more detailed in character than have traditionally been possible to use. Hierarchical analysis schemes were initially selected for study as an effective means for dealing optimally with large numbers and/or quite detailed classes. Other methods which have been studied relate to fundamentals of inference and decision-making in the face of imprecise or partial knowledge and absolute classification. A careful re-look at the use of spatial as well as temporal characteristics was also undertaken. Based upon what was learned from these studies, practical implementations were defined by seeking means to optimally train classifiers for identification of one or a small number of classes while maintaining the fundamental advantages of a relative classification scheme. The best means were formulated for incorporating into the training process both subjective knowledge which the analyst possesses, and quantitative information, such as the location of specific spectral absorption features, and class separability measures. [1, 7, 10, 12, 13, 14, 16, 22, 27, 28, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 48, 50, 51, 52, 53, 54, 55, 57, 58, 59, 61, 62, 63, 66, 69, 72, 73, 74, 75, 76, 77, 78, 79, 80, 84, 85, 86, 87]

- **System Simulation.** Create a capability to simulate an entire remote sensing system, including the ground scene, atmosphere, sensor system, and analysis procedure, so that it is possible to study the interrelated effects of various system parameter settings and noise sources across the entire system, including the functioning of the algorithms produced by the above research efforts. Here the definition of noise is taken to be any deleterious effect that occurs in such systems. The motivation for this study stems from the fact that as the information to be derived from such systems becomes more detailed, the interrelated effects between various system parameter selections and degrading influences within such systems need to become more fully understood if the full potential of such systems is to be realized.

2 Numbers in brackets refer to papers and reports listed in the Bibliography of Previous Results below.

The simulator is also useful for simulating data sets and analysis situations which are not yet available, but which will be in the future. This area of work was completed some time ago. [3, 9, 11, 15, 17, 21]

- **Earth Science Studies.** Develop the needed fundamental understanding of the variations in physical and chemical properties of soils and vegetation and their influence on high spectral resolution optical wavelengths. Effects of a human dominated landscape on soils and vegetation were initially a major emphasis. These studies provide a means for first-level testing of the new information extraction technology which results from the other research areas. [5, 18, 20, 23, 24, 25, 26, 45, 46, 60,67, 81, 82, 83].

- **Analysis System Implementation.** Create a data analysis system implementation which has the power and flexibility needed for both educational and research environments, and which is economical to acquire and use and has greater emphasis on ease of use than has been the case in past implementations.

MultiSpec - A Mechanism For Technology Transfer Of Results

This last area of work is motivated by the observation from previous land-oriented satellite programs that training, and technology transfer to current and future researchers and users is a key step that is often not given adequate emphasis. For analysis algorithms that are new and complex or require significant study in order for users to realize there full potential, it is especially important that there be a convenient means available for workers and students to gain hands-on experience on their own problems and data. Here, "convenient" means that the implementation hardware must be inexpensive or readily available and the software must be easy to learn and use, even for the occasional user. The hardware platform chosen for this work is the Macintosh[3], a system which is common in many universities and secondary schools. Thus the analysis system implementation is rather unique in that many of the current multispectral data analysis systems are implemented on more expensive hardware of the Sun Workstation class, equipment which is out of reach for many college level students and all students at the K through 12 level.

This work was begun by implementing a set of algorithms suitable for the analysis of multispectral data sets of the current, more modest dimensionality. More advanced capabilities were then added to the system as they emerged from the research. The current version of this analysis system, now called *MultiSpec*[4], is being distributed freely to requesters. A user's handbook entitled "An Introduction to *MultiSpec*" (79 pages)[3] has been written and is also provided. Current capabilities of *MultiSpec* include the following.

- **Import data** in either Binary or ASCII format with or without a header, and in Band Interleaved by Line (BIL), Band Sequential (BSQ), or Band Interleaved

3 Macintosh is a registered trademark of Apple Computer, Inc.

4 © Purdue Research Foundation, 1988-94

by Sample (BIS) formats. The data may have either one or two bytes per data value, and may have 4, 8, 10, 12, 13, 14, 15, or 16 bits per data value. In the case of two bytes per sample, the two bytes may be in either order.

- **Display multispectral images** in a variety of B/W or color formats using linear or equal area gray scales; display (internally generated) thematic images also in B/W or color, with an ability to control the color used for each theme.

- **Histogram** data for use in determining the gray scale regime for a display or for listing and graphing.

- **Reformat** the data file in a number of ways, e.g., by adding a standard header, changing from any one of the three interleave formats to either of the other two, editing out channels, combining files, adding or modifying channel descriptions, mosaicing data sets, changing the geometry of a data set, and a number of other changes.

- **Create new channels** of data from existing channels. The new channels may be the result of a principal components or feature extraction transformation of the existing ones, or they may result from the ratio of a linear combination of existing bands divided by a different linear combination of bands.

