EARLY SIMULATION RESULTS OF THE ARIES-1 SATELLITE SENSOR FOR MULTI-TEMPORAL VEGETATION RESEARCH DERIVED FROM AVIRIS

Ray Merton
Department of Geography
University of Auckland
Auckland, New Zealand.
r.merton@auckland.ac.nz
http://www.geog.auckland.ac.nz/public/merton

Jon Huntington
CSIRO Exploration and Mining, & ARIES Consortium
Sydney, Australia.
j.huntington@syd.dem.csiro.au
http://www.syd.dem.csiro.au/unrestricted/people/HuntingtonJon

1. INTRODUCTION

The Australian-based ARIES Consortium (Australian Resource Information and Environment Satellite), a commercial joint venture between CSIRO and private industry, is on track for deployment of the ARIES-1 hyperspectral resource mapping satellite in the year 2001/2002. The ARIES-1 spectrometer will be an area array scanning up to 105 spectral bands between 0.4 - 2.5µm at 30m spatial resolution. The satellite will also include a 10m panchromatic high spatial resolution imager.

With the deployment of hyperspectral sensors into Earth orbit, repeat coverage of sites will shortly enable spectral trajectories of vegetation to be compared on an inter-annual basis. Variations between datasets may indicate important ecological change related to increasing vegetation stress, plant succession, and spectral shifts associated with biogeochemical anomalies or changing environmental influences. The ARIES-1 system will provide a new tool for identifying inter-annual spectral shifts relating to succession and environment change at a significantly higher spectral resolution than current orbital multispectral sensors.

This paper utilizes multi-temporal AVIRIS data from Jasper Ridge, California, to simulate the likely performance of the ARIES-1 sensor for application to vegetation research. This research is linked to ongoing AVIRIS-based studies focusing on the design and utilization of a hybrid set of narrow-band vegetation indices at a range of landscape scales. Furthermore, the research aims to identify an appropriate single red-edge descriptor for vegetation stress analysis, defined not only by statistical techniques but by the identification and measurement of common red-edge geometric points. Defining complex red-edge symmetry through a range of simple measures has potential for seasonal and long-term vegetation monitoring at the community and global scales.

The construction of multi-temporal ARIES-1 datacubes provides a rare opportunity to examine the suitability of ARIES-1 as a new tool for producing ecologically meaningful data associated with changing vegetation phenology and stress. A selection of early simulation results provides an overview of the performance anticipated from the ARIES-1 sensor, specific to multi-temporal community scale vegetation research.

1.1 ECOLOGICAL CONTEXT

Remote sensing information is increasingly being used to quantitatively improve an understanding of how the Earth functions as an ecosystem. Spaceborne remote sensing is becoming an integral part of research programs because it provides the only means of observing global ecosystems regularly, consistently and synoptically. Imaging spectroscopy has also been identified as a valuable tool for clarifying relationships between the atmosphere and vegetation, in addition to the feedback and influence of vegetation on climate, both regionally and globally (Shukla Nobre, Sellers, 1990; Roughgarden, 1991).

In order to predict ecological responses to environmental change for example, it is necessary to understand, measure, and model the functioning of biotic, atmospheric, and hydrospheric processes and their interactions with community structures at different temporal and spatial scales. As this research focuses at the community scale, it provides a suitable link to ongoing and future multi-temporal research from high/low altitude aerial sensors such as AVIRIS, and to future orbital sensors such as ARIES-1. Although it is important to recognize the spectral contribution of individuals in a community, most global scale research with future high spectral resolution orbital sensors will be particularly suited to the identification of community-level dynamics.

Imaging spectroscopy can be applied in ecology to monitor change including successional change, land use change, deforestation, environmental change (Hobbs 1990, Pickup 1990; Roughgarden *et al.*, 1991). Monitoring of change is one of the most important contributions high spectral resolution remote sensing technology can make to studies of global ecology.

