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SEMIANNUAL RESEARCH PROGRESS SUMMARY

NASA GRANT NAGW-925

EARTH OBSERVATIONAL RESEARCH USING MULTISTAGE EOS-LIKE DATA

Principal Investigators

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Introduction.

This grant is funded as a part of a program in which both research and educational impact are 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 are (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, more recently it has become necessary to focus the work primarily on areas (a) and (c). During the last year, the level of effort on this grant has been reduced to half its previous value. We have also been advised that this grant will end with the current year, thus this will be the penultimate semiannual progress summary.

In the following we shall outline the results obtained over previous reporting periods followed by those of the current reporting period.

Research Directions and Previous Results.

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 ($n \geq 200$),

(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.).

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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 tradtional techniques for dealing with multispectral data may not be as well suited.

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 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 it was felt that one should begin by studying the problem of analysis of hyperspectral data from a quite fundamental point of view. Work was initially 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, 67, 69, 70][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 has also been undertaken. Based upon what has been learned from these studies, practical implementations are being 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 are being 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, 68, 71]

- **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

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

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 will need to become more fully understood if the full potential of such systems is to be realized. The simulator should also be 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].

- **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, 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 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 are then added to the system as they emerge from the research. The current version of this analysis system, now called *MultiSpec*[3], is being distributed

3 © Purdue Research Foundation, 1988-93

freely to requesters. A user's handbook entitled "An Introduction to *MultiSpec*" (65 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 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 any 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 transformation of the existing ones, a feature extraction algorithm, 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, or use of clustering results; compute field and class statistics, and define test fields for use in evaluating classification results quantitatively.

- **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 feature extraction method based directly upon decision boundaries defined by training samples, or (c) a second feature extraction 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 accuracy** results of training or test areas in tabular form on a per field, per class, or groups of classes basis.
- Showing 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.
- Showing 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** any intermediate or final **results**, be it text, B/W image or color image, to other application programs such as word processors, spreadsheet, or graphics program by copying and pasting or by saving and then opening the saved file within another application.

The current implementation already provides a state of the art analysis capability and quite adequate for analyzing multispectral data of large dimensionality. The next phase of its development, to incorporate additions which extend its capabilities toward optimality for hyper-dimensional data, has begun, as can be seen from the above list of capabilities. Such additions will continue and will be drawn largely from research results generated previously in this research program. Examples are new or modified algorithms to aid visualization of data, to select or construct optimal features for use in classification, and algorithms which assist where the number of classes is large. A number of new research results have been obtained during the current period and await implementation into the system.

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 four 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 266 in 34 states and 15 other countries.[4]

	INSTITUTION	DEPARTMENT	City	State
	University - U. S.			
1	University of Arizona	Arizona Remote Sensing Center	Tucson	Arizona
2	University of Arizona	Dept. of Electrical & Computer Engineering	Tucson	Arizona
3	University of California	Dept. of Forestry & Res. Mgmt.	Berkeley	California
4	University of California	College of Natural Resources Computer Services	Berkeley	California
5	University of California	Dept. of LAWR	Davis	California
6	University of California		Davis	California
7	California State University	Biology Dept.	Los Angeles	California
8	University of California	Dept. of Earth & Space Sciences	Los Angeles	California
9	Univ.of California Natural Reserve System	Principal Environmental Planner	Oakland	California
10	San Diego State University	Dept. of Geography	San Diego	California
11	San Jose State University	Dept. of Geography & Environmental Studies	San Jose	California
12	California Polytechnic State University	Dept. of Electrical Engineering	San Luis Obispo	California
13	California Polytechnic State University	Agricultural Engineering Dept.	San Luis Obispo	California
14	Stanford University	Dept. of Biological Sciences	Stanford	California
15	Stanford University	Dept. of Applied Earth Sciences	Stanford	California
16	Yale University	Dept. of Forestry & Environmental Studies	New Haven	Connecticut
17	University of Miami	Dept. of Geography	Coral Gables	Florida
18	University of South Florida	Dept. of Marine Science	St. Petersburg	Florida
19	Southern Illinois Univerisity	Dept. of Geography	Carbondale	Illinois
20	Southern Illinois University	Dept. of Geology	Carbondale	Illinois
21	University of Illinois	National Center for Supercomputing Appl.	Champaign	Illinois
22	Indiana University	Anthropological Center for Training & Global Environmental Change	Bloomington	Indiana
23	Indiana University	Dept. of Anthropology	Bloomington	Indiana
24	Indiana University	Dept. of Geological Sciences	Bloomington	Indiana
25	Indiana University	School of Public & Environmental Affairs	Bloomington	Indiana
26	Indiana Univ./Purdue Univ.- Indianapolis	Dept. of Electrical Engineering	Indianapolis	Indiana

