SLIDE 1

- The earliest record of coastal human settlement dates back to the Middle Stone Age, on sections of the African coast that have been continuously inhabited for over one hundred thousand years.
- The biological and behavioral evolution of Homo Sapiens as a result of adaptation to coastal environments is a deeply studied field of inquiry.
- Coasts provide for civilization in several ways—including as an abundant source of food and energy resources, and as a gateway for travel, commerce, exploration, and recreation.
- Humanity's most prolific polymaths including Plato, Aristotle, Galileo Galilei, Rene Descartes, Isaac Newton, Daniel Bernoulli, and Pierre-Simon Laplace, have sought to explain phenomena that occurs at the coasts.
- Our understanding of coastal processes has been intrinsically linked to our development as a civilization, in a trend which continues today.

SLIDE 2

- Most megacities are located in the Low Elevation Coastal Zone (LECZ), which represents 2% of the world's total land area inhabited by 11% of the global population.
- The number of people living in the Low Elevation Coastal Zone has increased by 200 million from 1990 to 2015, and is projected to reach 1 billion people by 2050.
- These areas are especially vulnerable to the damaging effects of coastal processes that are exacerbated by warming global climates—such as sea level rise, coastal erosion, and flooding.
- And so there exists a need for informed solutions to mitigate the impact the ocean has on us and vice versa.
- The goal of coastal science is to characterize these processes to inform coastal management projects and other applied use cases.
- Coastal environments are exceptionally dynamic—there are several marine and land processes that occur on a range of spatio-temporal scales, that influence the hydro- and morphological profile to various extents across discrete coastal sections.
- This stommel-type diagram shows the temporal and spatial scales of different processes that occur at the coast.
- The most recognizable of these processes are the clearly visible swell waves that break every ten seconds or so across a local stretch of beach…
- While at a global extent, tides rise and recede once or twice daily depending on where you are…

- And long-term sea level rise occurs on the order of decades to centuries.

- The periodicity and spatial extent of these processes are reflected in those of the morphological features which they influence.

- The large range of spatio-temporal scales poses a significant problem for data collection and modeling.

SLIDE 3

- The spatio-temporal sampling requirements for characterizing coastal processes, coupled with the volatile nature of the area, make in-situ sampling difficult, and traditional remote sensing techniques ineffective…

- Therefore, bespoke remote sensing solutions are required.

- The goal of my thesis is to aggregate knowledge and review modern practices that pertain to remote sensing of coastal environments for oceanographic and geological field research…

- And to provide a framework for developing low-cost integrated remote sensing systems for coastal survey and monitoring.

- We will first discuss the natural processes of interest…

- Then the remote sensing techniques and technologies used to sample them…

- And lastly the models used to analyze and predict them.

SLIDE 4

- Before that, although we all have a strong notion of what “the coast” is, let’s briefly define it:

- Broadly, a coast is the greater zone extending both landward and seaward from the shoreline—which is the threshold of where ocean meets land.

- There exist several definitions on the extent of the coastal area offered by different sources.

- Some are based on the distance from the shoreline, and others are based on the extent of processes of interest.

- The nebulousness of definitions for the coast are a cause of the dynamic nature of the area…

- Where, as I mentioned before, hydrodynamic processes occurring on a large range of spatio-temporal scales work simultaneously to continuously transform the environment.

- Given this broad range, it’s important to constrain the definition for the coastal zone according to the application.

- This is manifest in the outcomes for predictive models of coastal morphology…

- For example, models with strongly embedded equilibrium concepts are more successful in predicting short-to-medium term phenomena as opposed to long-term.

- Also, different types of models—such as data driven or process-based models—are more suited than others for characterizing processes based on periodicity.

- In adherence with the goal of providing a framework to developing systems that can sample environmental parameters regularly for a duration most likely limited by the usual time constraints of a scientific research grant, for the purposes of this project…

- We'll define the coast as the area where sub-decadal oceanic processes serve as a factor in influencing local morphology.

SLIDE 5

- In order to specify further, we first need to understand which processes affect sediment transport where…

- So, we’ll begin by discussing the various hydrodynamic processes that occur at the coast…

- As these are the basis for understanding all other environmental parameters there, including those that are morphological, biological, geological, and chemical.

SLIDE 6

- The predominant marine process that influences morphological change over our selected time scale, for the majority of coastal areas, are wind-generated ocean waves.

- Ocean waves are generated when a disturbing force transfers energy into the water…

- And a restoring force acts to return the system to equilibrium, resulting in a continuous cycle of near-frictionless water particle motion.

- These waves propagate across the surface of the ocean as potential energy…

- Are attenuated and refracted as they shoal through contact with bottom morphologies…

- To be released as kinetic energy as they break on the shoreface and other physical features of the coast.

- Wind waves are generated when friction drag from wind blowing over the ocean transfers energy into the water.

- First, wind blowing the ocean stretches the water’s surface…
- That is then restored by surface tension to form low energy, high frequency capillary waves.
- As wind continues to blow, capillary waves become compounded by wind energy, and grow.
- As they reach a wavelength of 1.74 cm, gravity takes over as the prevailing restoring force.
- As wind activity ceases or waves move away from the area of generation, they’re sorted into packets of uniform wavelength and direction.
- The longer wavelength Gravity waves travel away from the area of generation more quickly to form a swell.
- Gravity waves represent the most energetic band of the wind-wave spectrum.
- They’re also the most recognizable. If we were to walk outside, these are the waves we would see people surfing.
- The relationship between wind speed and the spectrum of wave energy distribution was defined by oceanographers Pierson and Moskowitz in the sixties, and has enabled decades of highly accurate wave forecasting.