- **Cluster** data using either a single pass or an iterative (isodata) clustering algorithm. Save the results for display as a thematic map. Cluster statistics can also be saved as class statistics.

- **Define classes** via designating rectangular or polygonal training fields, compute field and class statistics, and define test fields for use in evaluating classification results quantitatively. A feature called "**Enhance Statistics**" also allows one to improve the extent to which the defined class statistics fit the composite of all data in the data set.

- **Determine** the **best** subset of **spectral features** to use for a given classification using (a) any of four statistical distance measures or (b) a new method based directly upon decision boundaries defined by training samples, or (c) a second method based directly upon the discriminant functions. Also included are methods especially designed to search for narrow spectral features such as spectroscopic characteristics.

- **Classify** a designated area in the data file. Four different classification algorithms are available: use of minimum L1 or L2 distance, the maximum likelihood pixel scheme, or the ECHO spectral/spatial classifier. Save the results for display as a thematic map, with or without training and test fields being shown. Apply a threshold to a classification, and generate a probability map showing the degree of membership of each pixel to the class to which it was assigned.

- **List classification results** of training or test areas in tabular form on a per field, per class, or groups of classes basis.

- Show a **graph** of the **spectral values** of a currently selected pixel or the mean $\pm \sigma$ for a selected area. Show the coordinates of a currently selected area.

- Show a **color presentation** of the **correlation matrix** for a field or class.

- Several additional **utility functions** including listing out a subset of the data e.g., for use externally, conducting principal component analysis, etc.

- **Transfer** intermediate or final **results**, be they text, B/W image or color image, to other application programs such as word processors, spreadsheets, or graphics program by copying and pasting or by saving and then opening the saved file within another application.

The current implementation provides a state of the art analysis capability and is quite adequate for analyzing multispectral data of large dimensionality. Even though this grant is ending, further development of MultiSpec is planned.

Educational Impact.

The impact of this work on education at several levels has already been very significant. The availability of *MultiSpec* is proving to be of exceptional benefit in class room instruction and in otherwise bringing new students of remote sensing techniques up to the state of the art of multivariant data analysis very rapidly. It has been used for the last several years in the course EE 577, Engineering Aspects of Remote Sensing, which is taught each Spring Semester at Purdue. This class typically contains 25-30 students per semester, about equally divided between EE majors and those from Civil Engineering and the Earth sciences.

Further, a number of faculty members at other universities have requested copies and report using it in their classes. Though no accurate survey of its use has yet been conducted, it is reasonable to assume that several hundred students per year are using the system in an instructional setting. A list of U.S. and Non-U.S. colleges and universities where staff have requested and received copies is contained as a part of Table 1 below.

There are also recipients at a number of NASA sites and other federal, state, and local, government research and application agencies, as well as a few private and other organizations. Table 1 contains a list of the institutions who have requested copies to

this time. The total number of copies distributed so far is 393 in 43 states and 23 other countries.[5]

	INSTITUTION	DEPARTMENT	City	State
		University - U. S.		
1	University of Alabama	Earth System Science Laboratory	Huntsville	Alabama
2	University of Arizona	Arizona Remote Sensing Center	Tucson	Arizona
3	University of Arizona	Department of Electrical and Computer Engineering	Tucson	Arizona
4	-		Tucson	Arizona
5	Cal Poly	Agricultural Engineering Department	San Luis Obispo	California
6	California Polytechnic State University	Department of Electrical Engineering	San Luis Obispo	California
7	California State University	Biology Department	Los Angeles	California
8	San Diego State University	Department of Geography	San Diego	California
9	San Jose State University		Mountain View	California
10	San Jose State University	Dept of Geography and Environmental Studies	San Jose	California
11	Stanford University	Department of Biological Sciences	Stanford	California
12	University of California		Felton	California
13	University of California	Director, Geography Computing Facility	Berkeley	California
14	University of California	Department of Forestry and Res. Mgmt.	Berkeley	California
15	University of California	College of Natural Resources Computer Svs	Berkeley	California
16	University of California	Department of Earth & Space Sciences	Los Angeles	California
17	University of California	Dept of Environmental Studies	Santa Cruz	California
18	University of California	Department of LAWR	Davis	California
19	University of California		Davis	California
20	University of California	Natural Reserve System	Oakland	California
21	Stanford University	Department of Applied Earth Sciences	Stanford	California
22	Colorado University	Department of Biological Science.	Boulder	Colorado
23	Yale University	Dept of Forestry and Environmental Studies	New Haven	Connecticut
24	University of Miami	Department of Geography	Coral Gables	Florida
25	University of South Florida	Department of Marine Science	St. Petersburg	Florida
26	Southern Illinois University	Department of Geography	Carbondale	Illinois
27	Southern Illinois University	Department of Geology	Carbondale	Illinois
28	Southern Illinois University	Department of Geology	Carbondale	Illinois
29	University of Illinois	National Center for Supercomputing Appl.	Champaign	Illinois
30	Indiana State University	Department of Geography	Terre Haute	Indiana
31	Indiana State University	Department of Geography	Terre Haute	Indiana
32	Indiana University	Anthropological Center for Training and Global Environmental Change	Bloomington	Indiana
33	Indiana University	Indiana Geological Survey	Bloomington	Indiana
34	Indiana University	Department of Anthropology	Bloomington	Indiana
35	Indiana University		Bloomington	Indiana
36	Indiana University	Department of Anthropology	Bloomington	Indiana