4 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.

SEMIANNUAL RESEARCH PROGRESS SUMMARY
NASA GRANT NAGW-925
September 30, 1993

27	University of Indianapolis	Dept. of Earth, Space, & General Studies	Indianapolis	Indiana
28	Indiana State University	Dept. of Geography	Terre Haute	Indiana
29	Rose-Hulman Institute of Technology		Terre Haute	Indiana
30	Purdue University	Earth & Atmos. Sciences Dept.	West Lafayette	Indiana
31	Purdue University	Liberal Arts & Education	West Lafayette	Indiana
32	Purdue University	Dept. of Agronomy	West Lafayette	Indiana
33	Purdue University	Dept. of Agricultural Engineering	West Lafayette	Indiana
34	Murray State University	Mid-America Remote Sensing Center	Murray	Kentucky
35	Northeastern University	Marine Science Center	Nahant	Maine
36	John Hopkins University	Dept. of Earth & Planetary Sciences	Baltimore	Maryland
37	Johns Hopkins School of Medicine		Baltimore	Maryland
38	University of Maryland	Paterson Mac Lab	College Park	Maryland
39	University of Maryland	Dept. of Geography	College Park	Maryland
40	University of Massachusetts	Biology Dept.	Boston	Massachusetts
41	Harvard University	Nick Marsh-Armstrong Biological Labs	Cambridge	Massachusetts
42	Salem State College	Professor of Cartography	Danvers	Massachusetts
43	University of Michigan	Dept. of Elect & Comp. Sci.	Ann Arbor	Michigan
44	University of Michigan	Dept. of Elect & Comp. Sci.	Ann Arbor	Michigan
45	Gustavus Adolphus College	Dept. of Geography	Saint Peter	Minnesota
46	University of Minnesota	Dept. of Forestry	St. Paul	Minnesota
47	University of New Hampshire	Computing & Information Services	Durham	New Hampshire
48	University of New Hampshire	Dept. of Natural Resources	Durham	New Hampshire
49	University of New Hampshire	CSRC/SERB	Durham	New Hampshire
50	University of New Hampshire	Forest Resources	Durham	New Hampshire
51	Dartmouth College	Dept. of Earth Sciences	Hanover	New Hampshire
52	Keene State College	Science Division - Geology	Keene	New Hampshire
53	Princeton University	Dept. of Geology	Princeton	New Jersey
54	Princeton University	Dept. of Ecology & Evolutionary Biology	Princeton	New Jersey
55	Polytechnic University		Brooklyn	New York
56	State University of New York	Dept. of Geography	Geneseo	New York
57	Syracuse University	Dept. of Geography	Syracuse	New York
58	Syracuse University	Northeast Parallel Architectures Center	Syracuse	New York
59	University of North Dakota	Dept. of Space Studies	Grand Forks	North Dakota
60	University of North Dakota		Grand Forks	North Dakota
61	University of North Dakota	Scientific Computing Center	Grand Forks	North Dakota
62	University of Cincinnati	Dept. of Chemistry	Cincinnati	Ohio
63	University of Oregon	Dept. of LANDscape Architecture	Eugene	Oregon
64	University of South Carolina	Dept. of Geography	Columbia	South Carolina
65	University of South Carolina	Dept. of Geological Sciences	Columbia	South Carolina
66	Texas Christian University	Dept. of Geography Box 30798	Fort Worth	Texas
67	Texas A&M University	Texas Maritime College	Galveston	Texas
68	Univ. of Texas M.D. Anderson Cancer Center		Houston	Texas
69	Univ. of Texas M.D. Anderson Cancer Center		Houston	Texas
70	College of Forestry		Nachogdoches	Texas
71	Trinity University	Geography	San Antonio	Texas

