Course Name: An Introduction to Climate Dynamics, Variability and Monitoring

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SPATIAL AND SPECTRAL RESOLUTION OF SATELLITE IMAGERY AND APPLICATION OF VNIR IMAGING IN CLIMATOLOGY

Good morning class and welcome to another lecture in climate dynamics, climate variability and climate monitoring. In the previous class, we were discussing how a 2D detector of arrays can properly image a certain geographic location on the earth's surface without causing motion blurring through what is called the step-stair imaging technique. Now, there may be other types of detector systems which are instead of being an area is a linear array of detectors which is able to detect along a given column on the ground surface. So, this column of results is being detected by a linear array of detectors. So, in this case what is being done is the platform motion is used to cover the entire 2D surface area. At a given time t, the detector is mapping a given column of results for a certain time interval delta t and then once detector moves a certain distance away so that its nadir point is over the next set of results, then the control switches so that the detector covers the next column of results and this way the entire distance is covered. This system is called a push-broom imaging technique. There are certain sensors that have a single detector. Hence, it is detecting only a single square area of result at a given instant of time. In this case, we need to have a system of mirrors that can collect data from the results perpendicular to the direction of motion of the satellite.

It is along this column. So at a given time, t, up to $t+\Delta t$, this detector is detecting this result, then from delta t to $2\Delta t$ it is detecting this result, $2\Delta t$ to $3\Delta t$ it is detecting this result and this is happening by moving a mirror to collect optical information from these results. After this entire column is covered and the detector has moved to the next set, then the mirror shifts so that again this process repeats itself. This system for a 0D or a single result detector is called the whisk-broom imaging technique. So here, a mirror apparatus is used to do the perpendicular scanning, perpendicular to the direction of motion of the satellite.

Geostationary satellites have no motion with respect to the ground. So, it is fixed in a certain sub-satellite locus. So, it needs mechanical motion in both zonal and meridional directions. The zonal direction motion is obtained by the rotation of the satellite about its north-south axis. So, the satellite rotates about the north-south axis and since the detector is on the satellite, the detector can move along with the rotation along the circumference of this rotating satellite and hence collect information in the east-west direction.

In the north-south direction, again a set of mirrors is used that basically collects the electromagnetic optical information along the north-south or the meridional direction. This type of system is called the spin scan imaging. Spinning of the satellite in the meridional direction and scanning through mirrors in the meridional direction. That's why it's called a spin scan imaging technique. The next question of course comes to the resolution of the satellite systems both spatial resolution what is the smallest area which it can detect and the spectral resolution what is the wavelength band in which it can detect what we mean by resolution suppose I say the resolution of a satellite is 10 meter by 10 meter. This means it cannot detect features which are lower than 10 meters in width or length an entire 10 meter cross 10 meter region is averaged over in the information that the satellite is obtained. That is its resolution. If you compare it to the resolution size of another satellite which is 100 meters by 100 meters, then that resolution is averaging over a 100 meter cross 100 meter region. So, the resolution size or resolution area is increasing, but the resolution is itself decreasing because the image is coarser, a greater area is being averaged out. There are two points that is constraining the resolution of a detector in a satellite.

A physical constraint and a geometric constraint. The physical constraint is the diffraction effect. If lambda is the wavelength of radiation, D is the diameter of the lens because the optics is being focused onto the detector through a lens system usually and H is the distance between the sensor and the surface then the best obtainable spatial resolution is limited by diffraction effects and is given by $\frac{H\lambda}{D}$. So, diffraction effects will become significant if the spatial resolution is less than $\frac{H\lambda}{D}$ that is the size of the resolution is less than $\frac{H\lambda}{D}$ where lambda is the wavelength H is the distance between satellite and the ground and D is the length diameter okay however this is not all, there is also a geometric resolution in the sense that, this can be explained in this way. Suppose you have an individual detector in a CCD array or a photodiode array. You have an individual photodiode or individual CCD which has an area A over which it is detecting. That area A will give you a light intensity signal. A overall light intensity signal it will give.

clearly, it cannot distinguish. So, whatever it is collecting is the minimum spatial resolution for that detector system.