5 Further information on the availability of *MultiSpec* may be obtained from Professor David Landgrebe, Purdue School of Electrical Engineering, West Lafayette, Indiana 47907, Phone 317-494-3486, Fax 317-494-6440, Internet landgreb@ecn.purdue.edu.

37	Indiana University	School of Public and Environmental Affairs	Bloomington	Indiana
38	Indiana University	Department of Geological Sciences	Bloomington	Indiana
39	Indiana Univ/Purdue Univ-Indianapolis	Department of Electrical Engineering	Indianapolis	Indiana
40	Purdue University	Department of Agronomy	West Lafayette	Indiana
41	Purdue University	Department of Agricultural Engineering	West Lafayette	Indiana
42	Purdue University	Liberal Arts and Education	West Lafayette	Indiana
43	University of Indianapolis	Dept of Earth, Space, and General Studies	Indianapolis	Indiana
44	Murray State University	Mid-America Remote Sensing Center	Murray	Kentucky
45	Northeastern University	Marine Science Center	Nahant	Maine
46	Williams College	Geology Department	Williamstown	Maine
47	*		Brunswick	Maine
48	Johns Hopkins School of Medicine		Baltimore	Maryland
49	Johns Hopkins University	Dept. of Earth & Planetary Sciences	Baltimore	Maryland
50	University of Maryland	Paterson Mac Lab	College Park	Maryland
51	University of Maryland	Department of Geography	College Park	Maryland
52	University of Maryland	Botany Department	College Park	Maryland
53	Harvard University	Nick Marsh-Armstrong Biological Labs	Cambridge	Massachusetts
54	MIT Lincoln Laboratory	Radar Imaging Techniques Group	Lexington	Massachusetts
55	MIT Lincoln Laboratory		Lexington	Massachusetts
56	Salem State College	Professor of Cartography	Danvers	Massachusetts
57	University of Massachusetts	Biology Department	Boston	Massachusetts
58	University of Massachusetts	Dept of Forestry and Wildlife Management	Amherst	Massachusetts
59	University of Michigan	Dept of EECS	Ann Arbor	Michigan
60	University of Michigan	Dept of EECS	Ann Arbor	Michigan
61	Gustavus Adolphus College	Department of Geography	Saint Peter	Minnesota
62	University of Minnesota	Department of Forestry	St. Paul	Minnesota
63	Dartmouth College	Department of Earth Sciences	Hanover	New Hampshire
64	Keene State College	Science Division - Geology	Keene	New Hampshire
65	Notre Dame College	Assistant Professor of Biology	Manchester	New Hampshire
66	Plymouth State College	Department of Natural Science	Plymouth	New Hampshire
67	University of New Hampshire	Computing and Information Services	Durham	New Hampshire
68	University of New Hampshire	Department of Natural Resources	Durham	New Hampshire
69	University of New Hampshire	CSRC/SERB	Durham	New Hampshire
70	University of New Hampshire		Durham	New Hampshire
71	University of New Hampshire	Forest Resources	Durham	New Hampshire
72	Princeton University	Department of Geology	Princeton	New Jersey
73	Princeton University	Dept of Ecology and Evolutionary Biology	Princeton	New Jersey
74	Polytechnic University		Brooklyn	New York
75	State University of New York	Department of Geography	Geneseo	New York
76	Syracuse University	Department of Geography	Syracuse	New York
77	Syracuse University	Northeast Parallel Architectures Center	Syracuse	New York
78	North Carolina State University		Raleigh	North Carolina
79	North Carolina State University	Virtual Environments Laboratory	Raleigh	North Carolina
80	University of North Carolina	Department of Geography	Chapel Hill	North Carolina
81	University of North Dakota	Department of Space Studies	Grand Forks	North Dakota