72	Univ. Texas - Pan American	Coastal Studies Laboratory	South Padre Island	Texas
73	Baylor University	Dept. of Geology	Waco	Texas
74	The University of Vermont	Dept. of Geography	Burlington	Vermont
75	Middlebury College	Geography Dept.	Middlebury	Vermont
76	George Mason University	Dept. of Electrical & Computer Engineering	Fairfax	Virginia
77	College of William & Mary	School of Marine Science	Gloucester Point	Virginia
78	Central Washington University	Director GIS Laboratory	Ellensburg	Washington
79	University of Washington	Dept. of Geological Sciences	Seattle	Washington
80	Fairmont State College	Div. of Science, Math. & Health Careers	Fairmont	West Virginia
81	Wheeling Jesuit College	NASA Classroom of the Future	Wheeling	West Virginia
82	University of Wyoming	Dept. of Geology & Geophysics	Laramie	Wyoming
	Secondary Schools - U. S.			
1	Grizzly Hill School		North San Juan	California
2	Northview High School		Brazil	Indiana
3	Carmel High School		Carmel	Indiana
4	Liberty Middle School		Chesterton	Indiana
5	Highland High School		Highland	Indiana
6	Arlington High School		Indianapolis	Indiana
7	North Central High School		Indianapolis	Indiana
8	Tecumseh Middle School		Lafayette	Indiana
9	Sarah Scott Junior High School		Terre Haute	Indiana
10	Sarah Scott Junior High School		Terre Haute	Indiana
11	Woodrow Wilson Junior High School		Terre Haute	Indiana
12	Waldron Jr/Sr High School		Waldron	Indiana
13	West Lafayette High School		West Lafayette	Indiana
14	Coffin School		Cape Elizabeth	Maine
15	South Portland High School		South Portland	Maine
16	Lincoln Northeas High School		Lincoln	Nebraska
17	A Crosby Kennett High School	Math/Sci/Computer Coordinator	Conway	New Hampshire
18	Pinkerton Academy		Derry	New Hampshire
19	Fall Mountain High School		Alstead	New Hampshire
20	Souhegan High School		Amherst	New Hampshire
21	Belmont Junior High School		Belmont	New Hampshire
22	Concord High School		Concord	New Hampshire
23	Rundlett Junior High School		Concord	New Hampshire
24	Maple Street School		Contoocook	New Hampshire
25	Dover High School		Dover	New Hampshire
26	Exeter Area Junior High School		Exeter	New Hampshire
27	Philips Exter Academy	Dept. of Science	Exeter	New Hampshire
28	Gilmanton School		Gilmanton IW	New Hampshire
29	Crotched Mountain Rehabilitation Center, Inc.		Greenfield	New Hampshire
30	Hollis/Brookline High School		Hollis	New Hampshire
31	Conant High School		Jaffrey	New Hampshire
32	Keene High School		Keene	New Hampshire