The development of a new series of sensors using area arrays from dedicated free-flying orbital platforms is considered one of the ultimate goals for this area of scientific research. The advantages of satellite platforms include: the ability for repeat coverage, an off-nadir pointing option, larger swath width, reduction in geometric anomalies, elimination of platform instability, global coverage, elimination of operational down-time between flights, elimination of pre-flight and annual sensor calibrations, and a significant reduction in the cost of imagery. Lawrence, Williams, Ranson, Irons, Walthall (1994) comment that the repetitive, multi-scale, multispectral observation capabilities afforded by satellite sensors makes remote sensing data 'one of the premier tools for ecosystem modeling, environmental assessment, and the detection of global change' (Lawrence *et al*., 1994, p204).

Vegetation can be viewed as a dynamic system that is capable of responding directly to environmental pressures and change. By recognizing characteristic spectral reflectance features from selected vegetation, levels of biological stress and strain can be quantified at species, community, and ecosystem scales. As most research to date has been performed at the leaf, canopy, and community scales, the next challenge for orbital sensors such as ARIES-1 is to provide stronger links towards regional and global scales.

2. STUDY SITE AND DATA

The study site, Jasper Ridge Biological Preserve, is a 500ha natural area owned by the Stanford University, and has been used for research and instruction continuously since 1891 (JRBP, 1997). Jasper Ridge Biological Preserve is located in the foothills along the north-eastern margins of the Santa Cruz Mountains, CA, approximately 7km west of Palo Alto at 37°24'00"N, 122°13'30"W.

2.1 VEGETATION COMMUNITIES

Six communities are selected to identify an environmental gradient that spans the mesic to near-xeric environments found in the Jasper Ridge Biological Preserve. By including a selection of disparate communities along this gradient, it is possible to not only fully interpret community spectral and multi-temporal trends associated with stress, but also complex inter-community relationships. Rarely can such a disparate range of communities be identified within the swath of a single hyperspectral image. As ongoing research focuses on biogeochemical stress analysis, many communities located at Jasper Ridge retain the nomenclature representative of the underlying geology/soil (Merton, 1994).

The following is a brief description of communities. *Serpentine community*: restricted to the main serpentine deposit as a narrow-endemic tolerant of high geochemical toxicity and near-xeric conditions. Representative species include *Stipa pulchra* and *Eschscholzia californica*. *Sandstone community*: predominantly annual grassland species located on a sandstone substrate. Representative species include a range of annual grasses especially *Bromus rigidus*. *Halo community*: located in the moderate toxicity zone (geochemical halo) and is influenced by mobile serpentine-derived geochemicals. This distinctive community is regarded as an intermediate between the serpentine and sandstone communities. *Chaparral community*: a fire-climax community situated on dry southwest facing slopes containing chamise chaparral, *Prunus* chaparral, and *Baccharis* shrub. *Woodlands community*: an open canopy community situated predominantly on northwest slopes containing a range of oaks, buckeyes, and laurels. *Redwood community*: dense stands of *Sequoia sempervirens* are located adjacent to San Francisquito Creek to the north of Jasper Ridge.

2.2 AVIRIS DATASETS

Five AVIRIS datasets are selected to construct a near-consecutive multi-temporal database. Chronological five-date imagery is not available in any one year. Therefore, two spring datasets from 5 April 1996 (early spring) and 30 April 1994 (late spring) are combined with the consecutive 1992 datasets of 2 June (summer), 1 September (early autumn), and 6 October (late autumn). Non-sequential datasets are substituted into the beginning of the series to provide a valuable indication of spring spectral responses. Additionally, important environmental variables that strongly influence vegetation such as precipitation and temperature did not vary significantly between dataset years. The period between 2 June and 1 September is the largest with a 91 day interval. Ideally, another dataset flown in this period would have provided additional information on summer trends.

