Monitoring Pistachio Orchards

INTRODUCTION TO REMOTE SENSING

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The course is designed for vocational training in the application of remote sensing technology. It covers the fundamental concepts in remote sensing, emphasising the underlying physics, mathematical representations, and methods for evaluating the **TRUTH** and reliability of measurements, classifications, predictions, and models.

This course emphasises the study of sensing and sensors, particularly contact sensors used to measure soil moisture, temperature, and precipitation. Understanding all sensor types and the underlying principles of sensing is essential for their effective application in orchard management.

1. Key Concepts

- **Truth Values:** The evaluation of statements about remote sensing data and models, estimating their reliability or likelihood.
- **Sensors:** Devices that transform energy from one domain to another for data collection. Remote sensing sensors are often transducers.
- **Photons and Electrons:** Fundamental particles relevant to physical interactions in remote sensing.
- **Imaging Sensors:** Sensors, often based on arrays of cells, that convert photons into electronic signals.
- **Quantum Efficiency:** The probability of a photon transforming into an electron in a sensor cell.
- **Thermal Infrared Sensors:** Sensors that detect thermal radiation but face challenges distinguishing between photons and electrons generated within the sensor. Cooling is often required.
- **Bolometers:** Cheaper sensors based on heating due to radiation, measuring temperature change.
- **Microwave Sensors:** Sensors that measure the electrical field of microwaves, often employing electromagnetic resonators to increase the amplitude of the signal.
- **Resonator:** A system that amplifies a signal at its natural frequency, analogous to a swing.
- **Electromagnetic (E.M.) Radiation:** The form of energy detected by many remote sensing sensors. Understanding static or potential energy and dynamic or movement energy is important for evaluating statements about E.M. radiation.
- **Potential Energy:** Energy stored by position or state, proportional to height in a mechanical system or to the electrical field E in electromagnetism.
- **Kinetic Energy:** Energy of motion, proportional to the square of velocity in a mechanical system or to the square of current I in electromagnetism.
- **Conservation of Energy:** In a closed system without energy loss, the sum of potential and kinetic energy remains constant.
- **The E.M. Swing:** An analogy to a mechanical swing, representing the harmonic flow of energy between maximum voltage (potential energy) and maximum current (kinetic energy) in an electrical circuit with capacitance and inductance.
- **Man-made Resonators:** Devices designed to resonate at specific frequencies, including acoustic (guitar strings, tuning forks) and microwave (dipole antennas,

resonance cavities). MASERS and LASERS are examples of optical/quantum resonators based on molecular resonances.

- **Properties of Photons (and Microwave) Waves:** The effects of the electrical field (E) are often stronger than the magnetic field (M). The M field can be derived from the changing E field. The E field has a polarisation angle. The E field vector has components.
- **Frequency and Wavelength:** Frequency is the inverse of the time period required for the E(x,t) pattern to reproduce itself. Wavelength depends on the medium. The speed of propagation in a vacuum is constant.
- **Spectroscopic Data:** Horizontal scales of spectroscopic data often use "units" related to 2π times the frequency or 2π divided by the wavelength.
- **Output of Electro-Optical Devices:** An estimation of the number of photons "captured" per sensor cell during an exposure time.
- **Photon Stream or Photon Flux:** The number of photons falling on/into a sensor element.
- **Potential Energy of Electrons in a capacitor :** Vc = Q/C, where Q is the total charge and C is the capacitance. Voltage Vc is an analog value. The number of electrons is derived from Q = Vc x C as charge Q is the number of electrons x charge of 1 electron.
- **Analog to Digital Conversion (ADC):** Converting analog voltage values into digital data. RGB cameras usually have 8 bit adc’s per channel. Spectrometers may have 16 bit adc’s .
- **Numerical Output (N_e):** Represents steps of change in Vc, relating to the quantum efficiency and the number of photons.
- **Truth Interpretation:** Establishing an explicit model linking the numerical output of the ADC to the number of photons allows evaluation of the truth value of interpretations or sensor models. The likelihood of true measurement is reduced by systematic and random errors and the use of false sensor models.
- **Photon Sorting/Filtering:** Achieved using selective resonance absorption filters (e.g., RGB, IR cameras) or interference filters based on making resonance paths (layers) that pass a small range of wavelengths or frequencies.
- **Measurement:** The interaction between two objects in space-time that produces data about that interaction.
- **Information:** A relationship between possible questions and answers. Useful information specifies the data and the interaction models used to obtain the data. Information is a statistical relationship (likelihood).
- **Truth-of-Answer:** Prob(question, data|model), meaning the probability of the question given the data and model. The probability model for photon counts must be asymmetric with arrival time (e.g., Poisson distribution). Otherwise, the information extraction method is FALSE.
- **Knowledge:** Based on hypotheses and measured evidence.
  Know(hypothesis(i), evidence(j)) = prob(hypothesis(i) given evidence(j)).
- **Knowledge from Photon Sensors:** Derived from controlled experiments, hypotheses about object characteristics (radiometric properties, 2D/3D patterns) are evaluated based on coincidence statistics of the evidence given hypothesis(label,class, parameters) . Hypotheses should preferably be formulated as prediction models.