33	Mast Way Elementary School		Lee	New Hampshire
34	Elm Street Junior High School		Nashua	New Hampshire
35	Kenneth A. Brett School		Tanworth	New Hampshire
36	The Whitefield School		Whitefield	New Hampshire
37	Tibbetts Junior High School		Farmingtron	New Mexico
38	Northeast Middle School		Bethelem	Pennsylvania
	Government -Local, State, Federal - U. S.			
1	U. S. Geological Survey		Flagstaff	Arizona
2	Lawrence Livermore National Laboratory	Applied Technology Division	Livermore	California
3	Lawrence Livermore National Laboratory		Livermore	California
4	U. S. Geological Survey		Menlo Park	California
5	NASA Ames Research Center	USGS	Moffett Field	California
6	NASA Ames Research Center	Ecosystem Science & Tech. Branch	Moffett Field	California
7	NASA Ames Research Center	JCWS	Moffett Field	California
8	NASA Ames Research Center		Moffett Field	California
9	NASA Jet Propulsion Lab		Pasadena	California
10	NASA Jet Propulsion Lab		Pasadena	California
11	NASA Jet Propulsion Laboratory		Pasadena	California
12	NASA Jet Propulsion Laboratory		Pasadena	California
13	NASA Jet Propulsion Laboratory		Pasadena	California
14	NASA Jet Propulsion Laboratory		Pasadena	California
15	Joint Ice Center		Washington	DC
16	NASA Headquarters	Code SEP	Washington	DC
17	NASA Headquarters		Washington	DC
18	Naval Research Lab	Code 9120	Washington	DC
19	Naval Research Laboratory	Code 5640	Washington	DC
20	NOAA	NESDIS	Washington	DC
21	Smithsonian Institute		Washington	DC
22	NASA Kennedy Space Center		Kennedy Space Center	Florida
23	South Florida Water Management District		West Palm Beach	Florida
24	Indiana Dept. of Natural Resources		Indianapolis	Indiana
25	Information Services Section	Dept. of Environmental Quality	Baton Rouge	Louisiana
26	The Nature Conservancy of Louisiana	GIS Coordinator	Baton Rouge	Louisiana
27	Well National Estuarine Research Reserve		Wells	Maine
28	USDA ARS		Beltsville	Maryland
29	National Institutes of Health	NCRR	Bethesda	Maryland
30	NASA Goddard Space Flight Center	Laboratory for Atmospheres	Greenbelt	Maryland
31	NASA Goddard Space Flight Center	Laboratory for Atmospheres	Greenbelt	Maryland
32	NASA Goddard Space Flight Center		Greenbelt	Maryland
33	USRA/GSFC		Greenbelt	Maryland
34	NASA Goddard Space Flight Center		Greenbelt	Maryland
35	NASA Goddard Space Flight Center	National Space Science Data Center	Greenbelt	Maryland
36	Museum of Science		Boston	Massachusetts
37	NASA Stennis Space Center	Space Remote Sensing Center	Stennis Space Center	Mississippi

38	USDA Forest Service		Durham	New Hampshire
39	Army Corp of Engineers	CRREL/Geological Sciences Branch	Hanover	New Hampshire
40	Army Corp of Engineers	CRREL/Remote Sensing/GIS Center	Hanover	New Hampshire
41	Los Alamos National Laboratory		Los Alamos	New Mexico
42	Los Alamos National Laboratory		Los Alamos	New Mexico
43	Los Alamos National Laboratory		Los Alamos	New Mexico
44	USDA Forest Service	Northeastern Forest Exp. Station	Radnor	Pennsylvania
45	NASA Johnson Space Center		Houston	Texas
46	NASA Johnson Space Center	Flight Science Support Office	Houston	Texas
47	Lamoille County Planning Commission	GIS PLANNER	Morrisville	Vermont
48	U.S. Army Corp of Engineers	Topographic Engineering Center	Ft. Belvoir	Virginia

Commercial & Other - U. S.

