Section 4. Remote Sensing/Sounding

References
- *Stephens: chapter 1, pp. 3-11; chapter 3, pp. 123-135; parts of chapters 6,7,8*
- *Houghton, Taylor, and Rodgers: parts of chapters 1,6,7*
- *Liou: chapter 7, pp. 234-236*
- *Rees: chapters 1,7,8; chapter 4, pp. 82-92; chapter 5, pp. 94-107*
- *Sanchez and Canton: chapter 4, pp. 93-106; chapter 5, pp. 111-131*
- *Lenoble: parts of chapter 22*

4.1 Definitions and the Inverse Problem

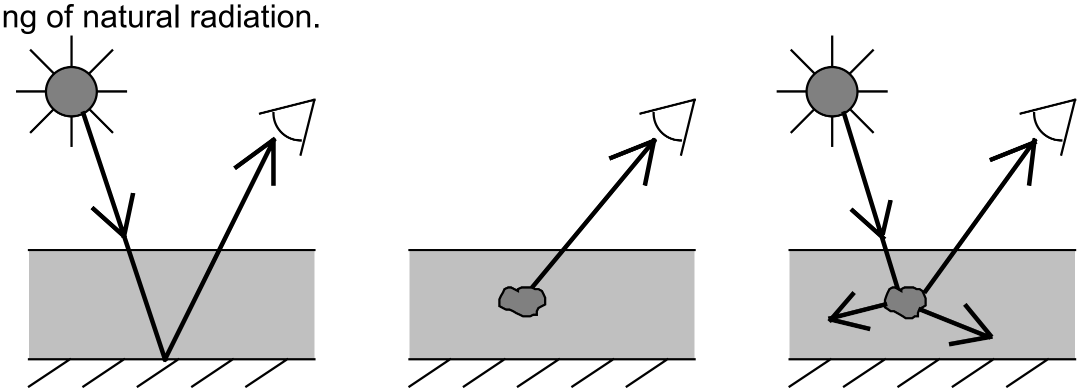
Recall the definition of remote sensing/sounding:
→ a means of obtaining information about an object or medium without coming into physical contact with it

This generally involves the measurement of EM radiation that has interacted with the object or medium of interest. Remote sensing/sounding techniques can thus be classified as passive or active, on the basis of the source of this EM radiation.

Passive RS techniques use the natural radiation emitted by the Sun, by stars, and by the Earth and its atmosphere.
→ usually in UV-visible ("solar"), infrared, microwave

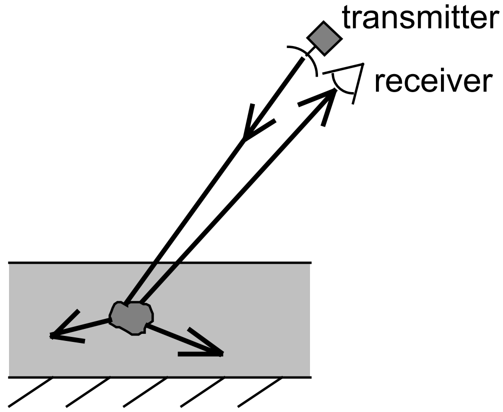
Active RS techniques use artificial sources that emit radiation, directing it towards the object of interest and collecting the return signal
→ usually LASERs (LIDAR) or RADAR

Space-based passive RS instruments are used to observe extinction, emission, and scattering of natural radiation.



Extinction	Emission	Scattering
radiation is absorbed or scattered out of the beam	radiation is emitted by the object (the atmosphere)	natural radiation is scattered towards the satellite

Space-based active instruments are used to observe backscattering of artificial radiation, i.e., source and receiver are generally co-located.

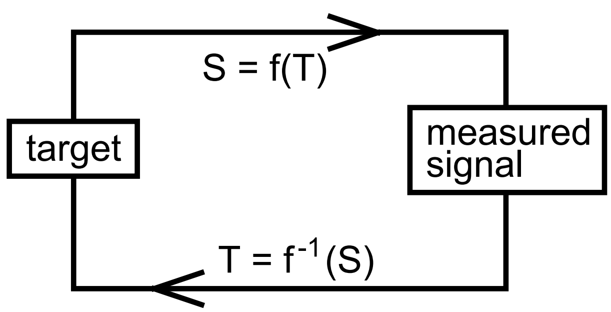


Backscattering

artificial radiation is backscattered towards the satellite

Remote sensing requires the solution of the inverse problem, a topic known as retrieval or inversion theory.

