TRACKING VEGETATION SPECTRAL TRAJECTORIES WITH MULTI-TEMPORAL HYSTERESIS MODELS

Ray N. Merton
Earth Observation Centre
CSIRO (Commonwealth Scientific and Industrial Research Organisation)
Sydney, NSW, Australia.
ray.merton@eoc.csiro.au
http://www.eoc.csiro.au/hswww/merton.htm

Eli A. Silver
Department of Earth Sciences, & Institute of Tectonics
University of California, Santa Cruz
Santa Cruz, CA United States of America.
esilver@earthsci.ucsc.edu
http://emerald.ucsc.edu/personnel/Silver/

1. INTRODUCTION

Remote sensing information is increasingly being used to quantitatively improve an understanding of how the Earth functions as an ecosystem. Monitoring of vegetation change has become one of the most popular areas of research in multispectral satellite remote sensing applications. Considerable effort has been given to the discrimination of ecosystem succession, seasonal changes, and disturbance-type changes such as air pollution, insect damage, and management treatments (Nilson and Peterson, 1994). However, hyperspectral dataset archives are only now reaching the number required to permit multi-temporal investigations of sites.

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 most research to date has been performed at the leaf, canopy, and community scales, the next challenge for orbital sensors is to provide stronger links towards regional and global scales. Multi-temporal research and modeling focuses at the community scale to provide a suitable link between current multi-temporal research using high/low altitude aerial sensors (*incl*. AVIRIS, *casi*, and Hymap), and future orbital sensors (*incl*. ARIES-1, CHRIS, Hyperion, NEMO, and Orbview).

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 (Levitt, 1980) can be quantified at species, community, and ecosystem scales. Most importantly however, imaging spectroscopy can be applied in ecology to monitor change including successional change, land use change, deforestation, environmental change (Hobbs, 1990; Pickup, 1990; Roughgarden, Running, Matson, 1991; Merton, 1998, 1999, Merton and Huntington, 1999). Monitoring change is one of the most important contributions high spectral resolution remote sensing technology can make to studies of global ecology.

With the deployment of hyperspectral sensors into Earth orbit, repeat coverage of sites will shortly enable spectral trajectories of vegetation to be tracked and 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 changing environmental influences (Merton, 1999). Together both orbital and aerial hyperspectral sensors, will provide new information to identify inter-annual spectral shifts relating to succession and environment change at a significantly higher spectral resolution than current orbital multispectral sensors.

This paper examines a selection of new techniques currently being programmed as multi-temporal modules for application in both aerial and orbital hyperspectral research. Multi-temporal 224 band AVIRIS data from Jasper Ridge, California, is used to examine the potential for hyperspectral data to track changes in spectral signatures of vegetation communities through time. The hysteresis model is examined as a new tool for *1*. mapping complex multi-temporal spectral relationships, and *2*. concatenating the extremely large data volumes to extract multi-temporal information. This paper applies a selection of red-edge measures to trial the performance of spectral hysteresis in modeling seasonal and long-term vegetation change at the community scale.

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, 1999) 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

Seven 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, 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 components of research continue to focus on vegetation biogeochemical stress, many communities located at Jasper Ridge retain the nomenclature representative of the underlying geology/soil (Merton, 1994). A range of spectral tools were used to define community spectral boundaries (*refer* Merton, 1999).

The following is a brief description of communities. *1*. *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*. *2*. *Sandstone community*: predominantly annual grassland species located on a sandstone substrate. Representative species include a range of annual grasses especially *Bromus rigidus*. *3*. *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. *4*. *Chaparral community*: a fire-climax community situated on dry southwest facing slopes containing chamise chaparral, *Prunus* chaparral, and *Baccharis* shrub. *5*. *Woodlands community*: an open canopy community situated predominantly on northwest slopes containing a range of oaks, buckeyes, and laurels. *6*. *Delta community*: a willow (*Salix lasiolepsis*) dominated community located in the swampy deltaic areas at the southern margin of Searsville Lake. *7*. *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 used to demonstrate in this research the construction a near-consecutive multi-temporal database. Chronological five-date imagery is not currently 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.