82	University of North Dakota		Grand Forks	North Dakota
83	University of North Dakota	Scientific Computing Center	Grand Forks	North Dakota
84	University of North Dakota	Space Studies	Grand Forks	North Dakota
85	Muskingum College	Geology Department	New Concord	Ohio
86	University of Cincinnati	Department of Chemistry	Cincinnati	Ohio
87	University of Oregon		Eugene	Oregon
88	University of Oregon	Dept. of Landscape Architecture	Eugene	Oregon
89	Brown University	Department of Geol. Sci.	Providence	Rhode Island
90	University of South Carolina	Department of Geography	Columbia	South Carolina
91	University of South Carolina	Department of Geological Sciences	Columbia	South Carolina
92	Baylor University	Department of Geology	Waco	Texas
93	College of Forestry		Nachogdoches	Texas
94	Southwest Texas State University	Department of Physics	San Marcos	Texas
95	Texas A&M University	Texas Maritime College	Galveston	Texas
96	Texas Christian University	Dept. of Geology	Fort Worth	Texas
97	Texas Tech University	Department of Physics	Lubbock	Texas
98	Trinity University	Geography	San Antonio	Texas
99	Univ. of Texas - Pan American	Coastal Studies Laboratory	South Padre Island	Texas
100	Univ. of Texas M.D. Anderson Cancer Center		Houston	Texas
101	Univ. of Texas M.D. Anderson Cancer Center		Houston	Texas
102	Middlebury College	Geography Department	Middlebury	Vermont
103	University of Vermont	Department of Geography	Burlington	Vermont
104	College of William and Mary	School of Marine Science	Gloucester Point	Virginia
105	George Mason University	Dept of Electrical & Computer Engineering	Fairfax	Virginia
106	University of Virginia	Department of Environmental Science	Charlottesville	Virginia
107	University of Virginia	Department of Environmental Science	Reston	Virginia
108	Central Washington University	GIS Laboratory	Ellensburg	Washington
109	University of Washington	Department of Geological Sciences	Seattle	Washington
110	Fairmont State College	Div of Science, Math & Health Careers	Fairmont	West Virginia
111	Fairmont State College	Professor of Biology	Fairmont	West Virginia
112	Wheeling Jesuit College	NASA Classroom of the Future	Wheeling	West Virginia
113	Beloit College	Department of Geology	Beloit	Wisconsin
114	University of Wyoming	Department of Geology and Geophysics	Laramie	Wyoming
115	University of Wyoming		Laramie	Wyoming

Secondary Schools - U. S.

1	Lake County Office of Education		Lakeport	California
2	Grizzly Hill School		North San Juan	California
3	Taylor Road Middle School		Alpharetta	Georgia
4	Sarah Scott Junior High School		Terre Haute	Indiana
5	Arlington High School		Indianapolis	Indiana
6	Arlington High School		Indianapolis	Indiana
7	*		Parker City	Indiana
8	Bellmont High School		Decatur	Indiana
9	Highland High School		Highland	Indiana
10	Connersville High School		Connersville	Indiana

11	Carmel High School		Carmel	Indiana
12	Liberty Middle School		Chesterton	Indiana
13	Northview High School		Brazil	Indiana
14	Center Grove High School		Indianapolis	Indiana
15	West Lafayette High School		West Lafayette	Indiana
16	Jay County High School		Portland	Indiana
17	North Central High School		Indianapolis	Indiana
18	*		Indianapolis	Indiana
19	Tecumseh Middle School		Lafayette	Indiana
20	George Rogers Clark Middle-High School		Whiting	Indiana
21	Charlestown High School		Lexington	Indiana
22	Morocco Elementary School		Morocco	Indiana
23	Waldron Jr/Sr High School		Waldron	Indiana
24	Woodrow Wilson Junior High School		Terre Haute	Indiana
25	Brownstown Central High School		Brownstown	Indiana
26	Sarah Scott Junior High School		Terre Haute	Indiana
27	Rose-Hulman Institute of Technology		Terre Haute	Indiana
28	Memorial Middle School		South Portland	Maine
29	Your Public Schools	Project COMPASS	York	Maine
30	Wiscasset High School		Wiscasset	Maine
31	Coffin School		Cape Elizabeth	Maine
32	Georges Valley High School	Science Department	Thomaston	Maine
33	Kennebunk High School		Kennebunk	Maine
34	South Portland High School		South Portland	Maine
35	Wiscasset Primary School		Wiscasset	Maine
36	Consortium for Mathematics and its Applications (COMAP)		Lexington	Massachusetts
37	Brookline Public Schools		Winchester	Massachusetts
38	Pattonville School District	Mathematics	St. Ann	Missouri
39	Lincoln Northeast High School		Lincoln	Nebraska
40	A Crosby Kennett High School	Math/Science/Computer	Conway	New Hampshire
41	Burnham Brooke Middle School		Cantebury	New Hampshire
42	Pinkerton Academy		Derry	New Hampshire
43	Conant High School		Jaffrey	New Hampshire
44	McKelvie School		Bedford	New Hampshire
45	Elm Street Junior High School		Nashua	New Hampshire
46	Concord High School		Concord	New Hampshire
47	The Derryfield School		Manchester	New Hampshire
48	Salem High School		Salem	New Hampshire
49	The Community School		South Tamworth	New Hampshire
50	Mastricola Middle School		Merrimack	New Hampshire
51	Gilmanton School		Gilmanton	New Hampshire
52	Dover High School		Dover	New Hampshire
53	Hollis/Brookline High School		Hollis	New Hampshire
54	The Whitefield School		Whitefield	New Hampshire