In simple terms:



The direct or forward problem:

A detector measures a signal S = f(T) which is generated by the interaction of radiation with the target (e.g., surface, atmosphere, clouds, etc.).
→ given properties of the target, calculate signal

The inverse problem:

Want to determine properties of the target, given by the inverse function $T = f^{-1}(S)$.
→ given signal, calculate properties of the target

Example:
direct problem – describe the tracks that a dog would leave in the snow
inverse problem – describe the animal that left the observed tracks

Solving the inverse problem is complicated by a number of difficulties.

(1) Non-uniqueness of the solution caused by several unknown parameters, which can be combined in different ways to generate the same observed signal.
i.e., have several solutions $T_1 = f^{-1}(S)$, $T_2 = f^{-1}(S)$, etc.

(2) Discreteness of the measurements when the measured quantity is a smoothly varying function.
e.g., T is a function of height z, while S is measured at discrete levels over some range of heights, so

$$S = \int_a^b K(z)T(z)dz$$

where K(z) is called a kernel function or a weighting function.

(3) Instability of the solution due to errors in the observations S.
e.g., If ε is the error on S, then $S + \varepsilon = \int_a^b K(z)T(z)dz$
where ε can produce a large change in the retrieval of T(z).

We will look at inversion theory and the calculation of weighting functions in more detail when we discuss specific measurements.

In addition to classifying RS techniques according to the source of radiation, they can be classified by the type of measurement and the spectral region.

- ACTIVE vs. PASSIVE
- IMAGING vs. NON-IMAGING vs. SOUNDING
- WAVELENGTH OF RADIATION MEASURED

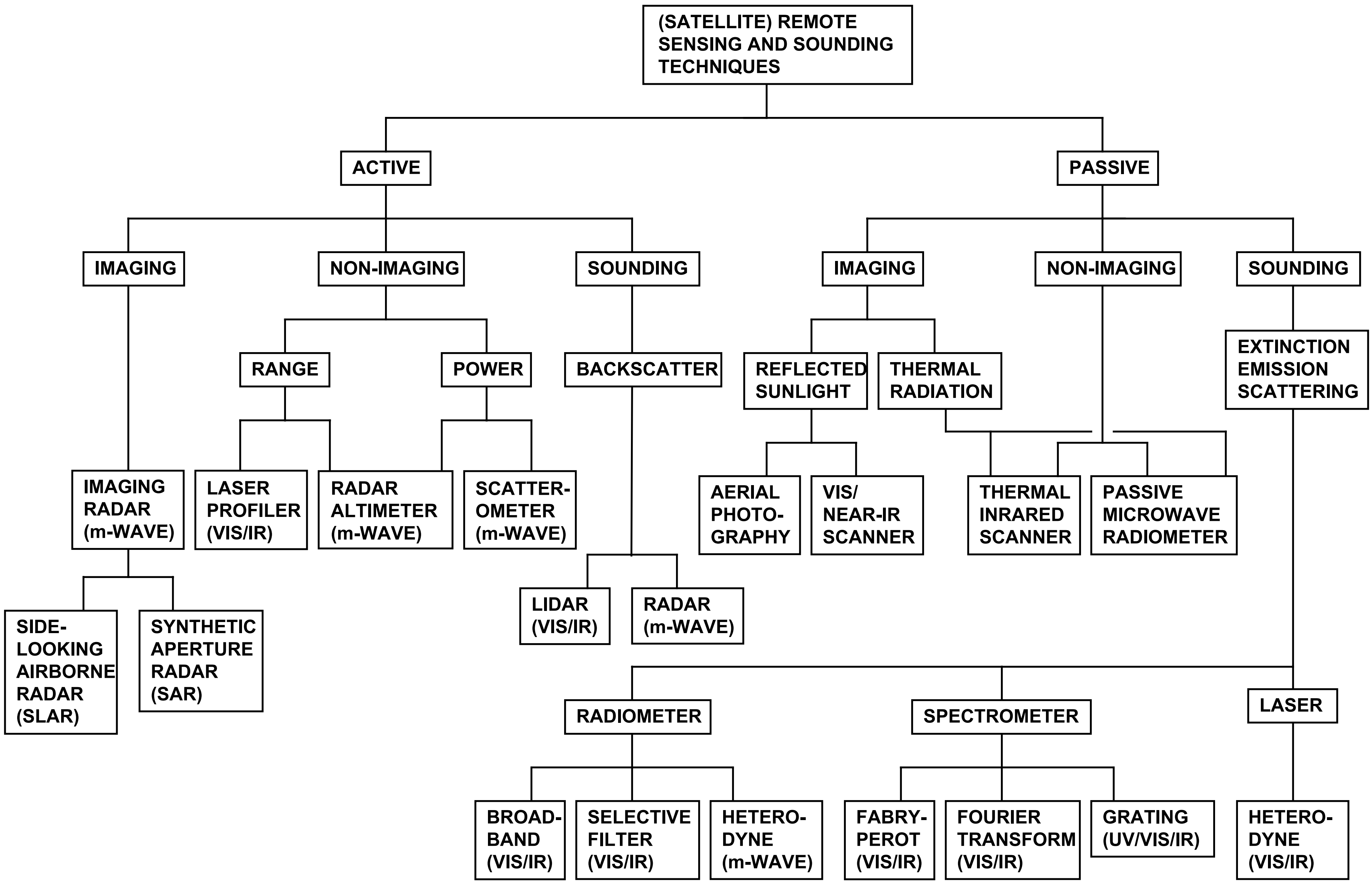
An imaging system measures the intensity of radiation reaching it as a function of position on the Earth's surface so that a 2-D picture of the intensity can be constructed. It can employ active or passive RS.