3. METHODS

3.1 HYSTERESIS ANALYSIS

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. Hysteresis curves (Merton, 1998; 1999) are constructed from paired data values calculated from any combination of indices or measures, plotted as multi-temporal co-ordinates. Sequential time-series data calculated for each community form unique hysteresis trends that describe the multi-temporal relationship between the two variables through time. Hysteresis plots can be used to identify the most appropriate measure to use at specific times of the year for each community. The hysteresis component of ongoing research attempts to model change between selected spectral measures to improve interpretation of complex multi-temporal trends relating to both intra- and inter-community 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 (Merton, 1999). Spline lines are used as *indicators only* and assist in interpretation as extrapolated trends between calculated values. Differences in the rate of trajectory change between communities is highly variable and may be associated with vegetation biomass, morphology, and phenology, for example. In the absence of dataset archives with high temporal frequency, a universal weighted spline (0.3) can be used to simulate the probable biological response trajectory between data points (Merton, 1999). Determining community-specific spline weightings is the focus of ongoing research.

The orientation of hysteresis curves can clarify relationships between community hysteresis shapes. Centroid co-ordinates ($\overline{x}_c$) (*refer* Figure 1), calculated as the mean of both community wavelength (*x*-axis) and reflectance (*y*-axis) data points, are used to approximate a central position for community hysteresis curves (Merton, 1999). The term centroid has been borrowed from GIS theory normally used to define the geometric center of a polygon. The centroid concept has been further modified to approximate hysteresis geometric centers, for inter-community comparisons. Mean calculations maximize data extremes compared to the median, and are incorporated into the equation to maximize the contribution of distinct seasonal hysteresis lobes. Furthermore, a radial line can be drawn from the centroid point to the approximate "winter bisect" (or other significant point in time) to provide hysteresis curve orientation information (*refer* Figure 1). In this paper, the winter bisect ($\overline{x}_{wb}$) is defined by the mean of co-ordinates between 6 October (last date of the temporal sequence) and 5 April (first date), across the winter aperture. The co-ordinate bisects a modeled line between the two dates. Although any common point along the hysteresis trajectory could be used, the hysteresis aperture was selected as it approximated winter (period of relative "spectral dormancy"). The winter aperture is selected as the time of the year not influenced by periodic stress events related to moisture deficit and heat stress.

An "orientation vector" ($\overline{x}_v$) is constructed between the winter bisect (origin, $\overline{x}_{wb}$) and centroid ($\overline{x}_c$) to measure annual "hysteresis orientation" and "hysteresis magnitude" (Merton, 1999). The magnitude of the vector is defined by the distance (*polar*) between the winter bisect and the centroid. The orientation vector can be expressed in terms of angle of rotation from vertical. A vertical orientation (north, in map sense) equals 0°, east = 90°, south = 180°, and west = 270°. For example, the orientation for the delta community (Figure 1) is identified with an orientation vector of approximately 310°. Orientation vectors and their magnitude (length of vector) may provide additional information to interpretation of community-specific annual patterns in response to the dominance of reflectance (y-axis) compared to spectral shifts (x-axis).

A significant problem of calculating basic orientation vector angles, relates to axis scales. By changing the x-axis or y-axis range, the orientation vector angles will also change. Orientation vector angles must therefore be regarded as *relative* indicators only. A constructive solution to overcome problems of scale-dependency is achieved by defining orientation vectors as simple linear equations, adopting the format $y = ax + b$. Therefore, x-axis values are related directly to y-axis values and are independent of plot scaling and angular distortions. Nevertheless, the simple orientation vector angle technique is particularly useful in comparing vector-types to describe patterns of hysteresis for figures with identical scaling.

3.1.1 Hysteresis Example: RVSI vs. Median Reflectance

As hysteresis relies on simple combinations of any measurable input variables, and is not restricted to spectral measurements alone, the relationship between remote sensing measures and traditional ground based measures such as canopy nitrogen, lignin, or chlorophyll content, can be used to identify change at different temporal resolutions. Long-term monitoring of hysteresis is especially suited to help quantify processes operating at an intermediate level especially in studies relating to vegetation change. In this example, the RVSI (Red-edge Vegetation Stress Index) (Merton, 1998) and median red-edge reflectance (M_d) (median of eight contiguous spectral bands between 0.6852 - 0.7523μm) (Merton, 1999) are selected to illustrate multi-temporal hysteresis relationships at the community scale between two variables, across seven Jasper Ridge vegetation classes.