- **Truth Value of Classification:** The probability of TRUE/false is reported by the frequencies of correct and misidentified data samples for discrete classes. This assumes the experimenter has determined the frequency of evidence for each class.
- **Relationship Probabilities:** Prob(E_i | C_j) is estimated from controlled, supervised measurements. This knowledge should be independent of sample size. Prob(C_j | E_i) can be calculated using frequencies (histograms, counts over intervals).
- **Likelihood Vector or Likelihood Array:** for each evidence datum the likelihood for all current hypotheses is calculated.
- **Maximum Likelihood:** Mapping to maximum likelihood by selecting the maximum of each likelihood array per datum, produces a binary approximation of probabilistic truth to pseudo-truth.
- **Coincidence (confusion) Matrix:** A table showing the counts or frequencies of co-occurrences between likely or predicted classes and actual or true classes over all data in a region of interest . This matrix is relevant for decision making.

Basic Physics and Mathematics:

- Everyday physics is based on interactions of atoms and molecules via electrons and photons.
- In medical applications, protons, electrons, and photons are relevant.
- Basic requirements for remote sensing are evaluating truth and reliability of statements about sensors, data, classification, predictions, and models.

Sensor Mechanisms:

- **Imaging Sensors:** Convert photons to electrons. Quantum efficiency is crucial.
- **Thermal Infrared Sensors:** It is challenging to distinguish photon-generated electrons from those generated in the sensor. Cooling helps. Bolometers are an alternative.
- **Microwave Sensors:** Use the electrical field of wavelets (photons) to generate voltages in antenna type detectors, often with resonators to increase the signal.

Energy Concepts:

- Potential and kinetic energy are important for evaluating statements about E.M. radiation.
- Conservation of energy is a fundamental principle.
- The E.M. swing analogy illustrates energy flow in electrical circuits.

- Relevant energy units are Joule per integration time. **Electron volt (Ev)** is used for the energy per photon.

Wave Properties:

- Frequency, wavelength, polarisation, and electric field components are key properties of E.M. waves.
- Spectroscopic data analysis relies on understanding these properties.

Data Acquisition and Conversion:

- The output of electro-optical devices estimates photon counts.
- Photon flux determines the charge accumulated in a sensor element.
- Analog voltage from accumulated charge is converted to digital data via an ADC.
- Understanding the relationship between digital output and photon count is crucial for evaluating truth.

Information and Knowledge:

- Information is a statistical relationship derived from measurements and models.
- The probability model for photon counts affects the validity of information extraction.
- Knowledge is built upon hypotheses and evidence, evaluated through probability.
- Truth values for classification are assessed using statistical analysis of classification accuracy, often represented in a confusion matrix.

2. Remote Sensing Basics: Physics, Mathematics, and Truth Values

2.1 Introduction

This section offers a fundamental overview of the physical and mathematical principles that underlie remote sensing. It specifically focuses on assessing the reliability or "**truth value**" of data, models, and predictions derived from remote sensing applications. The discussion includes the basic physics of energy interaction, the functioning of various types of sensors, the nature of information and knowledge in remote sensing, and methods for evaluating the accuracy or truth value of classifications.