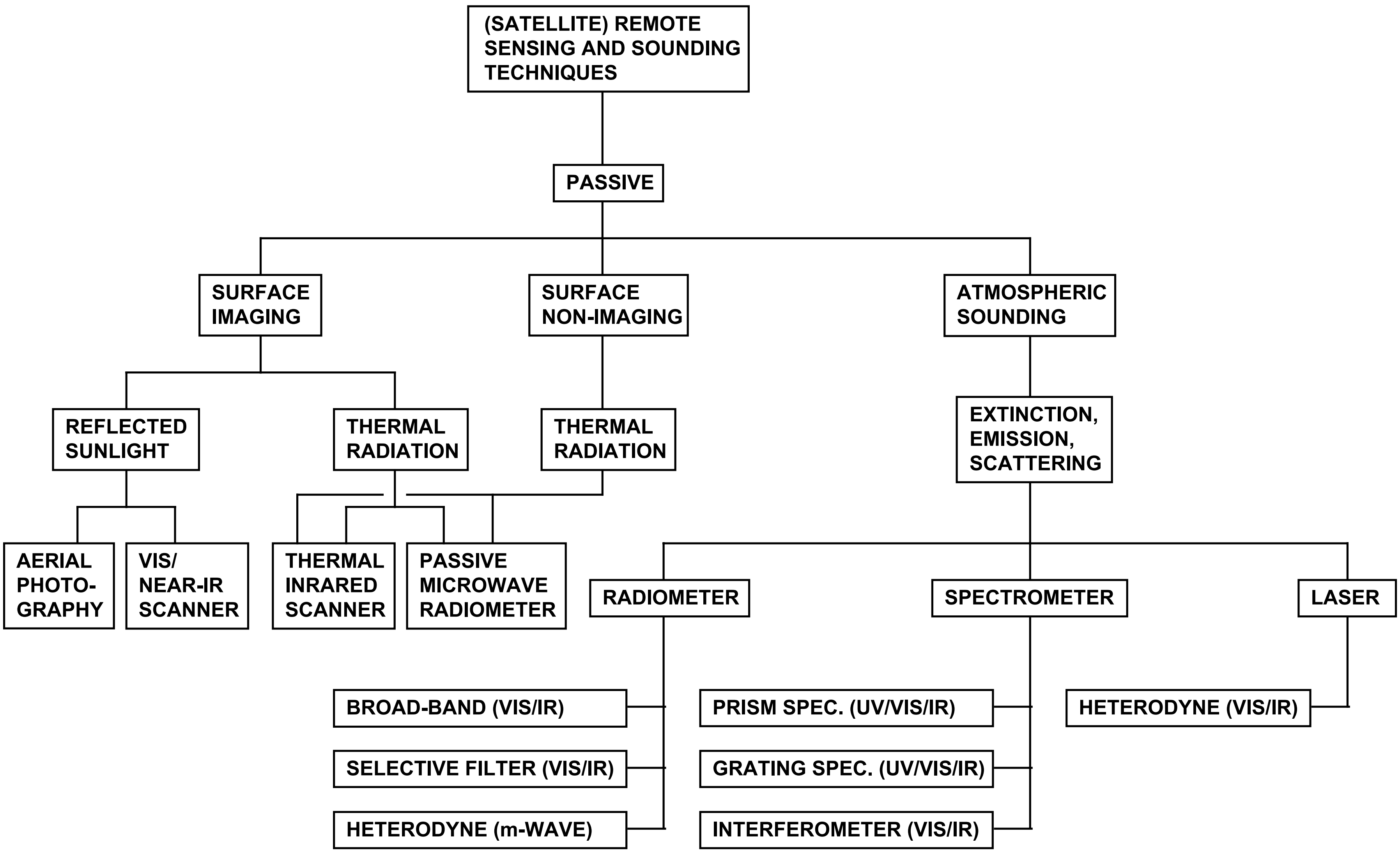
A non-imaging system either does not measure the intensity of radiation OR does not do so as a function of position on the Earth's surface.