RVSI is developed to identify inter- and intra-community vegetation stress trends at Jasper Ridge 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 1. Red-Edge Vegetation Stress Index (Merton, 1998)**.**

where:

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

Negative RVSI values plotted in Figure 1 indicate low apparent vegetation stress, whereas positive values indicate higher stress. Community hysteresis curves that advance from negative values to positive values cross a threshold approximate the onset of vegetation stress (Merton, 1998). The direction of hysteresis for all communities is clockwise (Figure 1). All community hysteresis curves display a looped form. Communities such as sandstone, serpentine, and halo, exhibit a more flattened (linear) geometry, indicating increased relative response to RVSI values for these communities. Furthermore, orientation vectors and slope of line equations clarify inter-community relationships. The most significant trend shows communities with negative RVSI centroid values have negative slopes, and positive RVSI values have positive slopes. Correlation analysis indicate strong relationships ($R = 0.814$) between community RVSI values and community vector slope. The generalized relationship confirms a visual interpretation that as RVSI community gradient values increase, hysteresis vectors trend from negative slopes to positive slopes. Correlation analysis indicate that as RVSI values increase, hysteresis magnitude decreases. Most importantly however, all hysteresis curve forms can be useful for determining the timing and magnitude of multi-temporal relationships, which can not be identified from calculating correlation values.

Patterns of hysteresis can therefore be reasonably quantified and explained in terms of vector orientation and magnitude for reflectance and RVSI. The relationship between these two variables shows that as multi-temporal community RVSI values increase, the magnitude of hysteresis vectors decrease, and the slope increases from positive to negative values. This measure may provide additional information to both inter- and intra-community analyses, especially suited for monitoring long-term vegetation change. The placement of additional communities along this gradient may provide further insights to community function and response to stress.