2.3 THE ARIES-1 SENSOR

A selection of early simulation results for the ARIES-1 satellite is included here to provide an overview of the performance anticipated from orbital sensors, specific to community scale vegetation research (Merton, *1999*). Importantly, the ARIES-1 system will incorporate for the first time a spectrometer *area array* instead of a single *line array* producing superior scan characteristics. Specification of the ARIES-1 satellite system are shown in Table 2.1.

Table 2.1 ARIES-1 Satellite System Specifications.

Satellite	C.O.T.S design, Weight: less than 500 kg
Orbit	Polar, sun synchronous, 500km above the Earth's surface
Sensors	• Australian designed and built, 105 contiguous bands: • visible and near infrared; (0.4 - 1.0um, 19nm FWHM), • optional bands between 1.0 - 2.0um (15 & 30nm FWHM) for sensor and atmospheric correction/calibration, • contiguous bands in the SWIR (2.0 - 2.5um, 15nm FWHM), • Panchromatic sensor
Spatial Resolution	Spectrometer - 30 metres at nadir, Pan - 10 metres
Ground Swath	15km at nadir
Off Track Pointing	+/- 30 degrees off vertical
Revisit Time	7 days at 30 degrees look angle
Command and Control	Australian based

Data Reception and Archiving	Australia and through overseas network
Launch Date	Late 2001

3. METHODS

The red-edge, centered at the largest change in reflectance per wavelength change, is located between two of the most widely used wavelength regions used for broad band vegetation studies, the red trough and the NIR plateau, and may hold valuable information that may benefit aspects of ecological-based research. Eight band high spectral resolution AVIRIS data encompassing the red-edge (670 - 760nm) has been used to describe community phenological response through time as a function of changes to red-edge symmetry (Merton, 1998; *1999*). This research utilizes AVIRIS red-edge data to simulate the spectral performance of the proposed ARIES-1 sensor over these "vegetation bands".

The objectives of this study require that the five ATREM (Gao, Heidebrecht, Goetz, 1996) calibrated AVIRIS datasets be resampled to simulate ARIES-1 reflectance data prior to vegetation analysis. All red-edge data is subsequently resampled from ~8.6nm (variable) FWHM AVIRIS values, to simulated 19.1nm FWHM ARIES-1 values.

Remote sensing indices are commonly cited as important tools for deriving vegetation properties at appropriate scales for ecosystem studies, ranging across leaf, community, and synoptic scales. A selection of geometric indices are used in this paper as important indicators against which multi-temporal vegetation dynamics can be compared at the community scale. The indices and measures include the Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1973), Red-edge Vegetation Stress Index (RVSI) (Merton, 1998), a new ARIES-1 index under trial ρ''_{728} (second-derivative value at 728nm), and are defined as:

1. **NDVI:** as a modified narrow-band equivalent is calculated as:

$$NDVI = \frac{\rho_{767} - \rho_{671}}{\rho_{767} + \rho_{671}}$$

Equation 1. Normalized Difference Vegetation Index.

where:

ρ_{671} = reflectance at 671nm
ρ_{767} = reflectance at 767nm

2. **RVSI:** is developed to identify inter- and intra-community vegetation stress trends based on spectral changes in upper red-edge geometry. In simple terms, reflectance spectra with upper red-edge convexity calculate negative RVSI values indicating low vegetation stress, whereas upper red-edge spectra with near-linear or concave curves indicate an "apparent stress" response (Merton, 1998;*1999*). The RVSI is defined as:

$$RVSI = \left(\frac{\rho_{714} + \rho_{752}}{2}\right) - \rho_{733}$$

Equation 2. Red-Edge Vegetation Stress Index.

where:

ρ_{714} = reflectance at 714nm
ρ_{733} = reflectance at 733nm
ρ_{752} = reflectance at 752nm

3. ρ''_{728} **values:** as most vegetation exhibits increasing reflectance values between the red trough and the NIR plateau, the first-derivative (ρ') and second-derivative (ρ'') transformations are designed to emphasize subtle absorption/reflection features as deviations along the otherwise near-linear red-edge. Reflectance derivatives are defined by the second iteration of the following equation:

$$\rho'_i = \frac{(R\lambda_{i-g} - R\lambda_{i+g})}{\Delta\lambda}$$

Equation 3. Derivative Calculation.

where:

ρ'_i = first difference transformation at band i,
g = band gap,
$R\lambda_{i-g}$ = reflectance at the i-g waveband,
$R\lambda_{i+g}$ = reflectance at the i+g waveband,
$\Delta\lambda$ = center to center span in wavelength between the bands 2g apart.