2.2 Key Themes and Important Ideas/Facts

The Fundamental Basis of Remote Sensing - Physics of Energy Interaction:

- Remote sensing fundamentally relies on the interaction of energy (specifically, electromagnetic radiation in the form of photons) with objects and molecules.
- Physics (under normal non nuclear conditions) is fundamentally based on the interaction of atoms and molecules via electrons and photons.
- Sensors are described as transducers that transform energy from one domain to another for data collection.

Sensor Operation and Energy Conversion:

- Most current remote sensing imaging sensors are based on arrays of cells that convert photons into electrons.

- This conversion involves photons giving energy to electrons, allowing them to escape from potential voltage "wells" or "buckets."
- The efficiency of this conversion (transforming a photon to a "free" electron) is called the quantum efficiency.
- The voltage over a capacitor in each sensor cell is a measure of the number of photons that have entered the cell.
- Thermal infrared sensors face the challenge of distinguishing between photon-generated electrons from photons and electrons generated by heat in the sensor elements, which often requires cooling. Cheaper sensors (bolometers) rely on measuring temperature changes per cell.
- In the microwave domain, the low energy per photon wavelet makes free electron generation difficult. Instead, the electrical field of microwave photons is used to increase the voltage and current variation of an electromagnetic resonator.

The Importance of Resonance:

- Resonance is a key principle in sensor operation, particularly in microwave and radio wave detection.
- A resonator is analogous to a swing. When pushed at its natural frequency, the amplitude increases.
- "Why is the principle of resonance important?"
- In photon-electron interaction, electrons are pushed to higher energy levels if their oscillation energy resonates with the photon's dynamic energy.
- In microwave and radio wave detection, resonance allows waves with the same frequency as the antenna (acting as a dipole antenna) to build up enough amplitude to be detected.

Understanding Electromagnetic Radiation (EMR) for Truth Evaluation:

- Evaluating the truth of statements about EMR radiation requires understanding concepts of static/potential energy and dynamic/movement energy.
- This is analogous to a swinging pendulum, where potential energy is proportional to height and kinetic energy to the square of velocity.
- In electromagnetism, potential energy is proportional to the electrical field (E) and kinetic energy to the movement/displacement of electrons/charge, which produces a magnetic field (M).
- The "electric swing and resonator," showing the harmonic flow of energy between maximum voltage (associated with the electrical field) and maximum current (associated with the magnetic field). The E and M field cannot have the same vector value at the same time . Verify the truth of graphs in RS handbooks on the E.M. field!
- Man-made resonators in different fields (acoustic, microwave, optical/quantum) play a crucial role in storing and releasing energy.

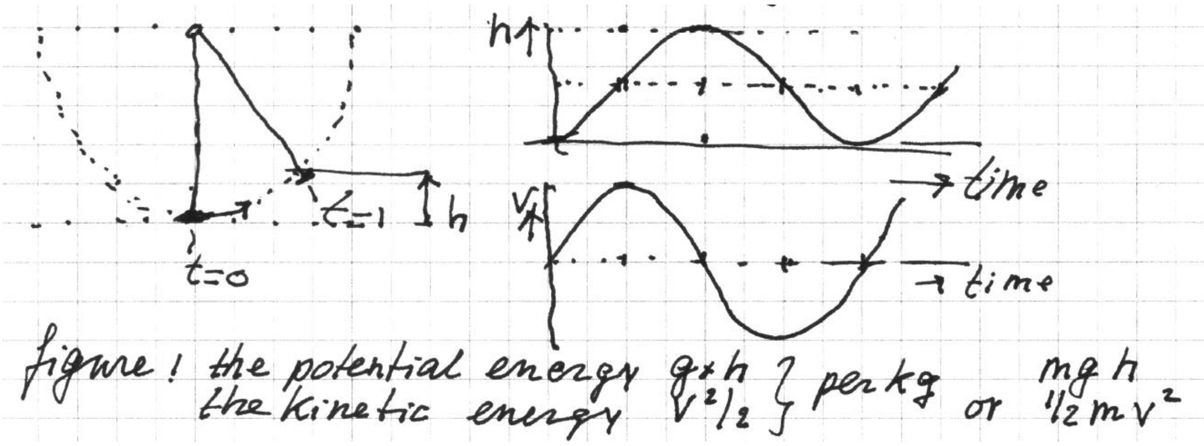

Figure 1: The potential energy = mgh (m stands for mass and is measured in kilograms, g stands for gravity and equals 9.8 m/s^2, and h stands for height and is measured in meters). The kinetic energy = ½ mv^2 (m is the mass and v is the velocity).