So, if the area of photodiode is 1 micrometer cross 1 micrometer, all the photons incident on that photodiode gives you a single averaged voltage signal at a given instant of time. And where does this photon come from? It is coming from the solid angle that is projected by the detector area onto the surface of the earth as modulated by the lens in between the detector and the surface. So the surface of the earth is emitting photons either through direct emission or reflection. The solid angle that is entering the detector with respect to the earth. So, the detector is projecting a solid angle through the lens apparatus on the earth surface.

So, everything within that solid angle is going into that individual detector element and that has to be the minimum obtainable resolution length for your satellite detector system. So, if A is the detector element size, H is the distance between the satellite and the earth and f is the focal length of the lens then the size of the razor and this is what the razor definition is $\frac{Ha}{f}$ the area projected on the ground by the detector is your razor so these areas are area projected on the ground by an individual detector. So, if you have 1, 2, 3, 4, 5, 6, 7, 8, 8 linear detectors, each of these detectors is projecting this square area on the surface and that is what is being defined as your razzle. And the razzle size, length and width is given by $\frac{Ha}{f}$, okay. For a well-designed system, $\frac{H\lambda}{D}$ is of the order of $\frac{Ha}{f}$.

So, the minimum physical resolution and the minimum geometric resolution are close to each other. If the physical resolution is greater than the geometric resolution, what this means is the diffraction effects are strong between adjacent results as defined by $\frac{Ha}{f}$. So, electromagnetic wave interference will make the signal from one result blend with the signal of the adjacent result. So, instead of having independent data you have strongly correlated data in the adjacent results and the image quality will be less. The opposite case where $\frac{H\lambda}{D}$ is less than $\frac{Ha}{f}$, you are actually having a poor design because you can always increase the focal length of your lens to get to that physical limit.

So, in general, these two are of the same order and the actual resolution is the maximum of these two quantities for a given satellite system. Okay. So, two points here. Resolution is proportional to h so greater the distance of the satellite with respect to the ground coarser is the bigger is the result area so coarser is the resolution okay second the focal length and the diameter of the lens makes a difference if you increase them then the result area shrinks. So a well-designed lens that is very important to get them get the maximum resolution that is achievable.

Finally, if you have a smaller detector area that also helps in decreasing the resolution and the resolution is also better improving the resolution. The resolution is also better that is the resolution length is smaller at smaller wavelength that is higher frequencies. So, what this means is in general Infrared radiation has a coarser resolution than UV radiation because its wavelengths are larger. So this is spatial resolution. Now we can discuss spectral resolution.

So most VNIR instruments are capable of discriminating between different wavelength components. Some systems detect a few broad bands with large bandwidths, 10 to 100 nanometers. So, of course, all of the EM radiation is coming in at once. There is some constraint based on the light emitting system itself. It can be activated by a certain wavelength band with certain energy, not more, not less.

So that is first constraint. Within this acceptable region in which the photodiode or your MOS gets activated also, we wish to often choose certain bandwidths. So, for VNIR imaging for example, we want certain bandwidths where there is minimum atmospheric interference. If we are looking at sea surface for example, using a VNIR image, we may prefer a certain bandwidth compared to if we are looking at a snow surface or a land surface or a cloud surface. So, each satellite based on its requirement will choose to accept certain bandwidths and to reject or filter out certain bandwidths, and the detector is able to detect a few broad bands with large bandwidths, 10 to 100 nanometers. So, what does this mean? So, suppose you want to detect around the blue region, which is around 6 micrometers for example, 6 micrometers is 6000 nanometers, correct, micro and nano. Now a band between say 550 nanometers and 650 nanometers is being chosen around this 6000 nanometers, 6000 minus 50 is 5950 nanometers to 6050 nanometers, 100 nanometer band is being chosen. So, this bandwidth is chosen for detection if we are wanting to detect signals at 6 micrometer bands. This can be 10 nanometers as well, so smaller micrometer bands.