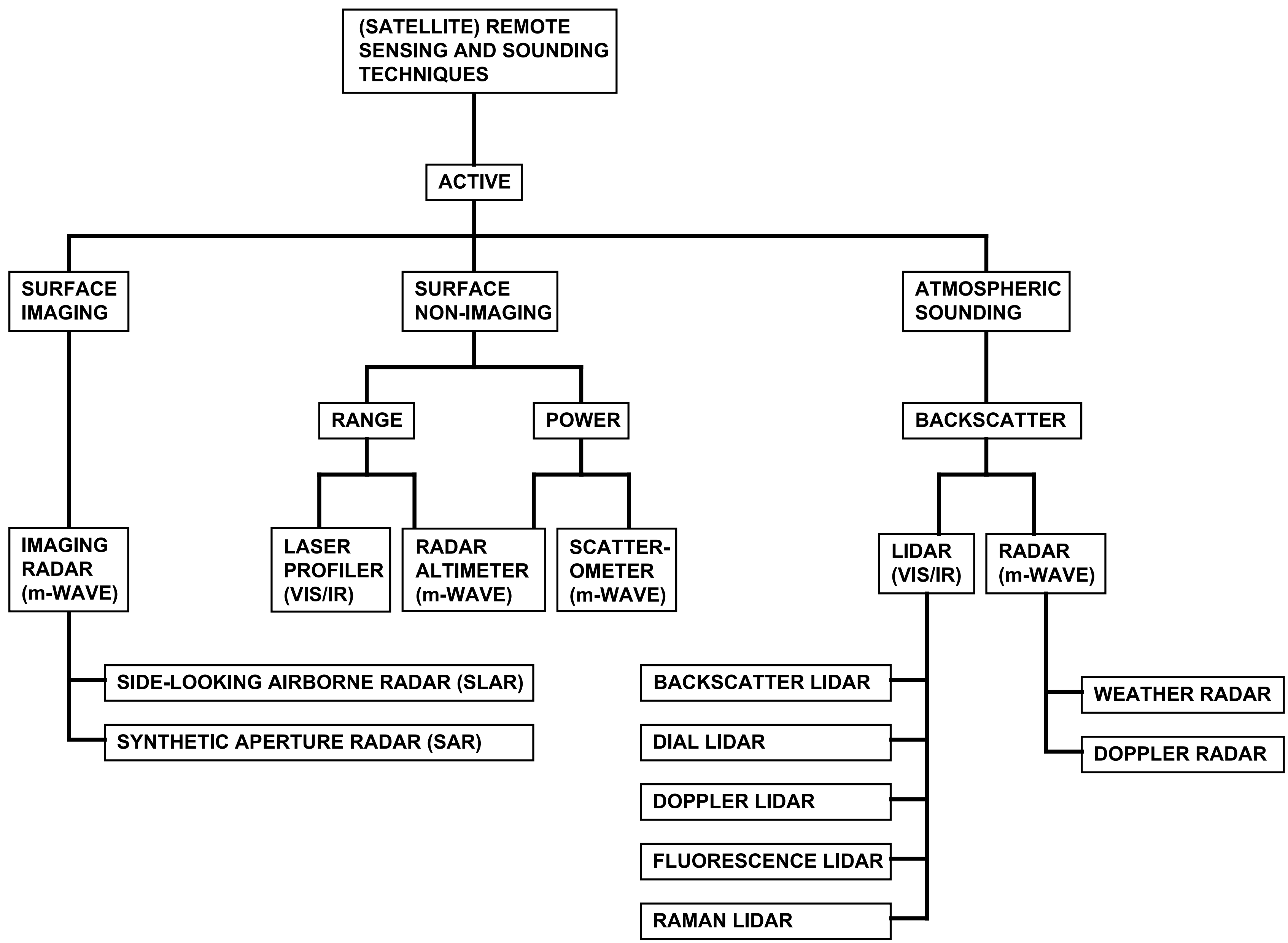
A sounding system ("sounder") measures the intensity of radiation to provide information about a particular property as a function of height in the atmosphere.

