Active Sensor Tidbits

Operations:

Active sensors measure radiation reflected from a target much like a passive sensor. The difference is that active sensors project a small amount of modulated (pulsed) light in one or more wavebands (from the near infra-red and/or visible part of the spectrum) onto the target. Some or all of this modulated radiation is reflected from the target and measured by the detector(s) in the sensor body. Electrical circuits within the sensor are able to differentiate between the modulated portion of the reflectance and natural component that originated with sunlight. This unique feature of active sensors is why they can operate equally well under all lighting conditions.

Active sensors modulate light generated by diodes at a base rate of ~40,000 Hz (cycles per second). Some sensors are able to modulate the wavebands simultaneously and others are designed so that the modulation only occurs for one waveband at a time before switching to another waveband. Each pulse of radiation results in a sensor reading that is summed and outputted at a prescribed interval (10 times per second is common). Design of the optics and electronic circuits dictates the specifics of how the manufacturers generate the modulated radiation, sense reflectance, and process the data. These characteristics influence a number of considerations such as distance from the sensor to the target (i.e., recommended window or minimum and maximum distances for reliable data), electronic noise (variability in sensor readings in a stationary position on the same target), and size of the field of view.

Distance from the Target:

Transmission of light from a source follows the inverse distance squared law (intensity = $1/\text{distance}^2$), which basically means that as distance doubles the intensity of the light is reduced four times (i.e., two squared or four). Therefore, at very close distances, the intensity is much greater than at a remote distance. The same principles apply to reflected light but in this case the target (leaf surface, soil, water, etc.) serves as the source. Therefore, the distance between the target and detector are an important consideration when using ground-based sensors. It should be noted that as the distance between the target and sensor increases, the general intensity of the light emitted from an active sensor decreases. This is why active sensors need to be positioned relatively close to the target to maintain responsiveness.

It should be apparent that the stability of the power supply and detector circuits has a large influence on the sensitivity of the device. If manufacturers do not provide information about the stability of sensor readings over a living plant and/or bare soil target at the recommended sensing distance, such data should be requested. It is not appropriate to use an artificial target (e.g., paper, plastic, metal) to generate this kind of information because reflectance from plant materials (biologic specimens) is quite different from synthetic materials. It follows that the sensitivity of active sensors should be relatively constant over the recommended range of distances.

The recommended working range for a sensor should be verified for the type of target (e.g., soil, plant, turf) being evaluated. This is because some targets will be highly reflective in one waveband (e.g., NIR) and almost totally absorb the irradiance (e.g., red) in another. It is important to know how close an active sensor can be to the target before a given waveband saturates (i.e., readings fail to change as distance decreases). If it is not possible to determine how individual waveband values change with distance, a less sensitive option is to monitor the calculated sensor output such as the normalized difference vegetation index (NDVI). Because indices like NDVI normalize the reflectance between wavebands, the value is intended to be insensitive to distance. Therefore, if the index value changes with distance from the target and the target is uniform, it implies that the reflectance detected by one waveband is changing relative to the other waveband. Unstable NDVI values at close distances usually mean that one of the wavebands is saturated. Unstable NDVI values for a uniform target (bare soil or turf works best) at greater distances can be caused by optical limitations, low detector sensitivity, high electronic noise, or a compounding of internal calibration coefficients.

Field of View / Footprint:

The size and shape of the footprint of the sensor's zone of illumination on the target is unique for each sensor. The fact that sensor readings are taken so frequently virtually means that everything within the field of view will be monitored with a high degree of spatial resolution. For example, traveling at 4 mph (5.87 ft/sec), the footprint advances at the rate of 0.00176 inch per reading (0.0447 mm per reading). Assuming that these readings are accumulated and outputted every 0.1 second, means that a new value is recorded every 7 inches (17.88 cm). Higher speeds increase the distance traveled between reported data points proportionately.