SLIDE 7

- Tides also have a significant impact on coastal areas.
- They cause local variation in sea level, causing sea water to inundate and recede from low-lying areas and augmenting other hydrodynamic activity.
- Tides can also be thought of as ocean waves, with the disturbing force being the combined gravitational forces of the moon and sun, and the restoring force being gravity.
- These disturbing forces act upon waters in irregular ocean basins bounded by continents, and so tidal activity is not linearly related to the Moon’s orbit around the Earth and the Earth’s orbit around the sun.
- Not to be confused with Tsunamis, tidal waves circulate about amphidromic points where the tidal range is zero.
- The Coriolis Force from Earth’s rotation also affects the circulation of tidal waves, causing them to move about the amphidromic points counter clockwise in the Northern Hemisphere and clockwise in the Southern.
- In areas sheltered from high wave energy, tidal activity can dominate local sediment transport, and produce a significantly different physical, biological, and chemical profile than those more influenced by wave action.

SLIDE 8

- Eustatic sea level changes are cumulative changes in the volume of the ocean over hundreds of thousands of years.
- This includes the addition of water through glacial melting and volcanic out-gassing…
- Thermal expansion of water…
- And changes in the shape of the seafloor through sediment deposit and tectonic spreading.
- Isostatic changes, are cumulative changes of the land level with respect to sea height caused by tectonic uplift from lithospheric convergence on the order of decades.
- These processes combine to have the most influence on shoreline change over longer timescales.
- For the last 20,000 years since the Last Glacial Maximum, sea levels have risen due to melting of ice sheets from the Late Pleistoscene era.
- Inundation of low lying continental areas, and the exposure of areas formerly covered by glacial ice in higher latitudes, created most of the coastal features we recognize today.

SLIDE 9

- Fluvial discharge can significantly influence hydrodynamics at areas where rivers empty into the ocean.
- At a river mouth, fluvial discharge creates a turbulent jet stream that may compound or counteract circulation and currents generated by tides and waves.
- The velocity and flow of the discharge are highly dependent on the geometry of the estuarine basin…
- And are subject to episodic phenomenon such as storm surges and flooding events.
- Fluvial discharge can be the prevailing hydrodynamic influence on areas well-sheltered from highly energetic marine processes.

SLIDE 10

- Now that we have an idea of the most significant marine processes that impose their influence onto all other coastal phenomena, let’s talk about the morphologies that they induce.

SLIDE 11

- The definitions for extent of constituent coastal sub-zones are even more nebulous than definitions for the coast itself

- Previously we had adopted a definition of the coast as being an area where sub-decadal ocean processes influence morphology.

- By that logic, the outermost boundary of the coast is where ocean waves shoal with contact through bottom morphologies.

- Any area beyond that, that is largely unaffected by wave-action induced sediment transport is considered to be the offshore area, and not part of the coastal zone.

- The Nearshore is the aquatic area from the offshore boundary to the shoreline…

- This can also be referred to as the surf zone…

- Where large waves break as the depth of the sea floor becomes less than half of the wave height…

- Causing waves to come into contact with bottom morphologies.

- Landward from the shoreline is the Foreshore, that encompasses the section of a shore subject to daily wave and tidal activity.

- The Backshore continues landward from there, to the end of where loose sediment particles are deposited.

- Sediment in the Backshore is largely sheltered from daily wave and tidal activity but is subject to the effects of episodic storm surges and aeolian, or wind-based, transport.

SLIDE 12

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SLIDE 13

- For morphological analysis, coasts are segmented into discrete sections called Littoral Cells.

- The bounds of a littoral cell are defined by the extent to where the sediment from an input source is either deposited or lost.

- There are clear geographic markers, such as headlands or submarine canyons that channel sediment away from the coast.

- For a single cell, sediment transport occurs in a net direction parallel to the shoreline…

- As waves approach the shoreline, they're refracted in shallow water to travel nearly perpendicular to the beach…

- but maintain a slight angle.

- As they crash onto the shoreface, a turbulent layer of water rushes upshore at the angle of the breaking wave.

- The water then rushes straight down the sloped shoreface.

- This repeated action causes sediments to be carried along the shoreline, or longshore…

- compounded by longshore currents in the same direction produced through a combination of hydrodynamic and wind action.

- Rivers are the largest contributor of sediment to the greater coastal area…

- as soil particles loosened by rain-erosion are carried to the coast by fluvial discharge.

- Sediment accumulation at river mouth areas sheltered from wave activity results in large deltas that penetrate into coastal waters.

SLIDE 14

- At erosional coasts, features are carved away from crustal bedrock by wave action.

- The lack of sediment accumulation exposes bedrock directly to marine processes.

- Waves hurl debris, push air and water into small fissures, and exert kinetic energy on rock faces to slowly notch away at them at the waterline.

- This notching may cause the rock above to collapse, forming the steep cliffs that are emblematic of erosional coasts…
- while under the waterline, a platform of rock extending offshore may remain submerged and largely unaffected.
- Often weaker zones of bedrock are carved away while stronger zones remain intact, resulting in more intricate structures like arches…
- and other formations, such as sea stacks and large rocks, may become completely disconnected from the shore.
- The particles of rock loosened by wave activity are a significant source of sediment to nearby beaches…
- As sediment is carried longshore and deposited in more sheltered areas, such as bays.