Using these three ways of classifying RS, we can construct a "family tree" of techniques. It is not an exhaustive or complete list, but it provides a useful framework for some of the instruments and techniques that we will discuss.

Our approach will be to briefly review these techniques, before proceeding to consider what properties of the Earth and its atmosphere need to measured and how this is done.


(SATELLITE) REMOTE SENSING AND SOUNDING TECHNIQUES
ACTIVE
PASSIVE
IMAGING
NON-IMAGING
SOUNDING
IMAGING
NON-IMAGING
SOUNDING
RANGE
POWER
BACKSCATTER
REFLECTED SUNLIGHT
THERMAL RADIATION
EXTINCTION EMISSION SCATTERING
IMAGING RADAR (m-WAVE)
LASER PROFILER (VIS/IR)
RADAR ALTIMETER (m-WAVE)
SCATTER-OMETER (m-WAVE)
AERIAL PHOTO-GRAPHY
VIS/ NEAR-IR SCANNER
THERMAL INRARED SCANNER
PASSIVE MICROWAVE RADIOMETER
SIDE-LOOKING AIRBORNE RADAR (SLAR)
SYNTHETIC APERTURE RADAR (SAR)
LIDAR (VIS/IR)
RADAR (m-WAVE)
RADIOMETER
SPECTROMETER
LASER
BROAD-BAND (VIS/IR)
SELECTIVE FILTER (VIS/IR)
HETERO-DYNE (m-WAVE)
FABRY-PEROT (VIS/IR)
FOURIER TRANSFORM (VIS/IR)
GRATING (UV/VIS/IR)
HETERO-DYNE (VIS/IR)


(SATELLITE) REMOTE SENSING AND SOUNDING TECHNIQUES
PASSIVE
SURFACE IMAGING
SURFACE NON-IMAGING
ATMOSPHERIC SOUNDING
REFLECTED SUNLIGHT
THERMAL RADIATION
THERMAL RADIATION
EXTINCTION, EMISSION, SCATTERING
AERIAL PHOTO-GRAPHY
VIS/ NEAR-IR SCANNER
THERMAL INRARED SCANNER
PASSIVE MICROWAVE RADIOMETER
RADIOMETER
SPECTROMETER
LASER
BROAD-BAND (VIS/IR)
SELECTIVE FILTER (VIS/IR)
HETERODYNE (m-WAVE)
PRISM SPEC. (UV/VIS/IR)
GRATING SPEC. (UV/VIS/IR)
INTERFEROMETER (VIS/IR)
HETERODYNE (VIS/IR)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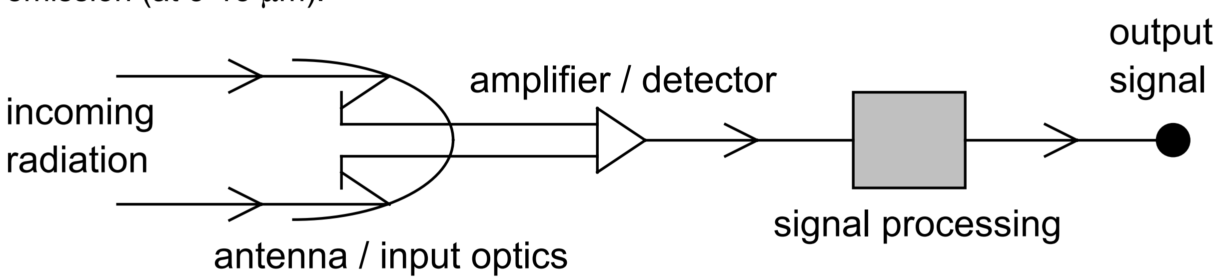
SCATTER-OMETER (m-WAVE)
LIDAR (VIS/IR)
RADAR (m-WAVE)
SIDE-LOOKING AIRBORNE RADAR (SLAR)
SYNTHETIC APERTURE RADAR (SAR)
BACKSCATTER LIDAR
DIAL LIDAR
DOPPLER LIDAR
FLUORESCENCE LIDAR
RAMAN LIDAR
WEATHER RADAR
DOPPLER RADAR

4.2 Passive Remote Sensing/Sounding Techniques

Passive Imaging Systems

These detect reflected sunlight in the visible/near IR (at 0.4-3 μm) or thermal IR emission (at 3-15 μm).



The antenna or input optics collect the passive radiation and direct it onto an amplifier/detector/sensor that generates a signal that can be processed and output.