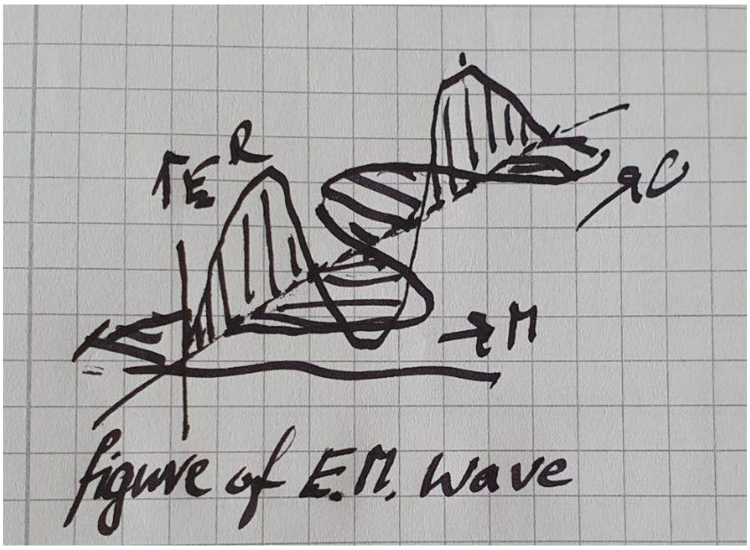

Figure 2: The Electromagnetic (E.M.) Radiation wave.

Properties of Photons and Microwave Waves:

- In most applications, the effects of the electrical field (E) are much stronger than the magnetic field (M). Properties of the E-field are used to derive properties of the M-field.
- The E-field has a polarisation angle.
- Frequency is the inverse of the time period required to reproduce the E(t) pattern ($f = 1/T$).
- Wavelength depends on frequency and the medium ($\lambda = c/f$).

- The output of electro-optical devices is an estimation of the number of photons "captured" per sensor cell during an exposure or integration time.

- Photon energy is expressed in Joule or Ev Electron Volt.

Photon Sorting and Filtering:

- Photons are sorted or "filtered" based on their properties, such as wavelength.
- RGB and Infrared cameras typically use selective resonance absorption filters.
- Transmission bands are frequency bands where photons are not transformed into "thermal" electrons.
- Absorption of photon energy can lead to de-coherence as thermal energy, quantum effects in chemical reactions (chlorophyll) or re-emission (fluorescence).
- Interference filters use resonant cavities to pass a small range of wavelengths or equivalent frequencies.

- Reflected photons are in general re-polarised .

Measurement, Information, and Knowledge in Remote Sensing:

- Measurement: The interaction between two objects in space-time that produces data about that interaction.
- Information: A relationship between possible questions and answers. Useful information must specify the data and interaction models used. It is a statistical relationship.
- The truth of an answer (e.g., from a model) is the probability of the answer given the data and model. The probability model for photon counts should be asymmetric, like the Poisson distribution, to avoid a false information extraction method.
- Knowledge: Is based on hypotheses and measured evidence. Knowledge (Hypothesis(i)) = probability (Hypothesis(i) given Evidence(j)).
- Knowledge about objects derived from photon sensors can be based on the frequency or counts of coincidence statistics of controlled experiments.
- Hypotheses can vary (radiometric, shape, 2D/3D patterns). They should preferably be formulated as prediction models for spatial and spectral features.

Evaluating the Truth Value of Classifications:

- This section focuses on evaluating the reliability of discrete class hypotheses.
- The probability of "true" or "truth" for a classification is reported by comparing the frequencies of true and false of classified data samples.
- This knowledge must be independent of sample size (must be large enough).
- The process involves mapping the frequency of evidence (Ei) given a class (Ci) to a probability.