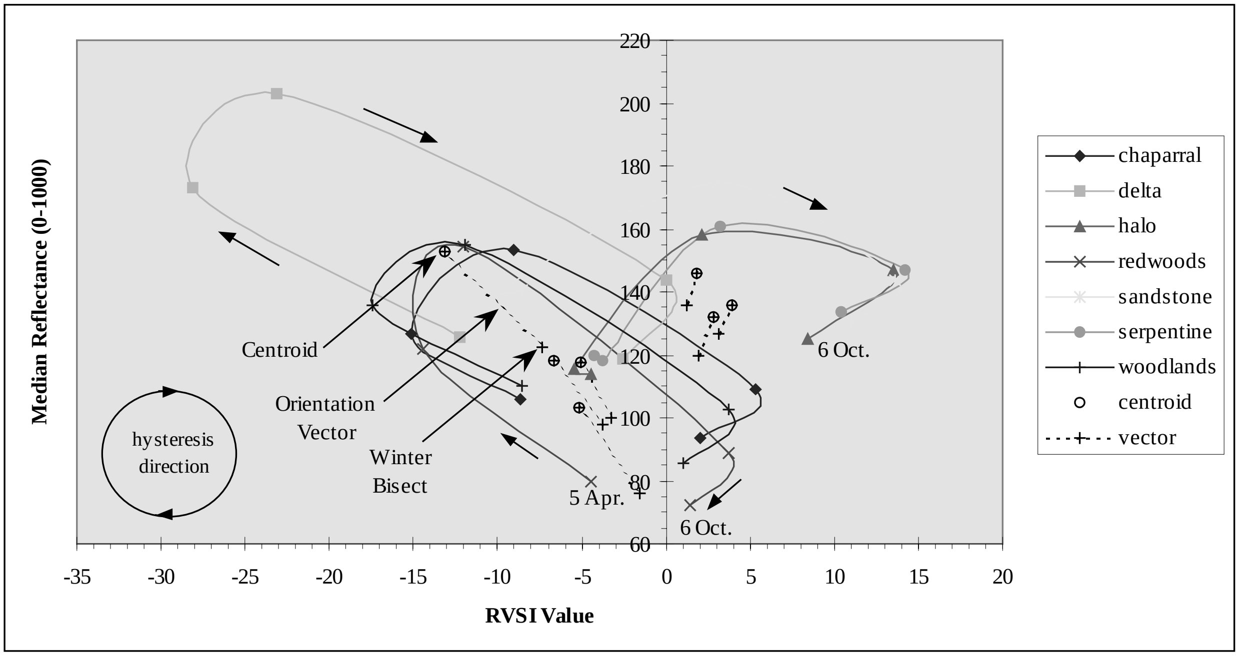

Figure 1 Hysteresis Plot Of Red-Edge Vegetation Stress Index And Median Reflectance Values, Plus Orientation Vectors.
Note: spline lines connecting data values are used to indicate data trends only. To conform to standard spectral plotting, reflectance values are displayed on the *y*-axis. The *y*-axis intercepts the *x*-axis at RVSI = 0. Delta community is labeled.

3.2 MAPPING HYSTERESIS TRAJECTORIES

As the identification of positive and negative feedback thresholds are important to monitor change in a climatic systems, hysteresis analysis may assist in providing evidence of the timing of critical episodic events. The rate at which hysteresis centroids *migrate* over a range of time scales correlated to known causal climatic and environmental variables may for example, provide valuable inputs to long-term climate models. The following sections provide an overview to the future direction of multi-temporal hysteresis analysis enabled through high resolution imaging spectroscopy.

3.2.1 Long-Term Hysteresis Modeling

The analysis of multi-temporal hysteresis trends for vegetation indices at the community scale can be further modified to provide a measure of inter-annual variability for vegetation at the global scale. High temporal imaging of vegetation with hyperspectral satellite sensors will permit tracking of spectral shifts at the community scale. Multi-temporal datasets allow models to be established that define patterns of hysteresis and long-term community centroid trajectories. Deviations from a nominal pattern can be identified as eccentric or anomalous hysteresis trajectories at seasonal, annual, and decade temporal scales ("hyper-temporal") (Figure 2). Significant annual shifts for example, can be detected by displacements in annual hysteresis centroid position. The cause of spectral shifts may range between the influence of regional and global climate change, to the effects of change in community structure and ecosystem scale dynamics.