55	Rochester Middle School	Science	Rochester	New Hampshire
56	Belmont Junior High School		Belmont	New Hampshire
57	Keene High School		Keene	New Hampshire
58	Philips Exter Academy	Department of Science	Exeter	New Hampshire
59	Memorial Middle School	Earth Science	Laconia	New Hampshire
60	Contoocook Valley High School		Peterborough	New Hampshire
61	Mast Way Elementary School		Lee	New Hampshire
62	Canaan Elementary School		Canaan	New Hampshire
63	Maple Street School		Contoocook	New Hampshire
64	Exeter Area Junior High School		Exeter	New Hampshire
65	Souhegan High School		Amherst	New Hampshire
66	Sant Bani School	Science Department	Franklin	New Hampshire
67	Stone Environmental School		Chocorua	New Hampshire
68	Kearsarge Regional Middle School		New London	New Hampshire
69	Rundlett Junior High School		Concord	New Hampshire
70	Kenneth A. Brett School		Tanworth	New Hampshire
71	Rundlett Jr. High School		Concord	New Hampshire
72	Fall Mountain High School		Alstead	New Hampshire
73	Tibbetts Junior High School		Farmingtron	New Mexico
74	Northeast Middle School		Bethelem	Pennsylvania
75	High School Science Teacher		Vancouver	Washington

Government - Local, State, Federal - U. S.

1	WGBH	Producer	Boston	Massachusetts
2	US Geological Survey		Flagstaff	Arizona
3	Jet Propulsion Laboratory	Mail Stop 306-336	Pasadena	California
4	U. S. Geological Survey	MS 901	Menlo Park	California
5	Carnegie Institution of Washington		Stanford	California
6	U.S. Geological Survey	Western Regional Geology	Menlo Park	California
7	NASA Ames Research Center	USGS	Moffett Field	California
8	NASA Jet Propulsion Lab	Mail Stop 11-116	Pasadena	California
9	NASA Jet Propulsion Lab	M/S 264-744	Pasadena	California
10	NASA Jet Propulsion Lab		Pasadena	California
11	NASA Jet Propulsion Laboratory	Mail Stop 168-414	Pasadena	California
12	NASA Jet Propulsion Laboratory	M/S 168/414	Pasadena	California
13	U.S. Geological Survey		Menlo Park	California
14	Lawrence Livermore National Laboratory	Applied Technology Division	Livermore	California
15	NASA Ames Research Center	Ecosystem Science and Technology Branch	Moffett Field	California
16	NASA/Ames Research Center	JCWS	Moffett Field	California
17	NASA Jet Propulsion Laboratory	MS 238-725	Pasadena	California
18	Lawrence Livermore National Laboratory		Livermore	California
19	NASA Ames Research Center	MS 242-4	Moffett Field	California
20	NASA Jet Propulsion Laboratory	M/S 238/725	Pasadena	California
21	Aspen Global Change Institute		Aspen	Colorado
22	Naval Research Lab	Code 9120	Washington	DC
23	Joint Ice Center		Washington	DC