SLIDE 15

- The most recognizable feature of depositional coasts are beaches.
- Beaches are zones of loose particle accumulation that cover a shoreface.
- Beaches may exhibit vastly different features based on the sources of sediment input to that area.
- As described briefly before, common sediment input sources include rivers and cliffs.
- In tropical regions, sources include biological particles such as shells and coral fragments…
- or fragments of cooled lava in regions of high volcanic activity.
- A single beach is composed of grains of many different sizes which become sorted through wave action.
- There is a strong correlation between mean grain size and wave energy level both up and offshore.
- Particles range in size from silt hundredths of a millimeters in size…
- to sand a half a millimeter to two millimeters in size…
- to pebbles and cobbles centimeters in size…
- And finally boulders that may be meters in size.
- Wave and tidal action create an accumulation of sediment on the shoreface at their furthest extent parallel to the shoreline called a berm.

- A berm on a beach marks the boundary between the fore and backshore areas.
- If that berm becomes eroded into a steep cliff, it then is called a scarp.
- Landward from that border, backshore areas commonly feature dunes shaped mainly by aeolian transport from oceanic winds.
- Coastal dunefields are highly complex and dynamic environments that are the sole subject of more focused study…
- but in short their structure and longevity is primarily dependent on their ability to hold moisture and host vegetation to protect from erosion…
- and exist on a continuum from highly stable to ephemeral.
- Dunes serve as natural barriers that reduce the impact of storms, high waves, flooding, and sea-level rise on nearby infrastructure.

SLIDE 16

- Sediment also accumulates underwater in depositional areas to form systems of longshore bars parallel to the shoreline in the nearshore area.
- Longshore bars dissipate wave energy in the surf zone and have a large impact on local circulatory patterns.
- Several hydrodynamic factors—including wave set-up, undertow currents, the deformation of bottom sediment from infragravity waves, and tidal action, contribute to their formation.
- These are combined with geometric factors, such as the bathymetric gradient of the nearshore zone, to determine the way longshore bars manifest.
- The number of bars, how closely they're grouped, and their shape, slope, and stability, vary from coast to coast.
- Longshore bars are dynamic morphologies, but the ability of bars to maintain stability over timescales of days and weeks suggests their positionality and form represent the equilibrium between local hydrodynamic forces.
- Longshore bars migrate toward and may weld to the beach when wave conditions are calm, and offshore during times of strong wave activity.
- Overtime, underwater sediment accumulations can grow to have an above water component, emerging as large barrier systems.
- These commonly occur at the boundary of a littoral cell and mark the end of the sediment transport cycle at depositional coastlines.
- The barrier may partially or fully trap water between itself and the mainland to form

unique aquatic features that are largely shielded from energetic marine processes such as bays, lagoons, and estuaries.

- Large scale depositional features are subcategorized according to their relation to the mainland.

- Barrier islands are fully separated from the mainland through sediment accumulation on submerged rises parallel to the shoreline.

- Sand spits form where longshore current slows, as it clears a headland and approaches a sheltered bay, creating a peninsula of deposited sediment across the inlet of water from the ocean to that bay.

- Sand spits may close the inlet to form baymouth bars, that when subject to high wave and tidal energy, are then broken to form an inlet again.

- Tombolos form as a bridge of deposited sediments between offshore islands and the mainland.

- These features lack firm central cores featured in islands that were once part of the mainland, making them highly subject to erosion and migration.

SLIDE 17

- Estuaries are partially or fully sheltered aquatic bodies of mixed salt and fresh-water composition, which occur at the coast where land-based watershed interfaces with oceanic water.

- They are generally sheltered from tidal and wave activity, but may be subject to daily and seasonal extremes.

- They're classified into four types:

- Drowned river mouths inundated as an effect of eustatic sea level rise since the last glacial maximum…

- bar-built estuaries, that are partially or fully enclosed by barrier systems which limit tidal access and provide shelter from waves…

- fjords, which are inundated valleys eroded by glaciers during the last pleistocene in high-latitude mountainous areas…

- and tectonic estuaries, such as the San Francisco Bay, that form in areas along fault lines that experience tectonic land subsidence to below sea level, and become flooded with ocean water.

- Estuaries are often at the focus of coastal sciences, as they represent some of the most highly dynamic and productive coastal environments.

- Similarly to dunefields, they also serve to protect infrastructure from damaging coastal processes.

SLIDE 18

- The dynamic processes that the coastal area is subject to makes it a difficult environment to sample, particularly in the surf-zone where wave and current action…
- as well as the sediment transport they induce…
- render the area unstable for traditional in-situ instrumentation.
- Obtaining data from subaqueous platforms carries unique challenges to continuous sampling in the way of connectivity to power and internet infrastructure.
- The processes and features of interest have large spatial extents, and are mostly inhomogeneous both across and alongshore…
- so sampling at the extent and resolution necessary to fully characterize them would require a large array of in-situ point sensors.
- Remote sensors are those that acquire information about a thing at a distance, by detecting propagated signals.
- Measurements are made by detecting and measuring changes imposed by the subject on incident fields.
- An important classifier for remote sensors is to distinguish those that are active versus those that are passive.
- Active sensors, like RADAR, are those that emit a signal and measure the properties of that signal as it returns after being reflected off of a targeted surface.
- Passive sensors, like cameras, detect signals that are either emitted by an object or generated from another source, such as the sun, that are then reflected by that object.
- Some remote sensors produce a two-dimensional array of values—i.e images—gathered from a grid of detectors, enabling simultaneous sampling of values across a spatial extent.
- The ability of remote sensors to collect data away from harsh marine environments, and to provide spatial information, make them an effective alternative to in-situ devices for measuring environmental parameters in the nearshore zone.
- Remote sensors can be deployed from a variety of platforms…
- they may be affixed to structures on the ground, mounted on manned or unmanned air and watercraft, or deployed as a payload from a spaceborne satellite.
- The most significant tradeoff between platforms is between dwell and footprint—the length at which data is gathered from one area, versus the size of the total area from

which data is gathered.