It is worth noting that each time a new reading is taken by the sensor (i.e., ~1/40,000th of a second) while moving through a field, the value from one reading to the next should be similar. This is because reflectance for the current frame (footprint) only changes minimally from the last frame (i.e., minus a small area on the back side, plus the same area on the leading side). In the case of the GreenSeeker sensor, the footprint advances by about 0.7% every time a new reading is taken, assuming about a 3/8 inch by 24 inch (1 by 60 cm) footprint. In the case of the Crop Circle ACS-210 sensor, the footprint is about 3 inches by 20 inches at 3 ft from the target, so every time a reading is taken the footprint advances about 0.18% in the direction of travel at 4 mph. In the case of the Crop Circle ACS-470 sensor, the footprint is about 6 inches by 24 inches at 24 inches from the target, so every time a reading is taken the footprint advances about 0.09% in the direction of travel at 4 mph. This simple analysis illustrates that if readings were taken at the rate of 40,000 samples per second, one shouldn't expect much difference from one reading to the next if the electronics are stable. A closer examination of sensor design reveals some possible implications.

> ***GreenSeeker*** - The foot-print of the GreenSeeker is intended to be stable regardless of height above the canopy. Energy is emitted from separate diodes (red and NIR) in alternate bursts such that the visible source pulses for 1 msec and then the NIR diode source pulses for 1 msec at 40,000 Hz. Each burst from a given source amounts to ~40 pulses before pausing for the other diode to emit its radiation (another 40 pulses). Thus, at the end of each 0.1 sec when readings are compiled, both the visible and NIR wavebands represent 50 segments of 40 pulses each for a total of 2000 bursts of light. All reflected radiation is measured by one detector, so the quality of the detector's electronics dictates if the detector circuits are able to accurately capture a low level of reflectance for the visible waveband and then instantaneously respond to a high reflectance level for the NIR waveband. It is perhaps worth noting that during the 40 pulses from a given diode source, the sensor advances 0.07 inches (1.788 mm) or about 3% of its footprint at 4 mph. This may not seem significant, but might become important when one considers that the reflectance for one waveband is only 97% of the area recorded by the companion waveband. At 8 mph the

concurrence reduces to 94% and at 16 mph to only 88%. The implications are that the targets for which subsequent calculations are made are not the same and users should expect greater variability in sensor readings at higher speeds. Output variability attributed to speed of the monitoring vehicle might be confounded by other sources or variability, which is why it is important to record the variability in sensor output for 15 sec or so (~150 points) in a stationary position over a crop target to better appreciate the quality of the data.

Crop Circle ACS-210 - The foot-print of this sensor increases in size with distance from the target. Both the color (typically amber) and near infrared (NIR) wavebands are projected simultaneously from the same diode so the field of view is identical with each pulse of light. Therefore, the same exact area of the target is illuminated for an instant and reflectance from that area is recorded by a separate detector for each waveband. As such, detector hysteresis is less problematic and eliminating the need to alternate radiation sources allows for higher sampling rates to be achieved.

Crop Circle ACS-470 - The foot-print of this sensor increases in size with distance from the target. All wavebands (visible and NIR) are projected simultaneously from special white diodes so the field of view is identical with each pulse of light. Therefore, the same exact area of the target is illuminated for an instant and reflectance from that area is recorded by a separate detector for each of the three selected wavebands that the user chooses to monitor. As with the ACS-210, the noise level for this sensor is low because the foot-print is identical for all wavebands selected and the photo detectors do not have to instantaneously respond to large changes in waveband reflectance.

The width of the foot-print in the direction of travel can be an asset or a liability depending on the application and the characteristics of the sensor involved. Calculation of sensor output variability over a distance or length of time is one way to assess spatial variability or uniformity in a crop canopy. If this is of interest, one needs to know if the calculated value (coefficient of variation) represents the variability in the output values that are provided at 0.1 second intervals over a given time or distance of travel (e.g., last 10 values outputted while traveling 6 ft) or the value calculated for the data points that went into the 0.1 second average value. If it is the latter, one needs to ask how many data points went into the calculation (the number could range from 50 to 4000 depending on the sensor type).