1	Alpine Exploration Group		Tucson	Arizona
2	*		Tucson	Arizona
3	SciComp Software		Cupertino	California
4	The Aerospace Corporation		Los Angeles	California
5	ConverseWardDavisDixon		Oakland	California
6	Sensible Research		Palo Alto	California
7	*		Sacramento	California
8	Ramtek Systems Division		San Jose	California
9	*		San Jose	California
10	Third Point Systems		Santa Monica	California
11	Third Point Systems, Inc.		Santa Monica	California
12	Carnegie Institution of Washington		Stanford	California
13	ESL, Inc. MS406		Sunnyvale	California
14	Geodynamics Co.		Torrance	California
15	Aspen Global Change Institute		Aspen	Colorado
16	Ball Aerospace Systems Group		Boulder	Colorado
17	*		Danbury	Connecticut
18	E.I. Dupont		Wilmington	Delaware
19	Landmark Technologies, Inc.		Jacksonville	Florida
20	*		Jupiter	Florida
21	Resource Dynamics Company (R.D.C.)		Athens	Georgia
22	SETS Technology, Inc.		Mililani	Hawaii
23	*		Hailey	Idaho
24	*		Buffalo Grove	Illinois
25	ITT Aerospace/Communciations Division		Fort Wayne	Indiana
26	DowElanco		Indianapolis	Indiana
27	Bennett & Peters Inc		Baton Rouge	Louisiana
28	ARKLA Exploration Co.		Shreveport	Louisiana
29	Capeshore Data		Hanover	Maine
30	Comsat Laboratories		Clarksburg	Maryland
31	Earth Observations Satellite Corp.		Lanham	Maryland
32	Earth Satellite Corporation		Rockville	Maryland

33	Science Applications International Corp.		Billerica	Massachusetts
34	MIT Lincoln Labs		Lexington	Massachusetts
35	TASC		Reading	Massachusetts
36	*		Eureka	Nevada
37	Advanced Computer Resources		Nashua	New Hampshire
38	Nicromac Inc.		Englewood	New Jersey
39	*		Brooklyn	New York
40	Island Institute Inc.		New York	New York
41	GE-CRD		Schenectady	New York
42	KBM Inc.		Grand Forks	North Dakota
43	*		Oklahoma City	Oklahoma
44	*		Eugene	Oregon
45	Hughes STX Corporation		Souix Falls	South Dakota
46	Falcon Information Technologies		Dallas	Texas
47	E-Systems		Richardson	Texas
48	ERIM		Arlington	Virginia
49	SPOT Image Corporation		Reston	Virginia
50	*		Vienna	Virginia
51	Pacific Northwest Laboratory		Richland	Washington

Universities - Non-U.S.

1	Australian Centre for Remote Sensing		Belconnen	Australia
2	Australian Defence Force Academy	Dept. of Geography & Oceanography	Campbell	Australia
3	Australian Defense Force Academy	Dept. of EE	Campbell	Australia
4	University College, University of New South Wales	Dept. of Geography & Oceanography	Campbell	Australia
5	University of Melbourne	Dept. of Surveying & Land Information	Parkville	Australia
6	Universiti Brunei Darussalam	Dept. of Geography	Brunei Darussalam	Borneo
7	University of Western Ontario	Dept. of Geography	London	Canada
8	Helsinki University of Technology	Lab of Engineering Geology & Geophysics	Espoo	Finland
9	Johann-Wolfgang Goethe Universitat	Institut fur Physische Geographie	Frankfort am Main	Germany
10	National Technical University of Athens	Dept. of Rural & Surveying Engineering	Zographos	Greece
11	University of Iceland	Dept. of Electrical Engineering	Reykjavik	Iceland
12	Tel-Aviv University Ramat- Aviv	Dept. of Geophysics & Planetary Sciences	Tel-Aviv	ISRAEL
13	University of Tokyo	Dept. of Agricultural Engineering	Tokyo	Japan
14	University of Bergen	Geological Inst. Dept. A.	Bergen	Norway
15	Universidade Nova de Lisboa	Quinta da Torre	Monte da Caparica	Portugal
16	Nanyang Technological University	School of Electrical & Electronic Engineering	Singapore	Singapore
17	Lund University	Dept. of Physical Geography	Lund	Sweden
18	Ecole Polytechnique Federale de Lausanne	Departement de Genie Rural	Lausanne	Switzerland
19	Universitat Zurich-Irchel	Dept. of Geography	Zurich	Switzerland

Government - Non-U.S.