- The platform which perhaps carries the strongest association to remote sensing as a discipline are satellites, from which the vast majority of available remote sensing data is captured.

- However, most satellite datasets do not meet the dwell or spatial resolution requirements needed to characterize some of the most central processes of interest to coastal science.

- Nonetheless, satellite-based programs will serve as our main reference for historical and current remote sensing techniques and technologies.

- There are several satellites purposed for environmental remote sensing currently orbiting the Earth, that carry the most cutting edge, carefully calibrated, and thoughtfully deployed sensors.

- Documentation and datasets from these satellite missions are both thorough and open to the public.

- In this section, I'll touch upon the different types of sensors that are useful for sampling coastal environments and marine processes.

SLIDE 19

- The most well represented remote sensors are electromagnetic imaging sensors—those which acquire two-dimensional arrays of radiant intensity values from the incident electromagnetic field.

- The first and most ubiquitous electromagnetic imaging sensor is the photographic camera, which passively acquires optical images of visible light,

- Visible light can also be thought of as radiant energy from the visible band of the electromagnetic spectrum.

- The first photograph was taken by Daguerre and Niepce in 1839, that used a lens to channel incident rays onto a copper plate coated with silver, made sensitive to light with iodine vapor.

- One decade later in 1849, Colonel Aimé Laussedat of the French Army Corps of Engineers developed a program to use oblique photography for topographic mapping.

- The next decade, Gaspard Tournachon took photographs of Paris from a hot-air balloon, marking the beginning of vertical airborne photography.

- Images of earth's surface have been continuously captured from above since 1972, beginning with the launch of the Landsat satellite, a joint mission between the NASA and USGS to gather data on terrestrial land use.

SLIDE 20

- Since its initial launch, Landsat has continuously captured millions of images of the Earth’s entire surface.

- Landsat deploys passive sensors, and so it travels in a sun-synchronous orbit to make use of the sun’s rays as a source for electromagnetic radiation, covering the Earth entirely every sixteen days.

- Currently, both the eighth and ninth iterations of Landsat operate simultaneously, allowing for more frequent coverage.

- Since its inception, each iteration of the Landsat satellite has deployed a type of sensor called a multispectral imager.

- The first iteration of this device was called the Multispectral Scanner, and the improved version carried by Landsats eight and nine is called the Operational Land Imager.

- The Operational Land Imager is able to passively capture solar radiation reflecting off of terrestrial and atmospheric materials…

- producing individual images from discrete bands in both the visible and infrared portions of the electromagnetic spectrum.

- A system of telescopic mirrors channels radiation onto the focal plane assembly.

- Filters on the focal plane divide radiation from the incident field into broad bands across the visible and infrared spectra.

- The filtered radiation from each band is exposed to a wafer of detecting elements that measure intensity across a spatial extent to produce an image.

- These images are made available to the public, to enable scientists and other analysts to readily map and characterize natural phenomena.

- Aquatic environments pose unique problems to this type of imaging.

- Water absorbs and scatters light, which is especially true for highly turbid waters in middle-to-high latitude coastal areas.

- This causes signals from aquatic areas to be weak or missing when capture is attempted from outside of the atmosphere.

- Also, the sixteen day temporal resolution, coupled with a spatial resolution of 15-100m, does not meet the requirements for being able to characterize the marine processes we had discussed earlier.

- However, there is still important information for coastal science applications that can be gathered from Landsat imagery.

- The most recent development with the Operational Land Imager added a Coastal and Aerosol band, which is sensitive to low-frequency information from the blue and violet sections of the visible spectrum.

- It's primary usage is to monitor shallow-water for coloring agents—such as chlorophyll, suspended solids, and dissolved organic materials—as well as atmospheric aerosols.

- For example, this is used to detect and study harmful algae blooms.

- It's also able to obtain bathymetric data for shallow nearshore areas in low-latitude clear water.

- Although this data alone is not sufficient for our needs, later, we'll discuss methods by which it can be merged with data from other sensors on more proximal platforms to more effectively characterize coastal processes.

SLIDE 21

- By analyzing spectral and intensity values of signals, and applying known characteristics of the way atmospheric and terrestrial materials reflect, emit, and scatter radiation…

- it is possible to quantify physical, chemical, and biological characteristics of the environment.

- Where spatial data is less of a priority, non-imaging sensors may better suited.

- A Spectrometer divides electromagnetic radiation from the incident field into narrow discretized bins, allowing for detailed spectral analysis.

- Spectrometers are used across fields for high-precision material identification based on electromagnetic absorption characteristics.

- For environmental remote sensing spectrometers are commonly used to monitor atmospheric gasses.

- They're also used in labs to test materials collected in the field for ground truth validation and calibration of remotely sensed data from multispectral imagers.

- Radiometers, on the other hand, are used for applications where the intensity of electromagnetic radiation is the most pertinent attribute in characterizing the phenomena of interest.

- In remote sensing, Radiometers are used for monitoring global sea surface temperature, soil moisture, and ice coverage.