24	NASA Headquarters	Code SEP	Washington	DC
25	Naval Research Laboratory	Code 5640	Washington	DC
26	Smithsonian Institute		Washington	DC
27	NASA Headquarters		Washington	DC
28	NASA Kennedy Space Center	MD-RES	Kennedy Space Center	Florida
29	South Florida Water Management District		West Palm Beach	Florida
30	*		Jupiter	Florida
31	Argonne National Laboratory	Energy Systems Division	Argonne	Illinois
32	Indiana Department of Natural Resources		Indianapolis	Indiana
33	Information Services Section	Department of Environmental Quality	Baton Rouge	Louisiana
34	The Nature Conservancy of Louisiana	GIS Coordinator	Baton Rouge	Louisiana
35	Well National Estuarine Research Reserve		Wells	Maine
36	Island Institute		Rockland	Maine
37	NIH/NCRR/BEIP		Bethesda	Maryland
38	NASA Goddard Space Flight Center	Laboratory for Atmospheres	Greenbelt	Maryland
39	USRA/GSFC	Code 913	Greenbelt	Maryland
40	NASA Goddard Space Flight Center	Code 923	Greenbelt	Maryland
41	National Institutes of Health	NCRR	Bethesda	Maryland
42	Oceanic Sciences Branch/NOAA	NESDIS	Camp Springs	Maryland
43	NASA Goddard Space Flight Center	National Space Science Data Center	Greenbelt	Maryland
44	NASA Goddard Space Flight Center	Laboratory for Atmospheres	Greenbelt	Maryland
45	USDA ARS		Beltsville	Maryland
46	NASA Goddard Space Flight Center	Code 913	Greenbelt	Maryland
47	Museum of Science		Boston	Massachusetts
48	Deaconess Hospital	Department of Radiology	Boston	Massachusetts
49	Consortium for International Earth Science Information Network (CIESIN)		University Center	Michigan
50	Mayo Foundation	Department of Physiology and Biophysics	Rochester	Minnesota
51	NASA Stennis Space Center	Space Remote Sensing Center	Stennis Space Center	Mississippi
52	Society for the Protection of New Hampshire Forests	Conservation Institute	Concord	New Hampshire
53	CRREL	Remote Sensing/GIS Center	Hanover	New Hampshire
54	USDA Forest Service		Durham	New Hampshire
55	Army Corp of Engineers	Cold Regions Research and Engineering Laboratory	Hanover	New Hampshire
56	U.S. Army Corps Of Engineers Remote Sensing/GIS Center		Hanover	New Hampshire
57	Los Alamos National Laboratory	Astrophysics and Radiation Measurements Group, NIS-2, MS D436	Los Alamos	New Mexico
58	Los Alamos National Laboratory		Los Alamos	New Mexico
59	Los Alamos National Laboratory	Astrophysics and Radiation Measurements Group, NIS-2	Los Alamos	New Mexico
60	Los Alamos National Laboratory	EES-3	Los Alamos	New Mexico
61	USDA Forest Service	Northeastern Forest Experiment Station	Radnor	Pennsylvania
62	NASA Johnson Space Center		Houston	Texas
63	NASA Johnson Space Center	Flight Science Support Office	Houston	Texas
64	Lamoille County Planning Commission	GIS PLANNER	Morrisville	Vermont
65	U.S. Army Topographic Engineering Center	CETEC-TD-RS	Alexandria	Virginia

66		US government	Woodbridge	Virginia
67	Pacific Northwest Laboratory		Richland	Washington

Commercial & Other - U. S.

1	Alpine Exploration Group		Tucson	Arizona
2	Third Point Systems		Santa Monica	California
3	Sugnet Associates		Roseville	California
4	*		San Jose	California
5	The Aerospace Corporation	Radar & Signal Systems Dept.	Los Angeles	California
6	1547 33rd Street		Sacramento	California
7	Geodynamics Co.		Torrance	California
8	Sensible Research		Palo Alto	California
9	Ramtek Systems Division		San Jose	California
10	The Aerospace Corporation		Los Angeles	California
11	ESL, Inc. MS406		Sunnyvale	California
12	SciComp Software		Cupertino	California
13	Geosphere Project		Santa Monica	California
14	Third Point Systems, Inc.		Santa Monica	California
15	Ball Aerospace Systems Group		Boulder	Colorado
16	*	MS 841	Danbury	Connecticut
17	*		Washington	DC
18	E.I. Dupont		Wilmington	DE
19	McDonnell Douglas Space Systems	Department F516	Kennedy Space Center	Florida
20	Landmark Technologies, Inc.		Jacksonville	Florida
21	Resource Dynamics Company (R.D.C.)		Athens	Georgia
22	SETS Technology, Inc.		Mililani	Hawaii
23	*		Hailey	Idaho
24	*		Buffalo Grove	Illinois
25	*		Western Springs	Illinois
26	ITT Aerospace/Communications Division		Fort Wayne	Indiana
27	DowElanco		Indianapolis	Indiana
28	ARKLA Exploration Co.		Shreveport	Louisiana
29	Bennett & Peters Inc	Forestry Consultants & Appraisers	Baton Rouge	Louisiana
30	Capeshore Data		Hanover	Maine
31	Earth Observations Satellite Corp.		Lanham	Maryland
32	Earth Satellite Corporation		Rockville	Maryland
33	Comsat Laboratories		Clarksburg	Maryland
34	TASC		Reading	Massachusetts
35	Pacific-Sierra Research Corporation		Beverly	Massachusetts
36	Applied Analysis		Billerica	Massachusetts
37	The Mitre Corporation	Mail stop K211	Bedford	Massachusetts
38	Deaconess Hospital	Radiology	Boston	Massachusetts
39	Nichols Research Corporation	Edgewater Office Park	Wakefield	Massachusetts
40	Science Applications International Corporation		Billerica	Massachusetts
41	Advanced Computer Resources		Nashua	New Hampshire