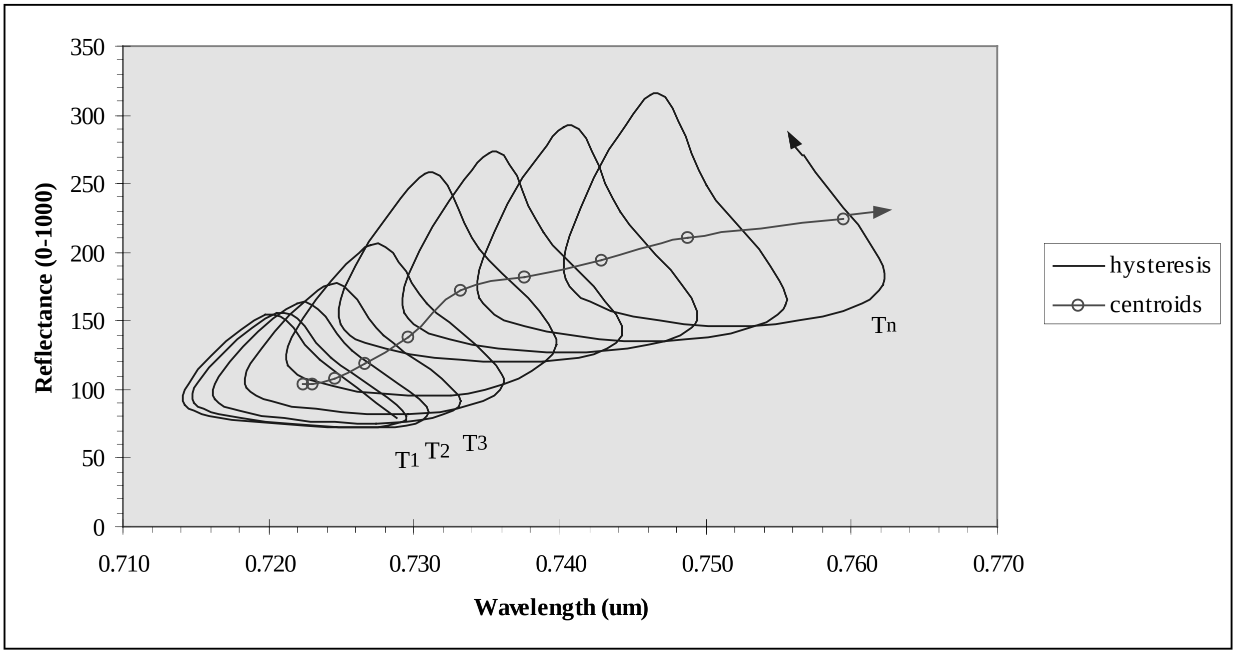

Figure 2 Inter-Annual Hysteresis Drift Model.

Note: Each hysteresis cycle represents a single year (T_1 = Time 1). Centroids are calculated for each cycle to indicate the net annual spectral shift for a single community. Seasonal spectral shifts are identified as changes in hysteresis symmetry and trajectory. T_n indicates additional datasets that may be used to construct a "hyper-temporal" sequence.

Figure 2 displays a modeled spectral shift in multi-temporal centroid trajectories caused by an increasing external influence. Multi-temporal spectral shifts can be induced by a wide range of causes. Increases in environmental pressure beyond a critical level may for instance, cause pixel centroids to *migrate* (as modeled in Figure 2). Communities that exhibit migration ("spectral drift") from an annually stable position (e.g., T_1) may indicate changes in spectral dynamics associated with changing environment, community structure, or vegetation stress. A reduction in hysteresis migration towards a new stable position (T_n) may similarly indicate the completion of a ramped successional event and an adjustment to a new spectral regime.

It is unlikely that spectral patterns will be identical on the same date for successive years, a degree of natural variation is likely. However, for studies of long term vegetation changes at community to global scales, variation beyond any nominal range may be significant. At short to medium time scales spectral shifts may explain annual variations related to variations in the onset of seasonal or cyclic events such as ENSO. However, where data drift is measured over longer time periods such as decades, subtle vegetation spectral trends may for example provide spectrally measurable confirmation of global change influencing sensitive biological systems.

3.2.2 *4*-Dimensional Hysteresis Mapping

With the deployment of hyperspectral sensors into Earth orbit, repeat coverage of study sites will shortly enable hysteresis spectral trajectories to be compared on an inter-annual basis. Variations between datasets may indicate important ecological change related to plant succession, increasing vegetation stress, or spectral shifts associated with changing environmental influences. A more suitable method is therefore required to be designed to measure and visualize long-term spectral shifts once sufficient numbers of datasets become available.

The calculation of hysteresis at the community scale can also be redesigned to operate at the *pixel scale*. Multi-temporal modeling of annual hysteresis curves for each image pixel can be constructed by fitting a *multi-temporal vector* through annual hysteresis centroids, calculated from chronologically sequential datasets. Using pixel centroids has the advantage of reducing higher dimensional relationships between indices down to representative *single point* descriptors. As the centroid is designed to be sensitive to seasonally anomalous hysteresis trajectories, each centroid can be regarded as the unique descriptor of spectral responses at the pixel scale.

Figure 3 illustrates this technique by generating *4*-dimensional image maps. The four dimensions are interpreted as: *1*. the spatial domain of images (first- and second-dimensions), *2*. annual hysteresis centroid for any one year (third-dimension), and *3*. the multi-temporal vector describing the net drift of centroids from *Time*-1 (T_1) to *Time*-n (T_n) (fourth-dimension). T_n can be used to represent any *future* annual dataset as a multi-temporal *target*. The net direction and magnitude of the multi-temporal vector from $T_1 \rightarrow T_n$ can therefore be measured as a *spectral drift* over the time interval selected.