Special consideration should be given to the spatial aspects of the target relative to the orientation of the sensor. Targets like turf probably do not usually have much of a spatial pattern within the foot-print so illumination aspects of the sensor will not be overly important. However, as spatial patterns caused by vegetation become more obvious the location of the sensor relative to the vegetation can become important, especially if the field of view is not uniformly illuminated. For a given crop and application of the sensor, this effect can be demonstrated by holding the sensor at the prescribed height above the target and slowly moving it perpendicular to the intended direction of travel (i.e., from one row to the next in the case of row crop). The variation in sensor readings will be proportional to the uniformity of illumination across the field of view. For crops like wheat that are typically planted in narrow rows (7-12 inches), non-uniformity of illumination across the field of view may not be much of an issue because several rows are likely to be within the footprint at any time. In the case of corn, where the row spacing may be wider than the footprint, positioning of the sensor becomes much more critical. If all segments across the footprint are illuminated to about the same extent at one time or another while moving in the direction of travel, then the operator should have modest flexibility (plus or minus 4-6 inches) while driving. On the other hand, the optical design of some sensors is such that the intensity of light diminishes from the center outward much like the beam from a flashlight. As such, positioning this type of sensor directly over the target is critical and careful driving becomes a necessity. A slightly over-exaggerated analogy might be to compare the illumination pattern of an incandescent light bulb and a fluorescent light tube at a distance of 3 ft from the light source.

Target Architecture:

As noted earlier, the amount of light reaching a photo detector is proportionate to the distance from the energy source. In the case of a crop, the energy source can be equated to the leaves in the field of view. A well-manicured lawn is probably the perfect target for active sensors because it is easy to maintain a constant distance between the vegetation and the sensor. As plants get taller, distance becomes an issue, especially for crops like corn because leaves are present at different levels in the canopy. Leaf removal studies in corn show that if leaves are removed from the bottom up to the top, differences in sensor readings are not observed until there are only five to six leaves remaining. When leaves are removed stating at the top of the plant, the sensor readings were affected immediately.

The reflectance recorded by a sensor is an integration of all reflecting surfaces. As such, there is a concern that leaves closer to the sensor might disproportionately bias sensor output (see distance discussion). In the case of corn, emerging leaves are usually more yellow than fully expanded leaves and also closer to the sensor. However, their architecture is largely vertical so they only comprise a small portion of the field of view. It is important to note that normalizing the raw data from individual wavebands as with the Normalized Difference Vegetation Index (NDVI) remove the effect of distance because both the visible and NIR wavebands are affected similarly.

Having some soil in the field of view can be an important asset when monitoring young plants. This is because soil has a relatively stable NDVI value (varies with color) and so as the crop grows, pure vegetation that typically has an NDVI value of 0.8 to 0.9 replaces soil in the field of view that ranges from 0.2 to 0.4 in extreme cases. Once there is adequate vegetation for canopy closure, nearly all of the NIR energy is reflected and the plant absorbs essentially all of the red and blue radiation during photosynthesis. This means that the usefulness of NDVI as an indicator of crop vigor diminishes considerably after canopy closure. This is also why some active sensors use yellow or green light instead of red light in that neither yellow nor green light are fully used during photosynthesis, Therefore, these sensors remain sensitive to leaf chlorophyll status over a much wider range of growing conditions even though they are slightly less sensitive than those that use the red waveband when vegetation is limited. An interesting consequence of what can happen when the red band becomes almost totally absorbed by the vegetation (canopy closure) is that there is no longer an appreciable amount of red reflectance to be recorded and used in the NDVI calculation. Further, the lack of response in the red band region means that there is no signal to correct for changes in the distance between the sensor and the target (crop) as is normally accomplished via the NDVI calculation. As such, once the visible band reflectance bottoms out (becomes non-responsive to changes in the amount of vegetation), one can expect the NDVI values to become unstable because the NIR signal is responding to a combination of sensor-to-target distance and the amount of biomass in the field of view.

Water Stress:

Crops respond to water stress much quicker than they do to most stress (the exception is certain herbicides). Water stress is expressed in terms of leaf turgidity. The same cells within a leaf that regulate turgidity are responsible for reflectance of NIR radiation. Water stress also affects photosynthesis and leaf color, but these symptoms are delayed compared to the effect on turgidity. In the case of biomass production the effect is cumulative. If active sensors indicate differences in NDVI values, the first thing to check should be the turgidity of the leaves. Reports of time of day and leaf moisture (dew) effects on active sensor performance can usually be traced back to a lack of appreciation for how water stress affects NIR reflectance.