So, we for this large bandwidths where the delta lambda is more than 10 nanometers, we can use filters. So, we use filters to separate large detection bandwidths from the incoming spectrum. However, certain systems may need very small width bandwidths, less than 0.1 nanometers, ok. So, just to give a sense, right, 1 micrometer is 1000 nanometers, ok.

So, 0.1 nanometers is an extremely small wavelength band, if you are looking at a micrometer range which is true for visible spectrum, ok. So, such fine bandwidths are typically separated from the incoming spectra not through filters which is not possible but by using prisms or diffraction grating. So, the prism we already have a idea that a prism basically has a has a differential refractive index for the various frequencies of light which helps us separate out different frequencies and hence the detector array is so ordered that this detector is only looking at a frequency at the blue end ±0.1 nanometers whereas this detector is looking at the red end ±0.1 nanometers and we can block this if we want only the blue system all right. And even finer resolution can be obtained through diffraction grating. So diffraction grating is basically a closely spaced series of lines with small openings between them, which causes interference among the various frequencies of the broadband radiation. due to this frequent interference multicolored spectrum is obtained on either side of the main line this is the broadband radiation going through but due to the infract interference there are certain spectra that is obtained separating out the various wavelengths on the top and on the bottom these are called n plus one or n minus one so if it's one spectrum to the left side one spectrum to the right side okay. And you can measure depending on the on the difference in wavelengths there will be a certain angle over which this wavelength will be spread okay and this angle is given by sine theta equals to $\frac{n\lambda}{D}$ where lambda is the order of the spectrum so for example this angle is theta. So, a given wavelength in the red zone will have a certain theta red another given wavelength in the blue zone will have a certain theta blue and these two thetas will be slightly different from each other and hence the two wavelengths can be separated out.

So, that theta value is basically obtained by this expression n is the order of the spectrum usually the first order, either plus 1 or minus 1 is chosen. So, N is either 1 or -1. So, it is basically lambda by D. So, D is the grating, spacing D of the dispersion grating. And you can have very small spacings of the order of 1.3 micrometers. So, if you put say d as 1.3 micrometers or even lower and suppose your lambda is around 0.5 micrometers, then you can see this is 0.5 and say this is 1, so sin theta is half. 0.5 sine theta is half. So, theta is sine inverse half. So, you will get a certain theta value. Now, if you move from 0.5 to say 0.7 or 1 micrometers, then the sine theta is 1 and you get a different angle value. Alright, so based on this with a D of 0.1, 0.3 micrometers, the difference in the angles between the red light and the blue light can be as much as 15 degrees. Between 0.4 micrometers, the blue zone and 0.7 micrometers, the red zone. Hence, good separation is achieved between even closely spaced wavelengths making fine band detection possible. So, prisms and diffraction gratings help to separate out lights of various wavelengths at better and better resolutions and that helps us to create even finer bandwidths less than point nanometers in length. Now, some applications of the VNIR imaging and we will stop today. The first application is land cover mapping. So VNIR are useful in constructing global data sets of land cover and tracking changes in land cover based on vegetation type, snow cover and water body systems.

So it can check what type of vegetation is in a certain land area, the quality of that vegetation, what type of snow cover is in the certain land area, what type of water bodies are in the certain land area. And it is doing so by looking at the type of reflected shortwave radiation that is coming from that surface. It can observe changes in extent and health of this vegetation, extent of snow or ice cover, expansion and contraction of water bodies. Detection depends on the reflectance properties of the various wave bands. For example, A pixel showing low reflectance in visible spectrum for red light but high reflectance in the near infrared region is likely to contain a high proportion of green leaf vegetation.