Four passive imaging techniques:

(1) Aerial Photography (visible and near IR)
- was the first type of remote sensing from balloons and aircraft
- traditionally done using cameras and photographic film, which must be recovered
- now more common to use digital techniques, particularly CCDs (charge-coupled devices) which consist of a 2-D arrays of pixels that convert incident radiation into electric charge
- used in mapping, surveying, and many related applications
- non-scanning systems – record full 2-D image at one time

See figures (Rees 5.1) – schematic view of a non-scanning electro-optic imaging system, and (Sanchez & Canton 4.8) – CCD-based imaging instrument.

(2) Optical-Mechanical Scanners (visible and near IR)
- build up a 1-D or 2-D image using a scanning mechanism
- most common type is the is whiskbroom, cross-track, line-scan, or single-element scanner, for which a rotating mirror scans perpendicular to the ground track and the signal is recorded by a single detector for each spectral band
  e.g., Landsat's MultiSpectral Scanner (MSS) and Thematic Mapper (TM), each of which has several spectral bands in the visible and infrared
- pushbroom scanners use a linear array of sensors to provide coverage in the cross-track direction, and use the forward motion of the satellite for coverage in the along-track direction, so there are no moving parts
  e.g., SPOT

See figures (Rees 5.2) – schematic view of a whiskbroom sensor, and (Sanchez & Canton 4.7) – optical-mechanical scanner instrument.

(3) <u>Thermal Infrared Scanners</u>

- analogous to the visible/near IR scanner
  e.g., Landsat instruments have a combination of detectors with the same input optics
- useful bands are 3-5 μm and 8-14 μm where blackbody emission is high at terrestrial temperatures (H_2O band at 5-6 μm)
- for imaging, used to detect artificial heat sources, identify geological materials, monitor vegetation and soil moisture

(4) <u>Passive Microwave Radiometers</u>

- measure thermally generated radiation at 5-100 GHz
- can apply the Rayleigh-Jeans Approximation to obtain temperature: $B_\lambda(T) \approx \frac{c_1}{c_2} \frac{T}{\lambda^4}$
- at microwave wavelengths, the atmosphere and clouds are almost transparent, so measurements can be made through clouds and at night
- for imaging, used to measure soil moisture and sea surface temperature, and to map ice cover (as ice and seawater have very different emissivities)

Passive Non-Imaging Systems

These include the thermal infrared scanner and the passive microwave radiometer, but not used in imaging mode.

e.g., thermal infrared scanners can be used in non-imaging mode to measure T, P, humidity, and composition (overlaps with sounding)

e.g., passive microwave radiometers can be used in non-imaging mode to measure wind speed over oceans, salinities from emissivity (aircraft only), atmospheric water vapour, cloud liquid water content, rainfall rate, and temperature

Passive Sounding Systems

These generally measure the extinction, emission, or scattering of radiation in order to retrieve atmospheric properties.

Classification on the basis of spectral resolution:

- relatively broad-band radiometers
- higher dispersion spectrometers
- monochromatic LASER techniques

(1) <u>Radiometers</u> – isolate bands of natural radiation using some form of spectral filter

Three types of radiometers:

- <u>broad-band radiometers</u> – typically use semi-conductor interference filters which transmit only a limited spectral range
- <u>selective filter radiometers</u> – include a sample of the gas of interest in the instrument, whose transmission is modulated so that only wavelengths corresponding to the gas absorption lines are detected. e.g., ISAMS, MOPITT

- heterodyne radiometers (microwave) – use a monochromatic local oscillator which is mixed with the signal to produce a new signal at a difference frequency that can be more easily analysed (these can be used to detect weak signals at high spectral resolution)

(2) Spectrometers – disperse natural radiation into its constituent wavelengths over a finite spectral range

Three types of spectrometers:

- prism spectrometers – simply use a prism to disperse the light, each wavelength being refracted at a different angle determined by the index of refraction of the prism (no satellite instruments)
  e.g., ground-based Dobson spectrometer used to measure ozone at UV wavelengths

See figure (Stephens 3.21) – the principle of the prism spectrometer.

- grating spectrometers – use a diffraction grating to disperse the wavelengths (widely used in remote sounding satellite instruments)
  e.g., used to measure atmospheric temperature, composition, and aerosol properties, and to study ocean colour (differentiates between organic and inorganic materials in water)

See figure (Stephens 3.24"a") – the principle of a grating spectrometer.