Growth Stage:

Canopy architecture is a function of growth stage. Limitations of active sensors noted above should dictate their use and application. For the most part, defining the growth stage of a given crop relays information about its size and implies certain things about nutrient and water needs.

Time of Day Effects:

Active crop canopy sensors were designed to quantify how plants respond to a little extra light that is specially “tagged” so that its effect can be monitored. Biologically, light is light, but time of day affects many things such as evapotranspiration and canopy temperature. Sensor users who do not realize this will quickly learn that active sensors can be very useful devices for measuring real-time responses, but the responses may not be the factors that they intended to quantify.

Effects of Wet Leaves:

Water and dew on leaves affects the reflectance characteristics. The net effect of moisture on individual wavebands in the visible range is probably about the same, but relative effects can be quite different depending on how much light is being reflected from given wavebands. For example, red-band reflectance is usually only 2-3% for a closed corn or wheat canopy, but reflectance in the amber and green bands could range from 5-8%. Therefore, a film of water would have a much greater relative impact on red reflectance values than other wavebands with higher reflectance values. The net effect on vegetation indices could be minimal or very significant depending on the wavebands used in the sensor and which vegetation indices are calculated. To illustrate these effects, a series of Crop Circle sensors were positioned over irrigated corn at the V11 growth stage. These sensors contained a variety of wave-band combinations to accommodate common vegetation indices (NDVI, VARI, Red-Edge). Sensor readings were taken at 9:00 AM to establish a dry-leaf baseline for each sensor. The canopy was then moistened with a sprayer after which more readings were taken. The net effect of moistening the leaves on individual waveband reflectance was NIR = +3%, Red-Edge = +2%, Green = -2%, Amber = -4%, Red = -12%.

Cultivar Effects:

Leaf structure and canopy architecture are sometimes defining characteristics of cultivars or hybrids. Reflectance patterns sometimes vary between cultivars even under adequately fertilized conditions. For these reasons, great care should be taken when comparing sensor data between fields that have different cropping histories, growth stages, and cultivars. Normalizing data to an adequately fertilized area within a field that has only received a little extra nitrogen should make it possible to make an equivocal comparison between fields, cultivars, etc.

Vegetation Indices:

Translating sensor data into meaningful information is partially accomplished by sensor software. Both Crop Circle and GreenSeeker sensors provide output in the form of NDVI and other ratios or indices. NDVI is especially sensitive to the amount of living biomass in the field of view. Active sensors do not generate enough light to measure very deep into the canopy, so in the case of corn they usually become saturated in terms of near infrared (NIR) reflectance once 5 to 6 layers of leaves develop. After the canopy closes (i.e., no soil is visible), sensors that are sensitive to leaf chlorophyll status are usually more useful. It is important to note that vegetation indices involving a ratio of reflectance values (i.e., red/NIR) are largely immune from the effect of distance between the sensor and target as long as the optics do not impose limitations, BUT reflectance data from the individual bands are not. Therefore, variability in data from the NIR band for example, can be due to either distance between the sensor and top of the canopy or the amount of living vegetation in the field of view. Normalizing data from several bands removes the effect of distance because both are affected the same as long as the foot-print for each waveband is the same. Processing and examining both normalized and NIR data can provide information about the height of vegetation. Data from the individual visible wavebands (e.g., blue, green, yellow, red) can be used to assess unique things about chlorophyll status and senescence (maturity of the crop). Because the current generation of active sensors only involves two or three wavebands, it is important to select the most appropriate visible band for the application. Sensors with a red waveband offer good potential for assessing living vegetation and ground cover until the canopy closes. Sensors with green, orange, and yellow wavebands are somewhat less sensitive when it comes to assessing early season biomass, but are superior during the growing season when the amount of vegetation is more than sufficient to absorb all of the red light emitted from the sensor. This difference is because plants are not able to use orange, yellow, and green light as effectively as red and blue light.

Revised January 26, 2008 by Jim Schepers (jim.schepers@ars.usda.gov)

For additional information see www.hollandscientific.com for the PowerPoint presentation that discusses operation of the Crop Circle and GreenSeeker sensors in more detail. This material was presented at the InfoAg 2005 conference. More recent material that augments information about the Crop Circle sensor was presented at the InfoAg 2007 conference (see “Crop Circle Experiences” at www.InfoAg.org).