Multi-temporal second-derivative plots centered at the 733nm band (ρ''_{733}) have recently been identified from AVIRIS data as responding to patterns of environment-induced vegetation stress (Merton, *1999*). There is sufficient variation in the equivalent ARIES-1 ρ''_{728} values across all communities and dates for this waveband to be trailed as a simple yet sensitive single band indicator of community stress in ARIES-1 data.

The hysteresis component of this research attempts to model change between selected spectral measures to improve interpretation of complex multi-temporal trends relating to plant phenology. Hysteresis is a form of analysis commonly used in geology to model multi-event data. Hysteresis is adapted to the spectral domain to describe a bivariate plot which evidences a looped form (Merton, 1998;*1999*). Elastic hysteresis events results in a displacement of data values along a trajectory with cyclicity being described as either clockwise or anti-clockwise. Spectral hysteresis curves are constructed from paired data values calculated from any combination of spectral indices/measures, plotted as multi-temporal coordinates. Sequential time-series data calculated for each community form unique hysteresis trends that describe both intra- and inter-community multi-temporal relationship between the two variables (Merton, *1999*). Plotting patterns of hysteresis between data points is achieved through the application of “exponential smoothing” functions to extrapolate data trajectories as spline lines.

With the current emphasis on the deployment of hyperspectral sensors into Earth orbit, the hysteresis model may provide an effective tool for identifying inter-annual spectral shifts relating to succession and environmental change, at a significantly higher spectral resolution than current multispectral investigations.

4. RESULTS

This section summarizes into graphical output a selection of multi-temporal red-edge reflectance and second-derivative data from the five dates and six vegetation classes. Comparative analyses of complex red-edge datasets distil the spectral information into single quantifiable variables, which can be plotted as community time-series trends. These techniques enhance the ability to monitor intra- and inter-community change responding to seasonal effects.