- interferometers – use interference effects to obtain spectral information

Michelson interferometers (used in Fourier transform instruments) split the incoming beam, direct the two beams into different optical paths, and then recombine the beams. The path difference between the two beams is varied, causing the measured intensity to vary as the beams move in and out of phase. The resulting interferogram (signal vs. path difference) can be Fourier transformed into a spectrum (signal vs. wavenumber) at high resolution.

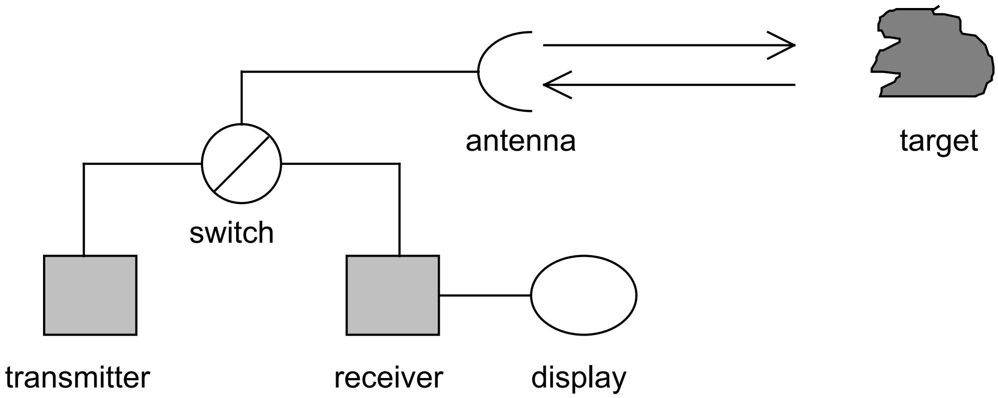
Fabry-Perot interferometers use the interference pattern created by two parallel plates

See figure (Stephens 3.25) – the Michelson interferometer.

(3) Monochromatic LASER Techniques
- visible/IR heterodyne spectrometers
- the LASER is used in a passive mode in a heterodyne system, serving as a local oscillator
- the incoming visible/IR source signal is mixed with the coherent LASER radiation (e.g., CO_2 LASER), and the difference frequency is detected using radio frequency techniques
- a set of filters is used to separate the signals along the line profile
- can get spectral resolution of 5 MHz = 0.00017 cm^{-1}

4.3 Active Remote Sensing/Sounding Techniques

These use radiation in the:
(1) radio (microwave) spectrum → RADAR (RAdio Detection And Ranging)



(2) visible and infrared spectrum
→ LASER (Light Amplification by Stimulated Emission of Radiation)
→ LIDAR (LIght Detection And Ranging)

Active Imaging Systems

- use imaging RADAR
- transmit short pulses at radio frequencies and receive these pulses after they have been reflected from the surface

RADAR is particularly useful for imaging because it is not sensitive to clouds or atmospheric composition, and because it can penetrate below the surface to reveal some subsurface features.

Two active imaging techniques:

(1) SLAR (Side-Looking Airborne RADAR)
- a "real aperture" RADAR
- looks to one side of the ground track to produce a continuous strip map of the surface
- not very useful from satellites because the spatial resolution is
  $\propto$ wavelength (long RADAR wavelength → poor resolution)
  $\propto$ altitude of observation (high for satellite → poor resolution)
  $\propto$ 1/antenna size (small for satellite → poor resolution)

(2) SAR (Synthetic Aperture RADAR)
- relies on the motion of the satellite to obtain high resolution, recording a series of reflected pulses from an area on the surface
- effective aperture is the distance that the satellite moves while collecting the image

See figure (Rees 8.5) – viewing geometry of a SLAR or SAR system.

e.g. SAR on Seasat: aperture = 10 m, λ = 24 cm (1.3 GHz), altitude = 850 km
In real aperture mode, resolution = 20 km.
In synthetic aperture mode, resolution = 25 m (the synthetic aperture is ~8 km)

Active Non-Imaging Systems

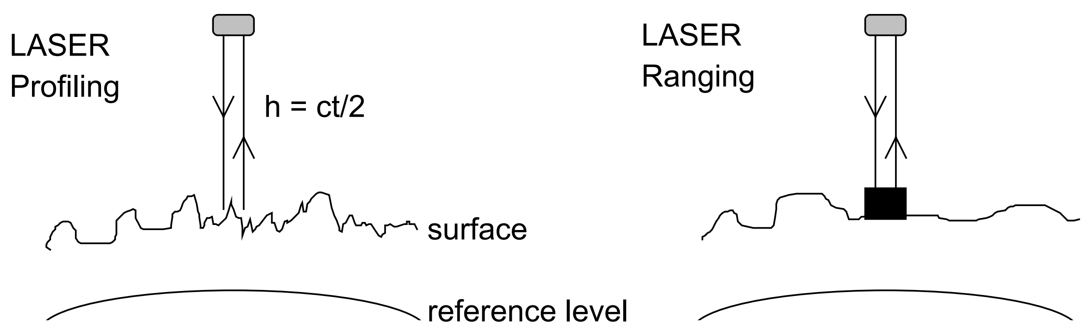
These can be further classified (with some overlap) as:
- ranging – measure the time delay between transmission and reception of a signal
- scattering – measure the strength of the received signal