- The average likelihood (over all hypotheses, classes) for a given dataset gives a truth estimate for the result of the classification.
- Mapping the likelihood array for each datum to maximum likelihood produces a binary approximation of truth to "pseudo truth."
- A coincidence matrix (or confusion matrix) is used to show the frequency of correct and incorrect classifications.
- The truth matrix, derived from the coincidence matrix, is crucial for decision making as it highlights the trade-offs between the benefits of a correct classification and the costs of a wrong one.

2.3 Key Quotes

- Physics under normal circumstances is fundamentally based on the interaction of atoms and molecules via electrons and photons."
- "A sensor is a transducer that transforms energy from one domain to another domain that is more accessible to data collection."
- "In current remote sensing practice, most imaging sensors are based on arrays or matrices of cells that convert photons with energy **hf (Planck x frequency)** to electrons with enough energy to escape free from each cell's energy 'wells' or buckets."
- "The voltage over the capacitor is a measure of the number of photons entering each sensor cell."
- "Why is the principle of resonance important?"
- "Measurement: the interaction between two objects in space-time that produce data about that interaction."
- "Information: a relationship between (possible) questions and answers."
- "Knowledge is based on hypotheses and measured evidence. K(Hypothesis(i)) = prob(Hypothesis(i) given Evidence(j))."
- "This truth matrix is very relevant for decision making where the benefits of a TRUE classification may be different from the costs of a wrong classification."

2.4 Conclusion

The training materials offer a detailed technical foundation for understanding how remote sensing systems work physically and how their data can be evaluated for accuracy and reliability. The concepts of energy conversion by sensors, the importance of resonance, and the statistical nature of information and knowledge are central to this understanding. The detailed explanation of truth evaluation for classifications highlights the practical aspects of assessing the utility of remote sensing data for decision-making.

3. Quiz

Q1: Are electro optical imaging sensors based on detecting radiant wave energy?

A1.1: Yes, the sensor measures the electrical field and the average squared voltage is a measure for light brightness.

A1.2: No, the sensor converts energy quanta to electrons. The free electrons are collected over integration time in a capacitor. The voltage over the capacitor is a measure for the number of photons entering each sensor cell.

Q2: Are scientists not sure if E.M. radiation consists of Waves or photons.

A2.1: No, the question is not what E.M. radiation is but how E.M. "radiation" interacts with the measuring device.

Q3: Why is the principle of resonance important?

A3.1: In photon-electron interaction, electrons are only pushed to high energy levels if their oscillating dynamic energy resonates with the dynamic energy of the photon.

A3.2: In microwave and radio wave detection only waves with the same frequency as for instance a dipole antenna will build up enough amplitude to be detected.

Q4: What is the basic requirement for vocational training in applying remote sensing?

- To work with tools such as QGIS.
- the ability to evaluate the truth and reliability of statements about sensors, data, classification, predictions, and model validity. This involves estimating their truth value or likelihood.

Q5: A sensor is defined as?

- A sensor generates digital numbers for input into an AI.
- A sensor is a transducer that transforms energy from one domain to another. This transformation makes the energy more accessible for data collection in remote sensing.

Q6: What is quantum efficiency in relation to imaging sensors?

- It is defined as the ratio of the squared image signal-to-noise ratio to the number of incident photons.
- Quantum efficiency is the probability that a photon transforming into a "free" electron will escape from the energy "wells" or "buckets" in a sensor cell. It is essentially the efficiency of converting photon energy into usable electron energy.

Q7: Why do thermal infrared sensors often require cooling?

- Because heat generates electrons within the sensor elements, making it difficult to distinguish these thermal electrons from those generated by photons. Cooling helps minimise this thermal noise.
- Because the sensor may overheat and malfunction.

Q8: How do microwave sensors utilize electromagnetic fields to generate a signal?

- Microwave sensors use the electrical field of microwave photons to increase the voltage and current variation of an electromagnetic resonator.
- Microwave photons generate electrical fields, and the signal is a squared voltage.

Q9: How can photons be filtered based on their properties?

- using selective transmission bands.
- using selective transmission bands.
- using polarisation filters.
- using interference filters.

Q10: What is measurement?

- Measurement is defined as the interaction between two objects in space-time that produces data about that interaction. In the case of photon sensors, the measuring device is a photon counter, and the measurement unit is the number of photons.
- Measurement is defined as the interaction between the interested object in the scene and the electrons.
- Measurements are expressed in voltage squared.