- The more detailed resolution of intensity measurement allows for Radiometers to be deployed at night and through clouds, where spectral imagers are ineffective.

- Each of these sensors represents a different point on the tradeoff gradient between spectral, spatial, and intensity information, that must be evaluated when developing a solution for characterizing a phenomena of interest.

SLIDE 22

- Max Planck theorized that heat propagates by radiation in 1914, and that heat rays are identical to light rays of the same wavelength.

- It can also be said, that an object with a temperature different than absolute zero emits electromagnetic radiation.

- Wein's law states that the peak wavelength at which an object emits the most energy is inversely proportional to that object's temperature.

- Thermal imagers leverage this fact to capture an image conveying the spatial distribution of a subject's temperature to the user at a distance.

- Although thermal radiation occurs at wavelengths across the entire electromagnetic spectrum, emission occurs primarily in the infrared spectrum.

- Thermal imagers purposed for remote sensing typically measure the electromagnetic radiation from the following bands…

- medium Wavelength Infrared with wavelengths between 3 and 8 micrometers, useful for identifying high temperatures emitted by phenomena such as forest fires or volcanic activity…

- and long Wavelength Infrared with wavelengths between 8 and 15 micrometers, for differentiating between Earth's surface materials like soil, water, and vegetation.

- From the Plank-Einstein relation it is implied that the energy of a photon is inversely related to its wavelength.

- Therefore infrared radiation is more susceptible to being attenuated by the earth's atmosphere than visible light.

- For detecting thermal radiation in the infrared band, Landsat carries a second device called the Thermal Infrared Scanner.

- This device makes use of larger detection elements than the multispectral imager, allowing for greater sensitivity at the cost of spatial and spectral resolution.

- Thermal cameras are available in low-cost and small footprint forms, similar to photographic cameras, and can be mounted to a large variety of platforms for terrestrial remote sensing.

SLIDE 23

- RADAR systems transmit radiation packets in the microwave portion of the electromagnetic spectrum…

- Then receive the echo of the emitted signal off of targeted surfaces…

- And measure the time elapsed between transmission and reception, referred to as time-of-flight, to ascertain the distance of the target relative to the source.

- RADAR systems are extended to use raw sensor data in calculations that allow for the detection, location, and tracking of objects.

- The first application of RADAR was as a aircraft detection and warning system pioneered during the Second World War…

- But it's role has since expanded to include a wide range of applications—including ecological, meteorological, and oceanographical monitoring and survey.

- A major landmark for the implementation RADAR for environmental remote sensing was the formation of the NASA Jet Propulsion Laboratory's Seasat program in 1973.

- The Seasat mission was primarily oceanographic and meteorological.

- System specifications and activities were collaboratively defined by governmental agencies, scientific bodies, and prospective users in private industry, to be able to meet use-case requirements for ocean-based applications.

- Although the mission only lasted 100-days before a catastrophic failure of the power bus, it was able to capture more information than the past century of data gathered from shipborne devices.

- Seasat deployed five sensors—a radar altimeter for geoidial altitude measurements…

- A microwave scatterometer to measure wind speed at the ocean's surface…

- A scanning multispectral microwave radiometer to measure ocean surface and ice temperatures as well as high speed winds…

- A visible and IR radiometer to passively obtain images of cloud, land, and water features…

- And an experimental synthetic aperture radar for high-resolution surface multispectral imagery.

- Then considered to be experimental, the RADAR technologies aboard Seasat have since become staples of oceanographic remote sensing.

SLIDE 24

- Let’s break down Seasat’s RADAR sensors further, to touch upon some of the common types of RADAR used in oceanographical remote sensing.

- An altimeter is used to measure the altitude of an object above a fixed level.

- Not all altimeters fall under the category of remote sensor.

- RADAR altimeters measure the time of flight of an actively emitted radio wave to ascertain the distance of a surface with respect to the platform.

- Spaceborne altimeters are the method of choice for obtaining measurements for geodesy—the science of understanding the earth's geometric shape.

- A RADAR scatterometer measures backscatter, by emitting a pulse and measuring the amplitude and phase of radiation reflected back toward the source.
- When an electromagnetic wave is incident on a surface, radiation is absorbed or scattered in different directions—some through the medium, some in all directions away from the surface, and some in the specular direction in relation to the angle of approach.
- There are backscatter characteristics associated with certain phenomena.
- Seasat was successful in obtaining accurate measurements of wind speed by measuring the backscatter from active electromagnetic emissions off of wind-generated capillary waves.
- At certain sizes, capillary waves produce a clear backscatter signal, and the spectrum of return signal is used to derive wind speed using Bragg's Law.
- Several radar configurations measure backscatter as a component of their output.

SLIDE 25

- The length of the radar antenna required to achieve a specified resolution is directly proportional to the wavelength of the emitted pulses and the distance to the target…
- and inversely proportional to the desired spatial resolution.
- RADAR transmits packets in the microwave portion of the electromagnetic spectrum…
- meaning wavelengths are longer relative to those captured by devices such as passive imagers operating in the visible and infrared spectrum.
- From a satellite in space operating at 850 kilometers above the Earth in the C-Band, at a wavelength of about 5 centimeters, in order to get a spatial resolution of 10 meters, you would need a radar antenna about 4,250 meters long.
- Synthetic aperture radar allows for high resolution measurements to be obtained from much smaller antenna.
- Aperture synthesis begins with successive acquisitions from a moving platform.
- Packets are actively transmitted and received to measure raw amplitude and phase data from backscatter.
- Each radar acquisition contributes to the final image resolution by providing a slightly different viewing geometry.
- When these measurements are applied to an image formation algorithm, the system uses phase alignment and coherent summation of Doppler-encoded signals to synthetically extend the aperture, thereby enhancing spatial resolution.