4.1 MULTI-TEMPORAL ARIES-1 NDVI VALUES

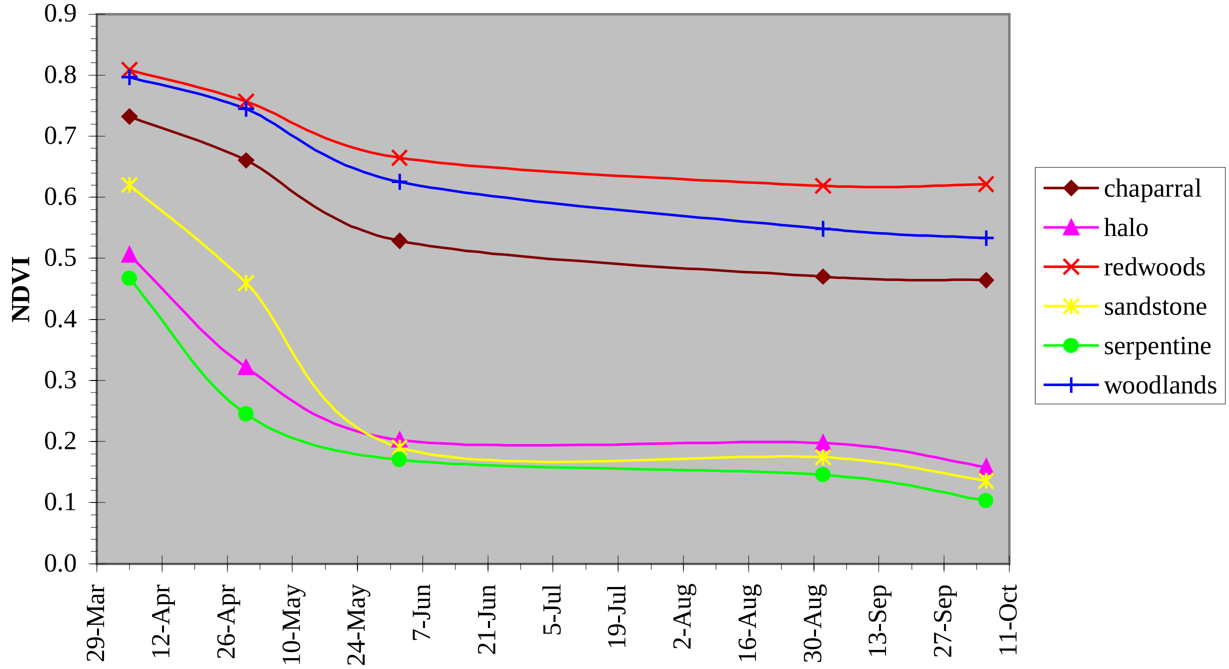

Figure 1. Plot Of ARIES-1 Multi-Temporal Mean NDVI Values Calculated For Jasper Ridge Communities.
Note: Dataset dates = 5 April 1996 (early autumn), 30 April 1994 (late autumn), 2 June 1992 (summer), 1 September 1992 (early autumn), and 6 October 1992 (late autumn). Spline line are drawn to indicate trends between data points only.

Figure 1 shows that annual NDVI values vary widely amongst the seven Jasper Ridge vegetation communities, especially from late spring onwards. NDVI values for all communities exhibit an abrupt decline over the spring to summer period. The trend over the spring period may be interpreted as a transition from early spring high productivity to low productivity summer conditions.