Q11: How do we estimate the properties of objects in a scene?

- Measure the reflectance of the objects.
- We estimate the reflectance of the objects from the modulated photon flux based on the reflectance and transmission model and measured photon counts.

4. Essay Questions

1. Discuss the role of physics and mathematics in establishing the truth value and reliability of remote sensing data and derived products. Use examples to illustrate your points.
2. Compare and contrast the operational principles of different types of remote sensing sensors (e.g., optical imaging, thermal infrared, microwave). What are the advantages and disadvantages of each for specific applications?
3. Explain the concepts of potential and kinetic energy in a mechanical system (like a swing) and an electromagnetic system. How do these concepts relate to the operation of remote sensing devices and the evaluation of statements about E.M. radiation?
4. Analyse the process of converting electromagnetic energy into a usable digital signal in electro-optical imaging sensors, from the arrival of photons to the numerical output. How does quantum efficiency and the concept of "buckets" or "wells" fit into this process?
5. Describe how knowledge is generated in remote sensing based on hypotheses and measured evidence, particularly from photon sensors. How are concepts like probability, statistical relationships, and confusion matrices used to evaluate the truth value of classifications and predictions?

5. Glossary of Key Terms

- **Truth values:** Evaluation of the reliability or likelihood of statements about sensors, data, classification, predictions, and models.
- **Sensor:** A transducer that transforms energy from one domain to another for data collection.
- **Evaluation:** Estimating the truth value or likelihood of something.
- **Photons:** Fundamental particles of light, carrying energy.
- **Electrons:** Subatomic particles with a negative charge, fundamental to electrical current and sensor interactions.
- **Imaging sensors:** Sensors based on arrays of cells that convert photons into electronic signals.
- **Quantum efficiency:** The probability of a photon being converted into a free electron in a sensor cell.
- **Energy "Wells" or "buckets":** In imaging sensors, regions that accumulate free electrons.
- **Thermal infrared sensors:** Sensors that detect thermal radiation.
- **Bolometers:** Cheaper sensors based on the heating effect of radiation.
- **Electromagnetic resonator:** A system that amplifies electromagnetic signals at a specific frequency.
- **Electromagnetic (E.M.) radiation:** Energy that travels in waves, consisting of oscillating electric and magnetic fields.
- **Static or potential energy:** Energy stored by position or state.
- **Dynamic or movement energy:** Energy of motion (kinetic energy).
- **The E.M. swing:** An analogy illustrating energy exchange in electrical circuits with capacitance and inductance.
- **Resonance:** Amplification of a signal at a system's natural frequency.
- **Polarization angle:** The orientation of the electric field vector of an electromagnetic wave.
- **Frequency:** The number of wave cycles that pass a point per unit time.
- **Time period:** The time required for one complete wave cycle.
- **Wavelength:** The spatial distance over which a wave's pattern repeats.
- **Speed of propagation:** The speed at which a wave travels through a medium.
- **Spectroscopic data:** Data that measures radiation intensity at different wavelengths or frequencies.
- **Photon stream or photon flux:** The number of photons falling on a sensor element per unit time or area.
- **Potential energy of electrons (Vc):** The voltage across a capacitor formed by accumulated charge from electrons.
- **ADC (Analog to Digital Converter):** A device that converts analog signals (like voltage) into digital values.
- **Numerical output (N_e):** The digital value produced by an ADC, representing the accumulated signal.
- **Truth interpretation:** Establishing a model to relate sensor output to physical quantities.