- Synthetic aperture radar has an extensive history of use for meteorological, oceanographical, and land based remote sensing.

- There are several public datasets available from active satellite missions that deploy synthetic aperture radar, that can be used to contribute limited but valuable data to characterizing marine processes such as surface currents, internal waves, tides, ocean surface wind, sea ice distribution, aquatic vegetation and biota distribution, and bathymetry.

SLIDE 26

- For RADAR, the microwave spectrum is divided into bands with a letter-based naming convention, each uniquely suited to provide data for an array of applications.

- Most RADAR systems are constrained to a single band to reduce complexity and bulk…

- the propagation characteristics of radiation from different bands demand different hardware specifications and signal processing algorithms.

- Higher frequency bands offer higher spatial resolution, but are more subject to atmospheric attenuation.

- The compactness, low-cost, and high resolution of X-band RADAR makes it a popular choice for terrestrial high frequency RADAR systems.

- The current complement of earth monitoring satellites deploy a variety single-band sensors…

- European Space Agency satellites Sentinel 1A and B deploy C-band synthetic aperture radar for land and ocean monitoring…

- while the Japanese satellite ALOS 2 uses the L-band for forest and disaster monitoring.

- An upcoming project by NASA and the Indian Space Research Organization will deploy the first dual-L-and-S-band synthetic aperture radar for unprecedentedly high-resolution observation of various earth processes.

SLIDE 27

- Similarly to RADAR, Light Detection and Ranging, or LiDAR systems, actively emit electromagnetic radiation and measure the time-of-flight of the emission to derive the distance of a targeted surface relative to the source.

- Differently from RADAR, LiDAR systems emit lasers as an alternative to radio waves as a source of illumination, and operate in the near-infrared region of the electromagnetic spectrum as opposed to the microwave region.

- A laser beam is a narrow column of light, consisting of coherent monochromatic waves of identical length, phase, amplitude, and direction…

- induced by the process of stimulated emission.

- Active illumination by laser offers several advantages:

- Sampling rates far exceed that of traditional RADAR, allowing for higher spatial resolution.

- Many LiDAR systems feature multiple returns, which can gather information about the three-dimensional structure of features above the surface.

- The uniformity of emitted radiation allows for highly accurate range measurement, but disallows the spectral analysis of surface materials achievable with RADAR.

- The product of LiDAR is a dense point cloud: a three-dimensional representation of the position of sampled points with respect to one another based on their relative distance from the source.

- LiDAR emissions are attenuated by water and unable to penetrate deep or turbid aquatic areas.

- However, recently LiDAR devices have been designed to operate on the green band to allow penetration through shallow water.

- LiDAR systems have also become significantly miniaturized, allowing deployment from small low-cost unmanned aerial platforms.

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- Rendering of data into accurate and usable products requires precise knowledge of the sensor's position and orientation, or pose, at the time of sampling.

- Global Navigation Satellite Systems, abbreviated as GNSS, provide latitude, longitude, and altitude information for the sensor platform.

- Real-time kinematic positioning using GNSS reference stations, enables systems to achieve centimeter-level accuracy.

- Inertial Measurement Units measure linear acceleration and angular velocity using accelerometers and gyroscopes.

- This is necessary in addition to GNSS on a remote sensing platform…

- as it’s better able to capture high-frequency changes in motion and orientation…

- useful for short-term tracking, and for when GNSS signals are lost.

- These systems are also necessary for geolocation, the process of determining the exact position on Earth where data was collected, which is often pivotal for applied use.

SLIDE 29

- Sound Detection and Ranging, or SONAR, systems are used used to measure the distance of objects relative to the source acoustically by the propagation of sound waves through a medium.

- Acoustic sensing techniques are particularly effective for underwater applications such as seafloor mapping or the tracking of ocean animals…

- because sound waves experience less attenuation in water compared to electromagnetic radiation…

- allowing for more accurate detection over longer distances.

- Sonar technologies may either actively emit sound waves or passively receive sounds emitted by other sources.

- Sound waves are converted into electrical signals through transducers…

- That are then used to derive further information, such as the distance or trajectory of an object.

- Like RADAR, with active Sonar, information on the material properties of surfaces is available through spectral analysis of backscatter.

- Sonar systems exist in various configurations.

- The first active sonar device was a single-beam echosounder, first deployed to locate the remains of the Titanic.

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- A single-beam echosounder pings a single small point to measure time-of-flight from the platform to a surface beneath.

- Several pinged points are used to form an approximate height map of the ocean floor.

- In the 1970s, the multibeam echosounder was developed to deploy hundreds of beams in a fan…

- In order to sample a large area simultaneously for more efficient and higher resolution mapping.

- Despite this, single-beam echo sounders are still used because of their relatively low-cost and size, in applications for which low resolution altitude information about the ocean floor is sufficient.

- Multibeam echosounders operate at higher frequencies, allowing for more data points to be gathered as the platform navigates through the water.

- This comes at the expense of the distance each emitted sound wave is able to travel, so single-beam echo sounders are necessary for deep sea survey when deployed from the surface.

- Side-scan sonar systems emit two beams from a transducer affixed both broadsides of a platform…
- allowing for orthogonal scanning of the surrounding seafloor as the platform passes through the water…
- Producing an image of backscatter measurements.
- Sub-bottom profilers are sonar devices that use low-frequency sound pulses to partially penetrate the seafloor substrate…
- in order to obtain information on subsurface sediments.