4.2 ARIES-1 RVSI AND NDVI HYSTERESIS CURVES

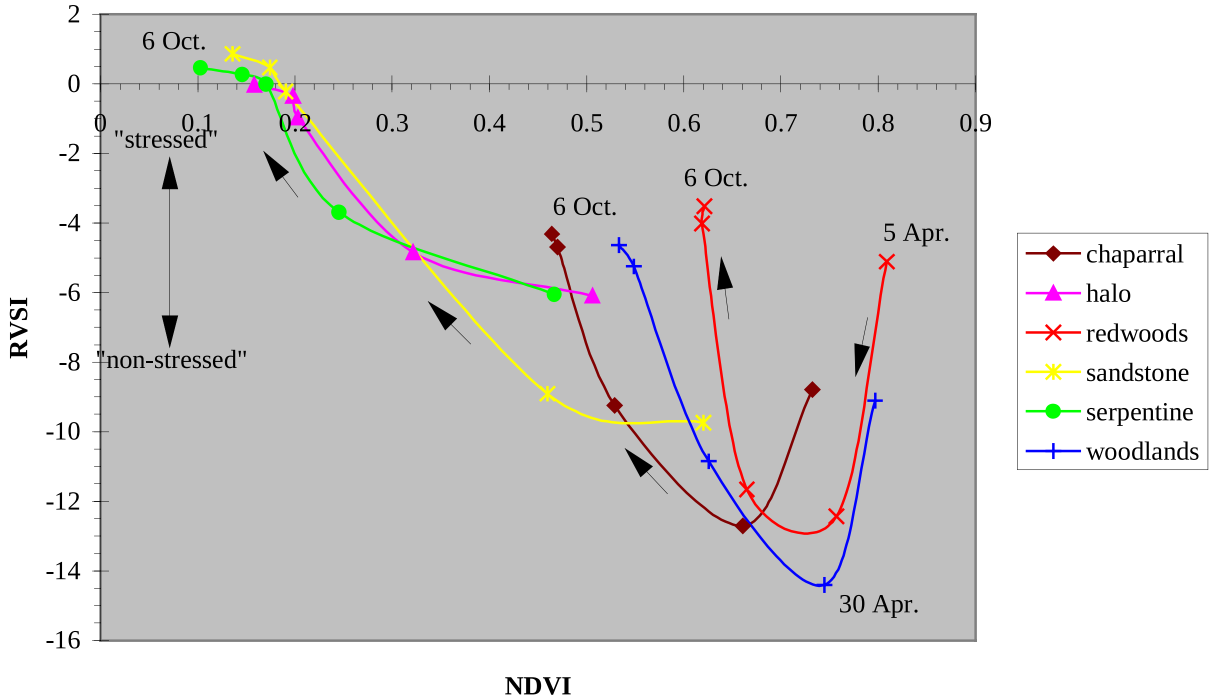

Figure 2. Hysteresis Plot Showing The Multi-Temporal Relationship Between ARIES-1 RVSI Values And NDVI Values.

Note: arrows indicate the direction of hysteresis. Dataset dates: 5 April, 30 April, 2 June, 1 September, 6 October. Spline lines between data values are exponentially smoothed to indicate data trends.

Most communities in Figure 2 display a clockwise direction of hysteresis between RVSI and NDVI values. However, a general trend towards decreasing RVSI values and increasing NDVI values is characterized by a drift from near-linear trajectories (e.g. serpentine) towards strongly cyclic hysteresis trajectories (e.g. redwoods). The direction of this trend is consistent with a decreasing environmental stress gradient (Merton, *1999*). Hysteresis curves illustrated in Figure 2, also highlight interesting temporal relationships between RVSI and NDVI values. The redwoods community for example, displays abrupt reversals in RVSI trend, whilst NDVI in contrast steadily declines over the same period.