1	Dept. of Mines & Energy	Environment Division	Darwin	Australia
2	RAN	Hydrographic Office	North Sidney	Australia
3	NSW Agriculture & Fisheries	Research Information	Orange South	Australia
4	Defense Science & Technology Org.		Salisbury	Australia

5	Geological Survey of Canada	Bedford Institute of Oceanography	Dartmouth	Canada
6	Institute for Space & Terrestial Science	Earth Observations Laboratory	North York	Canada
7	Energy, Mines & Resources Canada		Ottawa	Canada
8	Forestry Canada	Pacific Forest Centre	Victoria	Canada
9	Soil & Water Research Institute	Chief Researcher	Ginza	Egypt (ARE)
10	Geological Survey of Finland		Kuopio	Finland
11	Ecole Des Mines De Paris		Sophia	FRANCE
12	Forschungszentrum fur marine Geowissenschaften der Christian-Albrechts-Universitat zu Kiel	GEOMAR	Kiel	Germany
13	DLR	Planetary Remote Sensing	Oberpfaffenhofen	Germany
14	APSRAC		Hyderabad	India
15	Museo di Storia Naturale della Lunigiana	Laboratorio di Ecologia del Paesaggio	Aulla	ITALIA
16	Nat. Inst. for Agro-Environ. Sci.	Div. of Changing Earth & Agro-Environ.	Tsukuba	Japan
17	Nat. Inst. for Agro-Environ. Sci.	Div. of Changing Earth & Agro-Environ.	Tsukuba	Japan
18	Nat. Inst. for Agro-Environ. Sci.	Div. of Changing Earth & Agro-Environ.	Tsukuba	Japan

Commercial & Other - Non-U.S.

1	MacDonald Dettwiler & Assoc.	% Canada Center for Remote Sensing	Ottawa	Canada
2	MacDonald Dettwiler & Assoc.		Richmond	Canada
3	Frostafold 4		Reykjavik	Iceland
4	Sun Engineering, Inc.		Tokyo	Japan

Table 1. Organizations Receiving a Copy of *MultiSpec.*
A * in the Organization Column indicates an individual was the recepient, 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. At this time, the granting of a distribution license is pending for 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 9th grade curriculum are to be in schools in Madison Wisconsin, St. Louis, Missouri, and New Brunswick, New Jersey this fall. The curricula for the 10th and 11th 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, 75, 79], the first authors of each of the 73 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,

- 8 PhD theses (Chen, Ghassemian, Kerekes, B. Kim, H. Kim, Benediktsson, Lee, and Jeon)

which have received support from this grant. In addition,

- 3 additional PhD theses

are in various stages of their preparation at this time.

Bibliography of Previous Results.

Following is a bibliography of papers, reports, theses, published abstracts, and presentations produced previously by work supported by this grant.

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Results During the Current Reporting Period.

A bibliography of papers which appeared or were accepted to appear during the current reporting period is given below. A brief explanation of the contents of each publication follows.

Much of the work of previous years was of the nature of establishing fundamental understanding about the new situation which high dimensional data presents, and about what users of analysis technology will want to do in the face of the new possibilities which high dimensional spectral data provides. Work has more recently been turned to utilizing the fundamental knowledge thus obtained to formulate practical algorithms and procedures which match the possibilities and desires.

For example, while it is fundamentally true that relative classifiers may be expected to be more powerful than absolute ones, (i.e., discrimination between a complete list of classes is potentially a more powerful approach than identification of a single class), it is more common for Earth scientists to want to identify one or a small number of materials in the scene, and they ordinarily do not want to be required to define an exhaustive list of classes. Thus, while the general approach of multivariant pattern recognition is the most relevant to this problem, several ideas extending this body of theory are being pursued to result in algorithms which require training of only one or a small number of classes, but retain the advantages of having trained all classes in the scene. References [76], [77], and [78] reports on some results obtained for doing this. References [76] and [77] provide some preliminary results on the use of unlabeled samples, in addition to labeled (training) samples and modeling unknown classes so as to improve the accuracy of an analysis of such data. Reference [78] provides some further results on a different approach to dealing with circumstances where training samples are available for only a portion of the classes which exist in the data set.

References [72], [75] and [79] provide discussions of some of the key characteristics of high dimensional multispectral data which have been found in previous work and provide some new ways to view such data. References [73] and [74] relate to the matter of using a neural network implementation to analyze high dimensional multispectral data.

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