Three active non-imaging techniques:

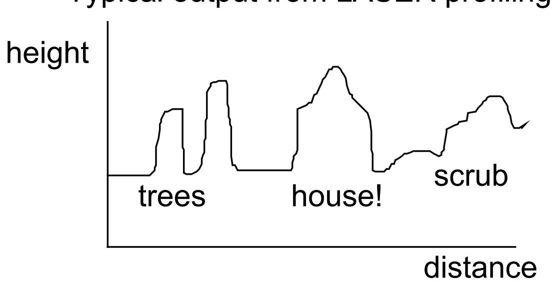
(1) <u>LASER Profiler</u>
- a LASER pulse (usually infrared) is transmitted through an atmospheric window towards the surface and its reflection is detected some time later
- by measuring the time delay and the speed of the light pulse, the distance to the surface can be determined
- with a sequence of pulses, a surface profile can be deduced
- has been operated from aircraft, but not from satellites because of the high power required and the exposure to LASER radiation on the ground!

Alternative version: also called <u>LASER Ranging</u>
- the LASER beam is directed from the ground to a satellite-based reflector, and the reflected signal is then measured on the ground
- useful for measuring orbital parameters of a satellite and Earth's gravitational field

e.g., used with lunar reflectors – only 1 in 10^{20} photons is received



Typical output from LASER profiling:



(2) RADAR Altimeter

- very similar to LASER profiling, but uses RADAR pulses
- these have been flown on satellites, using at $\lambda = 2.2$ cm
- used to measure the shape of the Earth's geoid (average surface topography) over oceans, sea surface height, and ice sheet profiles
- topographic measurements over land are more difficult because of the rapid variations
- the total power in the received pulse also contains information about the bi-directional reflectance of the surface, which allows features to be interpreted (e.g. edge of an ice pack), and information on the wind speed (higher wind speed $\rightarrow$ greater ocean surface roughness $\rightarrow$ less intense return signal)

(3) Scatterometer

- a series of RADAR pulses or a continuous signal is transmitted towards the surface at a selected angle, and the backscattered radiation is measured
- can derive information from intensity, phase, and polarization of the backscattered beam
- used to determine surface wind speed and direction from measured ocean surface roughness, to characterize surfaces, to determine moisture, roughness and texture of soils, and to monitor vegetation

Active Sounding Systems

- use both RADAR and visible/infrared LASERs (LIDAR)
- like a scatterometer, pulses or continuous signals are transmitted, backscattered, and received
- however, the target is the atmosphere, not the Earth's surface

Information can be obtained from

- the strength of the backscattering (related to the density, size distribution, and shape of the scattering particles)
- the absorption of the beam on its path to and from the target (related to the concentration and distribution of the absorbers)
- the polarization of the backscattered radiation (related to the properties of the target and of the absorbers)
- the change in phase after backscattering
- the spectral broadening of pulses after backscattering from particles of different masses

Two active sounding techniques:

(1) RADAR

Weather RADAR

- used to detect precipitation
- ground-based networks are essential to cloud physics research and operational weather forecasting
- first satellite-based weather RADAR is TRMM (Tropical Rainfall Monitoring Mission)

Doppler RADAR

- used to measure wind speed and direction of target from the Doppler shift in frequency between the transmitted and received signals
- not yet flown on a satellite

(2) LIDAR

- used to measure aerosol backscatter, concentration (H_2O, O_3) and temperature profiles, winds, cloud properties
- not yet flown on a satellite, but LITE (Lidar In-space Technology Experiment) was flown on Space Shuttle in 1994

LIDAR are further classified according to the properties measured:

- Backscatter LIDAR – intensity and polarization
- Differential Absorption LIDAR (DIAL) – extinction at two wavelengths
- Doppler LIDAR – phase shift
- Fluorescence LIDAR – intensity at a shifted wavelength
- Raman LIDAR – intensity at a shifted wavelength