SLIDE 31

- Also similarly to RADAR, the movement of the survey vessel deploying sonar can be used to synthesize a large aperture.
- Researchers have been able to use synthetic aperture sonar to obtain detailed seafloor maps…
- maintain accuracy at longer distances…
- lower the amount of transducers that are required to achieve high resolution…
- And in effect decrease the cumbersomeness of sonar systems, enabling their deployment from smaller platforms.
- There are physical properties of the way sound propagates through the ocean that must be considered in order to deploy sonar effectively.
- Sound travels through water differently based on factors like temperature, salinity, pressure, and turbulence.
- When traveling across water columns that exhibit different levels of each of these properties, sound waves may bend and cause inaccurate measurements.
- Most of the ocean can be divided into three main layers based on temperature variation from solar radiation…
- the mixed layer that includes the surface, where heat is linearly related to depth throughout…
- the thermocline where heat decreases more sharply with depth…
- and the deep layer unaffected by solar radiation that largely maintains uniform parameters throughout the column.

- There are tools that gather data from properties that affect the propagation of sound through water columns such as Conductivity, Temperature, and Depth probes and Expendable Bathythermograph probes, that can then be used to create a Sound Velocity Profile.

- The Sound Velocity Profile can be then be applied to ray tracing models to correct for bending paths in the deployment of sonar devices.

SLIDE 32

- Sonar transducers must be coupled with the transmitting medium to detect sound waves being propagated through it.

- For ocean detection, that means sonar is deployed underwater from a variety of platforms—including boats, buoys, aquatic structures, and submersibles.

- Historically, sonar for bathymetric mapping had to be deployed from large research vessels because of the weight of professional-grade echosounding units.

- Recently, echosounders have become increasingly miniaturized, enabling their deployment from small crewed and uncrewed vessels that allow for bathymetric mapping of shallow water areas where traditional research vessels would be unable to reach.

- Uncrewed vessels are able to operate discreetly in sensitive areas such as estuaries and remove the danger associated with operating a crewed vessel in the surf and other shallow zones.

- For high resolution at further depths, large research vessels may deploy submarine sonar platforms.

- The use of autonomous underwater vehicles and remotely operated vehicles, attached to a surface vessel by a long tether cable…

- Allow for more efficient mapping enabled by independent underwater navigation with real time data transmission.

- When deploying sonar from a submerged platform, GNSS systems are unable to connect with GPS devices underwater, so often the topside intermediary vessel equipped with GPS maintains the relative location of the underwater platform.

- A common method for underwater positioning is through acoustic triangulation of a transponder mounted to the underwater platform by transducers on the surface vessel.

- This type of system is called either a Long, Short, or Ultrashort baseline system, according to the spacing of the transducers attached to the the surface vessel, the length of which is correlated with accuracy.

- The submersible platform responds to pings from the surface vessel, enabling position tracking and packet transmission.

- Submerged sonar systems may make use of the Sound Fixing and Ranging (SOFAR) channel.

- This is a naturally occurring horizontal layer of water that acts as a waveguide for sound about a thousand feet deep in most areas.

SLIDE 33

- Retrieval algorithms are needed to extract information about environmental variables from the raw data collected by remote sensors.

- This includes empirical retrieval algorithms that use statistical relationships between satellite data and known measurements…

- and physical algorithms, that use forward models that simulate how environmental parameters affect what the sensor sees.

- Data fusion algorithms combine outputs from multiple sensor types to produce a more accurate, complete, or higher-resolution environmental dataset.

- Then, the physical dataset can be rendered visually for analysis, or applied to a predictive model to forecast phenomena.

- Data assimilation algorithms are used to update models by reconciling model outputs with observations.

- The use of these techniques together form a framework that has been validated scientifically and implemented by environmental remote sensing organizations globally to increase the overall accuracy of outputs.

- In this section, I'll describe some of the most widely applied models for coastal analysis based on remotely sensed data.

SLIDE 34

- Narrowly, a topographic map depicts the relief features, or terrain, of land surfaces according to a geodetic reference frame.

- Traditionally, topographic maps depict terrain geometry quantitatively through the use of contour lines, and the boundaries of significant surface features such as bodies of water and man-made structures, symbols representing landmarks, and toponymy.

- As universities gained access to computer systems, Geographic Information Systems, or GIS, software was developed by researchers to store, retrieve, and process spatial data…

- And report geographic information through maps and charts, marking a significant change in the way topographic maps are created and used.

- Today, the vast majority of topographic products such as spatial maps and terrain models are digitally generated from large spatial datasets that are compiled and maintained by a range of sources—including scientific, commercial, and government organizations.