Variations in the direction and magnitude of the multi-temporal vector can be represented as displacements away from a central spectral position to the tip of the vector arrow head. Furthermore, the multi-temporal vector is converted through a 2-*D* color coding scheme (Figure 3) from vector-space to color-space. A horizontal rainbow color ramp (B↔G↔R) modified by a vertical white to black (W↔K) ramp, is overlain on top of the nominal range of centroid values for reflectance and wavelength. Centroid vectors that drift strongly over time to longer wavelengths (red-shift) are coded red, whereas strong blue-shifts are coded blue. A more subtle spectral shift to longer wavelengths may be represented by yellow hues for instance. Similarly, centroids with increasing reflectance (*y*-axis) will be color coded increasingly white. No drift from $T_1 \rightarrow T_n$ is represented by mid-green. For example, the pixel in Row1:Column3 (R1:C3) in Figure 3 shows the migration of hysteresis centroids over time to longer wavelengths and increased reflectance. This pixel is therefore color coded light yellow in the image matrix.

The construction of the matrix as a single layer pseudocolor image enables a 3-*D* image to be built with full spatial geometry preserved. The *x*- and *y*-axes are identical to that of the georeferenced hyperspectral image and the *z*-axis displays the color coded spectral shift data. Figure 3 shows a modeled 25 pixel multi-temporal 3-*D* map displaying spectral shifts as colored *topographic* features. The colored 3-*D* effect emphasize areas of pixels that have experienced a blue- or red-shift between T_1 and T_n. As these maps are fully georeferenced, they can be taken into the field for verification.

3.2.3 Animation of Annual Hysteresis Trajectories

To better understand the timing, magnitude, and spatial location of spectral shifts in annual hysteresis sequences, pixels can be animated at regular time intervals. Animation allows time-series data to be displayed to highlight the relationship between important hysteresis variables. Animation also provides an alternative technique to display seasonal spectral shifts at the pixel scale. The timing of a hysteresis may be equally important as the magnitude of the spectral shift. For example, all pixels in an image may exhibit a spectral shift of 5nm at some stage throughout the year, but pixels that exhibit an anomalous early response in an otherwise homogenous community may indicate dissimilar environmental influences.

Although multiple datasets in any one year are usually obtained at irregular intervals, hysteresis trajectories defined by exponential spline calculations can be used to locate additional co-ordinate positions from *modeled* datasets. Intervals between datasets can be resampled to two weekly intervals to produce simulated pseudocolor images. For example, Figure 4 shows that the modeled dataset *frame2* is not located directly between the *real* datasets of *frame1* and *frame3*. Animation using simple linear calculations between real datasets would produce erratic jumps in the animated sequence. Figure 4 shows that the most likely path is displaced to longer wavelengths. The hysteresis spline is therefore used to calculate the most likely *x*- and *y*-co-ordinate position between each real dataset, for every pixel in the image.

Figure 4 shows a rainbow color ramp overlain on the nominal range for hysteresis NDVI and λ_i (red-edge inflection) (Merton, 1999) wavelength values (top figure). Temporally-adjusted frames are *1*. color coded according to the color ramp superimposed (*refer* Section 3.2.2), *2*. assembled as sequential animation frames (middle figure), and *3*. animated as a 3-*D* multi-temporal sequence (lower figure). A calendar can be positioned on each frame to show the time of year. Animation speed can be slowed to identify anomalous features at specific times of the year. Changes in hysteresis geometry can be identified as colored topographic features (*spectral topography*) that are displaced vertically responding to changes in hysteresis trajectory. Variations between datasets may indicate important ecological change related to plant succession, increasing vegetation stress, or spectral shifts associated with changing environmental influences.

4. Conclusions

The primary purpose of this paper is to highlight aspects of ongoing research that may benefit aspects of multi-temporal vegetation analysis, at a range of spatial scales. In particular, measurements of short- to medium-term changes in vegetation phenology will likely immediately benefit from the identification of spectral shift analysis and plotting hysteresis variability. The timing and progression of critical plant phenological events may provide valuable information to enable researchers to make inferences about the condition of vegetation and environment.