42	Crotched Mountain Rehabilitation Center, Inc.		Greenfield	New Hampshire
43	Nicromac Inc.		Englewood	New Jersey
44	Avian Systems, Inc.		Fort Lee	New Jersey
45	GE-CRD		Schenectady	New York
46	Geophysical & Environmental Research Corp.		Millbrook	New York
47	*		Brooklyn	New York
48	Applied Communications Concepts		Durham	North Carolina
49	4pi Analysis, Inc.		Durham	North Carolina
50	KBM Inc.		Grand Forks	North Dakota
51	*		Oklahoma City	Oklahoma
52	Hughes STX Corporation		Souix Falls	South Dakota
53	Falcon Information Technologies		Dallas	Texas
54	Texaco Remote Sensing Laboratory		Houston	Texas
55	E-Systems		Richardson	Texas
56	Texaco		Bellaire	Texas
57	ERIM		Arlington	Virginia
58	The Mitre Corporation Mail Stop W766	Consulting Engineer	McLean	Virginia
59	Advanced Research & Technology Division	Autometric, Inc.	Alexandria	Virginia
60	SPOT Image Corporation		Reston	Virginia
61	SPOT Image Corp.		Reston	Virginia
62	Wyle Laboratories		Arlington	Virginia
63	Flambeau Mining Company	Kennecott	Ladysmith	Wisconsin

Universities - Non-U.S.

1	Australian Centre for Remote Sensing		Belconnen	Australia
2	University College, University of New South Wales	Department of Geography & Oceanography	Campbell	Australia
3	Australian Defence Force Academy	Department of Geography & Oceanography	Campbell	Australia
4	Australian Defense Force Academy	Department of EE	Campbell	Australia
5	Macquarie University	School of Earth Sciences		Australia
6	University of Melbourne	Department of Surveying and Land Information	Parkville	Australia
7	University of Western Australia	Department of Geology and Geophysics	Nedlands	Australia
8	University of New South Wales	Office of Postgraduate Studies	Kensington	Australia
9	Universiti Brunei Darussalam	Department of Geography	Brunei Darussalam	Borneo
10	University of Manitoba	Centre for Earth Observation Science	Winnipeg	CANADA
11	York University	Department of Phiysics and Astronomy	North York	CANADA
12	University of Western Ontario	Department of Geography	London	Canada
13	Universite de Sherbrooke	Departemant de biologie, Faculte des sciences	Sherbrooke	Canada
14	University of Manitoba			Canada
15	McGill University	Department of Geography	Montreal	Canada
16	Universite De Sherbrooke	Dept of Geography and Remote Sensing	Sherbrooke	Canada
17	Earth University	Soil Science	San Jose	Costa Rica
18	*	Lecturer in Geography	Silkeborg	Denmark
19	*	Student	Silkeborg	DENMARK
20	University of Copenhagen	Institute of Geography	Copenhagen	Denmark

21	Liechester University	Department of Zooliogy	Leicester	England
22	Helsinki University of Technology	Lab of Engineering Geology and Geophysics	Espoo	FINLAND
23	Ecole Des Mines De Paris		Sophia	FRANCE
24	Johann-Wolfgang Goethe Universitat	Institut fur Physische Geographie	Sendrenberganlage	Germany
25	National Technical University of Athens	Department of Rural & Surveying Engineering	Zographos	Greece
26	University of Iceland	Department of Electrical Engineering	Reykjavik	ICELAND
27	Tel-Aviv University Ramat- Aviv	Dept of Geophysics and Planetary Sciences	Tel- Aviv	ISRAEL
28	Universita' della Calabria	Dipartimento di Difesa del Suolo	Montalto Uffugo (CS)	Italy
29	The University of Tokyo	Department of Agricultural Engineering	Yayoi, Bunkyo-ku	Japan
30	University of Bergen	Geological Inst. Dept. A.	Bergen	Norway
31	Norwegian Institute of Technology	Dept of Geology & Mineral Resource Eng.	Trondheim	Norway
32	Universidade Nova de Lisboa	Quinta da Torre	Monte da Caparica	Portugal
33	Nanyang Technological University	School of Electrical and Electronic Eng.	Singapore	Singapore
34	Lund University	Department of Physical Geography	Solvegatan	Sweden
35	Stockholm University	Department of Systems Ecology	Stockholm	SWEDEN
36	Ecole Polytechnique Federale de Lausanne	Departement de Genie Rural	Lausanne	SWITZERLAND
37	Universitat Zurich-Irchel	Department of Geography	Zurich	Switzerland

Secondary Schools - Non U. S.