- **Selective resonance absorption filters:** Filters that absorb radiation at specific wavelengths or frequencies.
- **Interference filters:** Filters that use layers to create resonance paths that pass a narrow range of wavelengths.
- **Measurement:** The interaction between two objects in space-time that produces data about that interaction. In the case of photon sensors, the measuring device is a photon counter, and the measurement unit is the number of photons.
- **Image:** A visual representation of data captured by a sensor, often composed of multiple bands (e.g., RGB, infrared).
- **Information:** A relationship between possible questions and answers, based on data and interaction models.
- **Statistical relationship:** The basis of information, often described by probabilities.
- **Truth-of-answer:** The probability of a question being true given the data and model.
- **Poisson distribution:** A probability distribution often used for modelling photon counts with arrival time.
- **Knowledge:** Based on hypotheses and measured evidence.
- **Hypothesis:** A proposed explanation or statement to be tested.
- **Evidence:** Data or observations that support or refute a hypothesis.
- **Coincidence statistics:** Statistical analysis of the co-occurrence of different events or classifications.
- **Radiometric properties:** Properties of an object related to its interaction with electromagnetic radiation (e.g., reflectance, emittance).
- **Prediction models:** Models forecasting future states or properties based on current data.
- **Truth value of classification:** Evaluation of the accuracy of assigning data to specific categories.
- **Discrete class hypotheses:** Hypotheses that assign data to distinct, separate categories.
- **Frequencies:** The number of times something occurs within a sample.
- **Prob(E_i | C_j):** The probability of observing evidence E_i given class C_j.
- **Prob(C_j | E_i):** The probability of the class being C_j given the evidence E_i.
- **Likelihood vector or array:** A representation of the probabilities of different classes given the evidence.
- **Maximum likelihood:** A method of choosing the class that is most probable given the evidence.
- **Binary approximation:** Reducing multiple possibilities to two outcomes (e.g., true or false).
- **Pseudo truth:** A simplified or approximate representation of truth.
- **Confusion matrix:** A table showing the relationship between predicted and actual classifications.

6. Q&A

What is a sensor in the context of remote sensing?

A sensor is a transducer that transforms energy from one domain to another, making it accessible for data collection. In current remote sensing practice, most imaging sensors are based on arrays or matrices of cells that convert photons with energy into electrons.

How do imaging sensors work based on converting photons to electrons?

These sensors utilise arrays of cells that function as "wells" or "buckets." When a photon strikes a cell with sufficient energy, it can release an electron. The probability of transforming a photon into a free electron is called quantum efficiency. The collected electrons within these cells over an integration time represent the number of photons captured, and the voltage over the cell's capacitor serves as a measure of the number of photons.

Why do thermal infrared sensors require cooling?

Thermal infrared sensors face the challenge of distinguishing photon-generated electrons from electrons generated by the sensor elements themselves due to heat. Cooling the sensors helps to reduce this background noise and improve the accuracy of measurements.

How do microwave sensors detect radiation?

In the microwave domain, the energy per photon is too low to generate free electrons directly. Instead, microwave sensors use the electrical field of microwave photons to increase the voltage and current variation of an electromagnetic resonator.

What is the significance of resonance in remote sensing applications?

Resonance is important because it describes how systems respond to oscillating energy. In photon-electron interaction, electrons are pushed to higher energy levels if their dynamic energy resonates with the dynamic energy of the photon. In microwave and radio wave detection, using the same frequency as a dipole antenna's natural frequency allows enough amplitude to build up to be detected.

How are photons sorted or "filtered" based on their properties?

Photons can be sorted or filtered using selective resonance absorption filters, as seen in RGB (red, green, blue) and infrared cameras. These filters allow transmission in specific frequency bands while blocking others. Interference filters, based on making resonance paths using transparent layers, can also be used to pass a small range of wavelengths or equivalent frequencies.

What is the relationship between measurement, information, and knowledge in remote sensing?

Measurement is the interaction between two objects in space-time that produces data about that interaction. Information is a statistical relationship between possible questions and answers, requiring data and the interaction models used to obtain the data. Knowledge is based on hypotheses and measured evidence, often expressed as the probability of a hypothesis given the evidence. Knowledge about objects derived from photon sensors can be based on the frequency of coincidence statistics of controlled experiments, where hypotheses are preferably formulated as prediction models for spatial and spectral features.

How is the truth value of a classification determined?

The truth value of a classification (which represents discrete class hypotheses) is reported by the frequencies of proper and misclassified data samples. This assumes the experimenter has experimentally determined the frequency of evidence for each class. The relationship between the probability of evidence given a class and the frequency of evidence given a class from a controlled, supervised measurement provides the knowledge. The given data set is then classified, and for each data point, the likelihood vector is updated to the frequency average. This can be mapped to maximum likelihood, producing a binary approximation of probabilistic truth, like class membership.