Furthermore, new methods developed from high resolution spectral measurements may help to define the role of ecological processes at regional and global scales, and to determine whether processes have been altered by changing environmental influences. The ongoing goal of synoptic-scale hyperspectral research will be to assess the validity of these and other measures for application to monitoring global environmental change and inventory. The spectral sensitivity and response of both disparate and "indicator" vegetation types to changes in environmental conditions, may provide appropriate measures of the influence of environmental and climatic change at seasonal, inter-annual, and medium- to long-term time scales.

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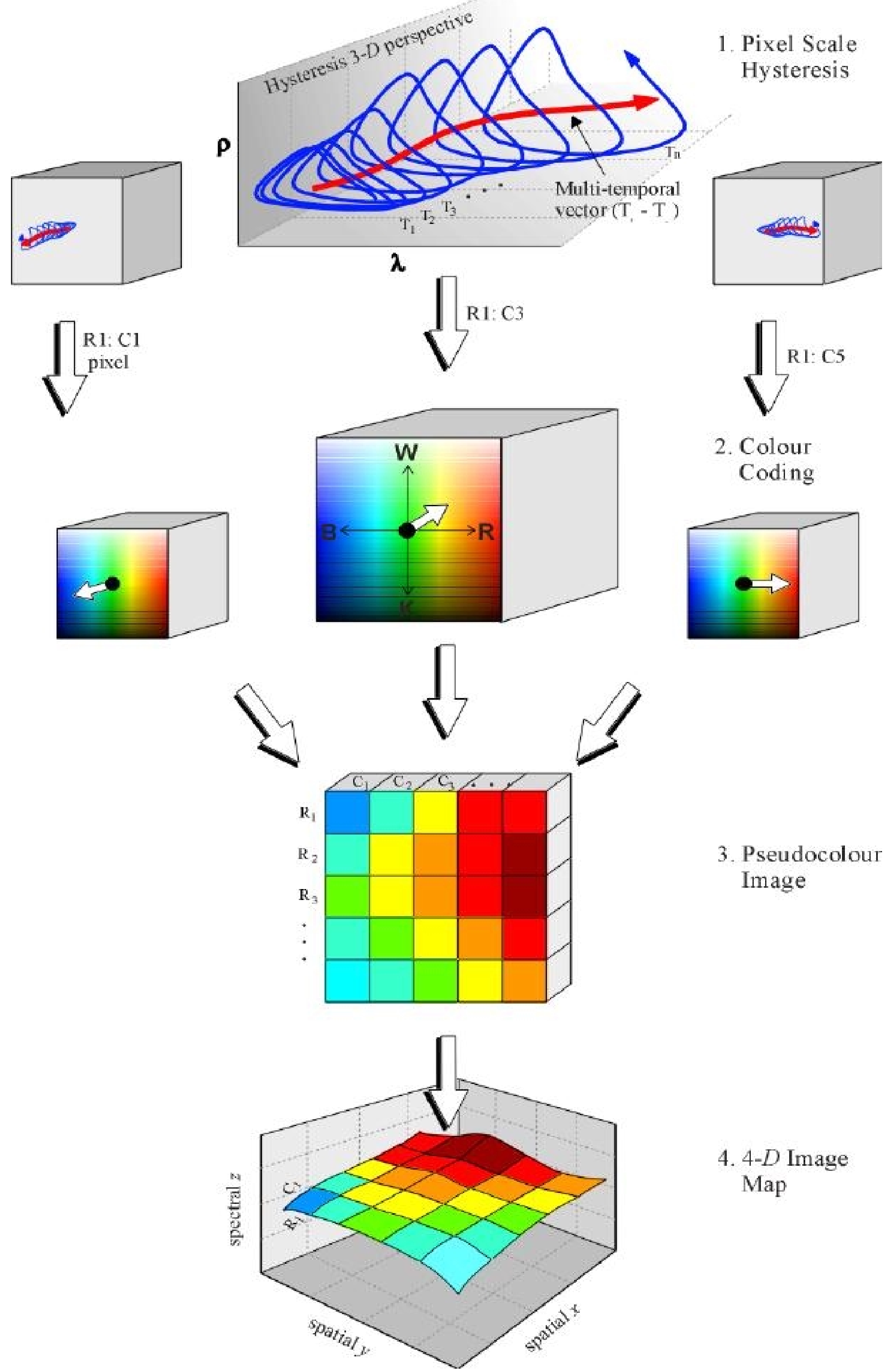