1	Kolding Gymnasium	Department of Geography	Kolding	Denmark
2	Esbjerg Gymnasium		Esbjerg	Denmark
3	"		Aabenraa	Denmark
4	"	Geography Teacher	Hojbjerg	Denmark

Government - Non-U.S.

1	Department of Mines and Energy	Environment Division	Darwin	Australia
2	RAN	Hydrographic Office	North Sidney	Australia
3	NSW Agriculture & Fisheries	Principal Officer(Research Information)	Orange South	Australia
4	Defense Science & Technology Organization		Salisbury	Australia
5	de Impacto Ambiental - CNPMA	Centro Nacional de Pesquisa de Monitoramento e Avaliacao	Caixa Postal 69 - CEP :13.820	Brasil
6	Geological Survey of Canada	Bedford Institute of Oceanography	Dartmouth	Canada
7	Energy, Mines and Resources Canada		Ottawa	Canada
8	Prince Albert National Park	Interpretive Media Specialist	Waskesiu Lake	Canada
9	Forestry Canada	Pacific Forest Centre	Victoria	Canada
10	"		Richmond	Canada
11	Fisheries & Oceans		Winnipeg	Canada
12	Institute for Space and Terrestrial Science	Earth Observations Laboratory	North York	Canada
13	Earth Observations Laboratory	Institute for Space and Terrestrial Science	North York	Canada
14	Canada Centre for Remote Sensing	Applications Technology Division, Forestry	Ottawa	Canada
15	Institute for Space and Terrestrial Sciences	Earth Observations Lab	North York	Canada
16	Ministry of Agriculture	Soil & Water Research Institute	Giza	Egypt (ARE)
17	Earth Observation Sciences		Farnham	ENGLAND
18	Forschungszentrum fur marine Geowissenschaften der Christian-Albrechts-Universitat zu Kiel	GEOMAR	Kiel	Federal Republic of Germany
19	Geological Survey of Finland		Kuopio	Finland
20	Telecom Bretagne/ENST	Image Processing Department /ITI		France

21	DLR	Planetary Remote Sensing	Oberpfaffenhofen	Germany
22	*		Glyfada, Athens	Greece
23	Frostafold 4		Reykjavik	Iceland
24	APSRAC		Hyderabad	India
25	Museo di Storia Naturale della Lunigiana	Laboratorio di Ecologia del Paesaggio	Aulla (MS)	ITALIA
26	National Institute for Agro-Environmental Sciences	Div of Changing Earth and Agro-Environment	Tsukuba	Japan
27	National Institute for Agro-Environmental Sciences	Div of Changing Earth and Agro-Environment	Tsukuba	Japan
28	National Institute for Agro-Environmental Sciences	Div of Changing Earth and Agro-Environment	Tsukuba	Japan
29	Instituto de Ciencias de la Tierra (CSIC)		Barcelona	SPAIN

Commercial & Other - Non-U.S.

1	MacDonald Dettwiler and Associates	% Canada Center for Remote Sensing	Ottawa	Canada
2	Apple Global Education	Curriculum Manager	Aabenraa	Denmark
3	Sun Engineering, Inc.	AB Bldg. 3-1-3 Roppongi	Tokyo	Japan
4	Earth Observation Sciences Ltd.		Farnham	United Kingdom

Table 1. Organizations Receiving a Copy of *MultiSpec*. A * in the Organization Column indicates an individual was the recipient, and the organization is unknown in that case.

A now rapidly growing interest in *MultiSpec* is reflected in the number of requests from schools at the K-12 level, as is apparent from the table. Because of this demand, a version of *MultiSpec* which does not require a math co-processor has been made available, since many Macintosh computers in secondary and primary schools are of the less expensive models which do not have a math co-processor. A distribution license has been granted to The Consortium for Mathematics and Its Applications (COMAP), a National Science Foundation funded program based in Lexington, Massachusetts, for use in their ARISE (Applications/Reform in Secondary Education) program. This is a 5-year project to generate a new mathematics curriculum for grades 9-11. Pilot test sites for their 9^{th} grade curriculum are under way at several sites across the U.S. The curricula for the 10^{th} and 11^{th} grades are to follow a year at a time. The use of space imagery has been found to be a strong motivating factor for secondary level students of math and other fields, and thus MultiSpec can serve as an important enabling tool for secondary school teachers.

It is further noted that with the exception of references [18, 23-25, 45, 57, 67, 76, 80-83], the first authors of each of the 87 references listed below were graduate students reporting on work which was a part of their graduate education. The list contains citations to,

- 4 Master's theses (Benediktsson, Wu, Henderson, and Woo) and,
- 9 PhD theses (Chen, Ghassemian, Kerekes, B. Kim, H. Kim, Benediktsson, Lee, Jeon, and Shahshahani)

which have received support from this grant. In addition, several additional PhD theses are in various stages of their preparation at this time.

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