4.3 MULTI-TEMPORAL ARIES-1 ρ''_{728} VALUES

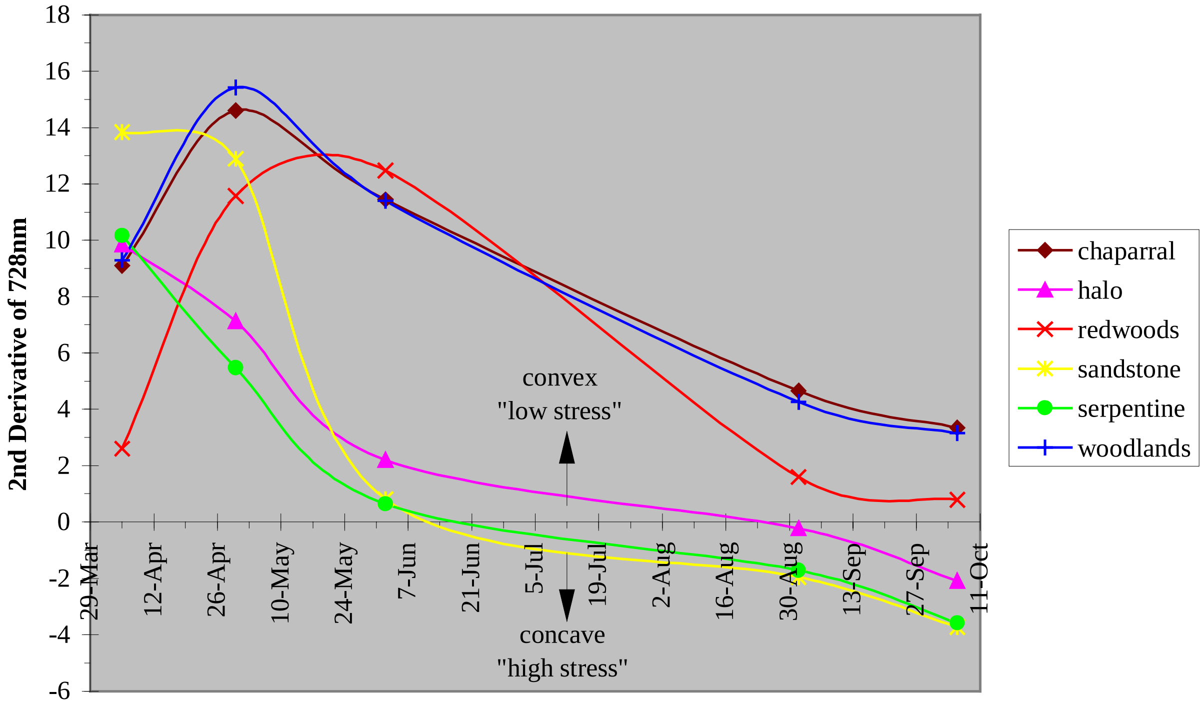

Figure 3. Multi-Temporal ARIES-1 728nm Band Second-Derivative Reflectance Value Trends For Jasper Ridge Communities.
Note: arrows indicate the direction of hysteresis. Dataset dates: 5 April, 30 April, 2 June, 1 September, 6 October. Spline lines between data values are exponentially smoothed to indicate data trends.

Large positive values at the 728nm band indicate “low stress” curves, whereas large negative values indicate “high stress” curves. However, thresholds between stressed and non-stressed responses for disparate communities are likely to be variable, and can not therefore be fixed at $\rho''_{728} = 0$.

With the exception of sandstone and redwoods, second-derivative values for 5 April (Figure 3) are nearly identical for all communities, indicating similar reflectance curve convexity at the 0.728nm wavelength. By 2 June communities are separated into two groups *1*. redwoods, woodlands, and chaparral (low stress tree communities), *2*. halo, sandstone and serpentine (high stress annual/perennial communities). Therefore, annual/perennial communities at this wavelength exhibit only slightly convex (or near-linear) upper red-edge reflectance spectra in contrast with other Jasper Ridge communities with strongly asymptote full red-edge spectral form. The period from 2 June onwards is characterized by a “flattening” in the shape of red-edge reflectance spectra, and the appearance of the upper red-edge concavity (-ve ρ''_{728} values) “stress feature” in autumn for annual/perennial communities (*refer also* Figure 2).

5. CONCLUSIONS

This paper describes a selection of early ARIES-1 simulation results specific to vegetation research. ARIES-1 NDVI values display multi-temporal patterns consistent with AVIRIS derived values. ARIES-1 RVSI values remained sensitive to subtle spectral changes in upper red-edge geometry for identifying inter- and intra-community stress trends. Positive RVSI values are returned from concave upper red-edge spectra, and indicate increased relative stress at the community scale.

Second-derivatives of the 728nm band (ρ''_{728}) in ARIES-1 data may provide a particularly sensitive and simple indicator of patterns of environment-induced vegetation stress. Additionally, the presence or absence of upper red-edge concavity in second-derivative spectra may be used to simply identify a community stress response. Positive ρ'' values indicate non-stress asymptote curves, whilst negative values indicate a stress response characterized by upper red-edge concavity.

ARIES-1 hysteresis plots assist in the clarification of multi-temporal relationships between vegetation indices and measures. Inter-community relationships can also be identified from the shape and trajectory of multi-temporal hysteresis curves. Analyzing annual patterns of hysteresis from important measures may prove a useful tool for long-term global studies of environmental and ecosystem change. Hysteresis models will shortly be used to generate *4*-dimensional "spectral topography" image maps with ARIES-1 data for this purpose.

Most importantly, the reduction in spectral resolution of the ARIES-1 sensor, compared to well studied aerial systems such as AVIRIS, does not necessarily degrade the quality of information that is required for many aspects of high spectral resolution vegetation research. Additionally, if the ARIES-1 sensor exhibits performance comparable to well studied sensors such as AVIRIS, then important scale-dependent relationships may be readily established between aerial and satellite based research.

6. References

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