So, a land that is covered with green leaves will have low reflection in the red light because chlorophyll absorbs the red side of the spectrum that is why it is it looks green. So, it has low reflectance in the red zone, but high reflectance in the near infrared light. So, it reflects a lot of the near IR shortwave radiation. So, a land, a razor that is covered with a large amount of vegetation will have low reflectance of red light, high reflectance of near IR light and based on those values, we can find out how much of that razor is covered with green. in contrast a pixel that shows high reflectance throughout the visible region and low reflectance the near infrared region is likely to have snow cover snow is white it reflects a lot of the visible spectrum so entire 0.4 to 0.7 micrometer if you have high reflectance but in the near infrared zone snow actually absorbs so one to three micrometer range it will have low reflectance. So, such a signature coming from a certain result will imply that it is covered with snow. Depth of shallow water, so depth of rivers and lakes can also be estimated by comparing reflectance between the green band and the near IR band ok. So, depending on the depth, how much of the green light is coming back and how much of the near IR light is coming back will change and that will show how deep a certain lake or a certain water is okay especially for landlocked water bodies here you can see such a case for a vegetation cover. So based on VNIR imaging, over a 20 year span, 2020-19, we can see the change in vegetation cover for the boreal forests, the coniferous forests that are present in a large segment of Canada.

And what you are seeing is decrease in vegetation cover in certain regions and increase in vegetation cover in certain other regions. And why this is happening? This is happening because in the lower regions here because of the warming the atmosphere and the temperatures are becoming hostile to having coniferous forests though these are becoming hotter and drier for longer periods in the summer and less snow in the winter so the conifer forest wells are suffering and decreasing in their density and coverage. Whereas, In the regions at higher latitude, these regions are increasing in coniferous vegetation because these regions were originally too cold. But as the globe is warming, the coniferous forests are invading these high Arctic regions where tundra originally existed and the forest is expanding northwards and contracting southwards. So, this kind of shows a real time impact of global warming on a forest ecosystem that would not be possible without a remote sensing based VNIR imagery. Another important type of application is ocean color mapping. For example, marine phytoplankton population can be estimated by increased reflectance in the 0.4 to 0.5 micrometers, the green region basically. So there, if there is a phytoplankton or algal bloom in an ocean, then that ocean turns green.

So you have a higher reflectance in the green region. So ocean reflectance across different bands also help to distinguish between sediment laden coastal waters against deep blue ocean waters. Furthermore, these turbidity variations can also distinguish and help us identify the strength and the distribution of various ocean currents. So the ocean color mapping provides excellent information of various important features of oceans and this is also something that VNIR imaging does. So for example, this is the coast of southern Africa and this is the ocean around it where an algal bloom has been occurring. In the optical spectrum, just the photography, you can see this green and light blue-green blooms of algae.

So this is basic photography. The other two images have been taken by the Ocean Color Instrument, OCI, in the PACE satellite mission. PACE is plankton, aerosol, cloud, ocean ecosystem. So this mission contains multiple detectors in a single satellite which maps planktons in oceans, aerosols in the climate, cloud cover, as well as the ocean ecosystem. And here the ocean color instrument data is being used. The true color image showing the bright plankton glooms are shown.

In the middle, we can see the first plankton diversity product. It is basically an algorithm that is processing the image of VNIR region using a certain algorithm using the spectral data. So, here the VNIR spectral data is being used mapping the pink algae from the green algae. So this is a different algae blend type and this is a different algae type. A sinucoccus algae which has been colored by the pink color and the picoucariotus algae which is being colored by the green color.

So based on the specific reflectance spectra, we can also identify between the different types of algae that are growing in different parts of the ocean at different population levels. Finally, we can see the chlorophyll concentration values also. So, very high chlorophyll concentrations, the red region, the yellow region, the green region and lower chlorophyll concentrations further down, further away in the deep blue ocean. Through these systems, we can get a lot of information about the ocean ecosystem.

We will stop here. In the next class, we will look at the last few examples of VNIR and then go to the thermal infrared imaging systems. Thank you for listening and see you in the next class.