Figure 3 ***4*-Dimensional Hysteresis Model.**

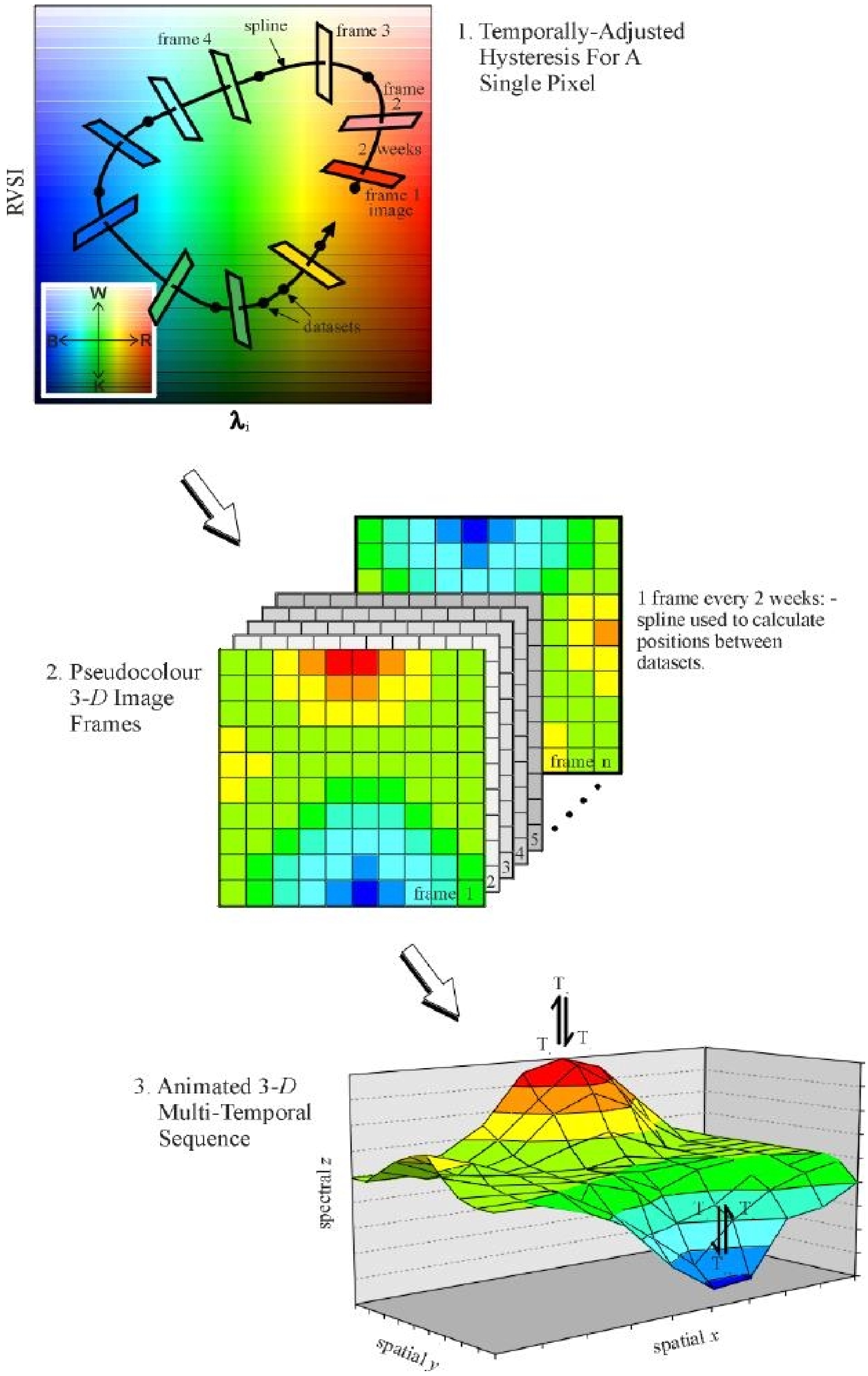

Figure 4 Annual Hysteresis Animation Model.