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- Topographic products have expanded to include three-dimensional representations of surface geometry expressed as a Digital Elevation Model, abbreviated as DEM
- A DEM is a statistical representation of the continuous surface of some area, that has been measured and then abstracted through mathematical assumption to obtain a nominal digital model of that terrain.
- For use in GIS software, DEM data is typically formatted as a raster image, a two-dimensional array of values, where each value corresponds to the elevation at a square area on the Earth's surface.
- To be generated, a DEM requires associated metadata in addition to the dataset of sampled height measurements from the natural terrain, including—temporal data, pose data, a global coordinate system, and a coordinate reference system.
- Raw DEMs are used to derive a variety of products for increased visual clarity.
- For example a color gradient may be applied to encode height, or the height data may be rendered as a three-dimensional digital object that can be draped with image data to create a realistic digital visualization of the original terrain.
- DEMs are used to map and analyse other phenomena that have strong elevation, slope, and aspect components.
- For environmental science, a few applied use-cases include—hazard mapping of damaging processes like floods, landslides, and erosion, and informing models such as snow accumulation, watershed, species distribution, and habitat modeling.
- DEMS are used to geometrically correct satellite imagery through the process of orthorectification---i.e. the removal terrain-induced distortions caused by topographic relief, earth curvature, and other errors in the sensing process.
- Orthorectification combines a model of the sensor being used with detailed information on the sensor's positionality while obtaining an image, and employs an external DEM to geometrically correct pixels by displacement.
- This technique has been applied by government satellite programs to their open-source Earth imagery datasets.
- However, orthorectification is a relatively new method, the accuracy of which is still in question, especially when used to georeference remotely sensed images from high relief terrain, such as that in mountainous regions.
- There are several carefully maintained and publicly available DEMs available, including: ALOS DEM, SRTM DEM, ASTER GDEM, and TanDEM-X, offering spatial resolutions between 30 - 90m.

- Different DEMs offer height data gathered from a variety of different sensors and platforms, and may be merged by data fusion to help fill spatial gaps, reduce errors, and improve vertical accuracy,

- Data fusion also occurs at the stage of DEM generation, when datasets gathered from a variety of different terrain height measuring techniques—such as laser altimetry, stereo imagery, and theodolite triangulation—are combined to fill gaps and reduce errors in the same way.

- DEMs can be divided into two subtypes: Digital Terrain Model (DTM) and Digital Surface Models (DSM).

- A DSM represents the surfaces of the top-most extent of the ground and all objects arising from it, including treetops, buildings, and exposed ground…

- While a DTM represent the terrain elevation of the lithosphere, or bare-earth surface, excluding objects such as vegetation and buildings.

- Sensors such as LiDAR and RADAR can sometimes penetrate surface objects to directly sample ground elevation, but DTMs may also be derived from DSMs using other sources of height measurements for features like buildings and trees.

- A DSM may be optimal for applications such as urban or network coverage planning, while a DTM may be more effective for watershed analysis or ground stability monitoring.

- Performing combinatory operations on a DSM and DTM of the same area can be used to obtain other models, for example through subtraction to obtain a Canopy Height Model.

SLIDE 36

- Bathymetry refers to the underwater topography, that is the shape and depth of the seafloor, lakebeds, or riverbeds, much like topography describes land elevation.

- Bathymetry can also be mapped using DEMs, and merged with land height data to generate a full elevation map for a coastal area, called a Coastal Elevation Map.

- Height data for bathymetric DEMs can be sampled directly from beneath the surface of the ocean using echosounder systems…

- And to a lesser extent by LiDAR and optical imagery at shallow depths in non-turbid water.

- Bathymetric data can also be derived by retrieval algorithm using measurements of the ocean's surface, gathered by satellite RADAR altimeters and optical imagery.

- A fusion of data from these sources are used to generate bathymetric DEMs.

- Bathymetric data is essential to predictively modeling physical, ecological, and geomorphic processes in coastal zones.

- However, only a small fraction of the ocean floor has been mapped, and there is high demand for scalable solutions to that end.

SLIDE 37

- Remotely sensed data is used model a large range of coastal hydrodynamic processes and the sediment transport they induce.
- These practices are at the forefront of coastal science.
- Continuous video imagery of wave motion, captured from cameras mounted on fixed coastal platforms…
- is used to predict the spatial pattern and spectral content of coastal phenomena such as wave run-up…
- as well as sediment transport characteristics such as swash zone sediment distribution and longshore bar morphology.
- High-frequency RADAR systems mounted on the ground are used to directly measure surface current vectors for modeling of local circulatory patterns.
- Data from HF RADAR is also able to model sandbar migration, ripple patterns, and nearshore bedform evolution.
- Terrestrial and UAV-based LiDAR and video imagery are used to map coastal dune evolution, cliff erosion, and sediment budgets, enabling the measurement of morphological change over time to support coastal management and infrastructure planning.
- These proximal remote sensing methods offer high temporal resolution and detailed spatial coverage, making them well-suited for monitoring the dynamic and complex coastal environment.
- These datasets are often fused with satellite observations, which cover larger spatial extents and provide complementary sensor types, enabling more comprehensive modeling across scales.

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- Robust predictive models are needed to effectively manage and mitigate the damaging effects of extreme marine processes exacerbated by rising global temperatures and increased coastal settlement.
- A multidisciplinary approach that incorporates biological, physical, and chemical data gathered through a combination of remote sensing, ground truth observations, and numerical models subject to data assimilation techniques is currently the optimal method for characterizing coastal phenomena.
- Data fusion algorithms that integrate data from disparate sensor types deployed in conjunction are used to produce more accurate and detailed information.

- There is an international network of remote sensing systems that deploy a variety of sensors from a range of platforms to compile robust open-source datasets that facilitate coastal research.

- However, models are currently limited by a lack of data pertaining to particular environmental parameters, such as bathymetry, and the extent and regularity of high-resolution data collection projects.

- The scientific coastal monitoring and survey network must be expanded to address this need.

- Recent technological advancements—including heightened accuracy and decreased footprint of sensors and microprocessors, increased coverage of GNSS and internet services, and implementation of machine learning techniques for data processing—have enabled the development of scalable remote sensing solutions that may be used to expand the global network of environmental survey and monitoring systems.