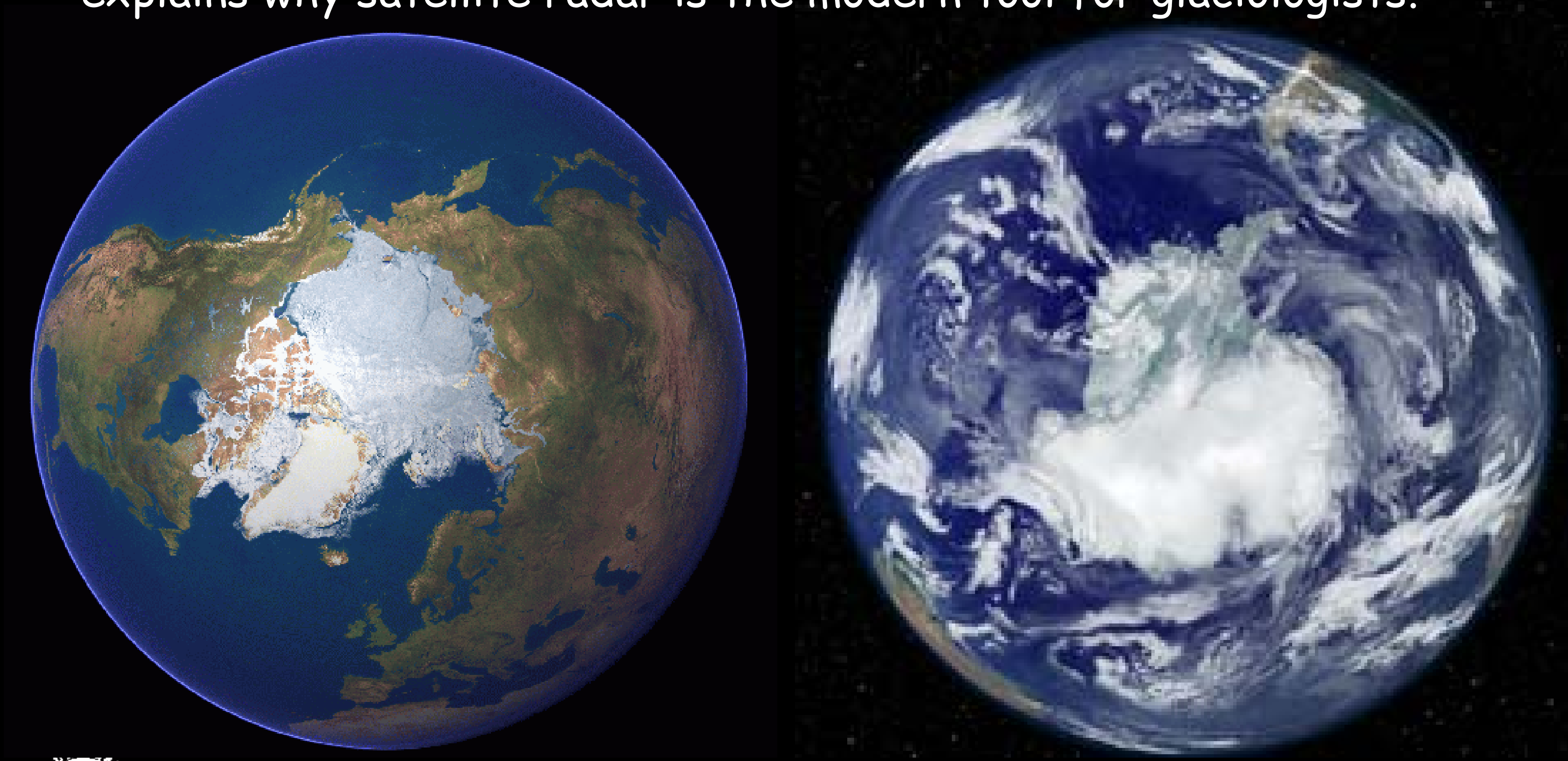
Satellite radar – 21st century glaciology

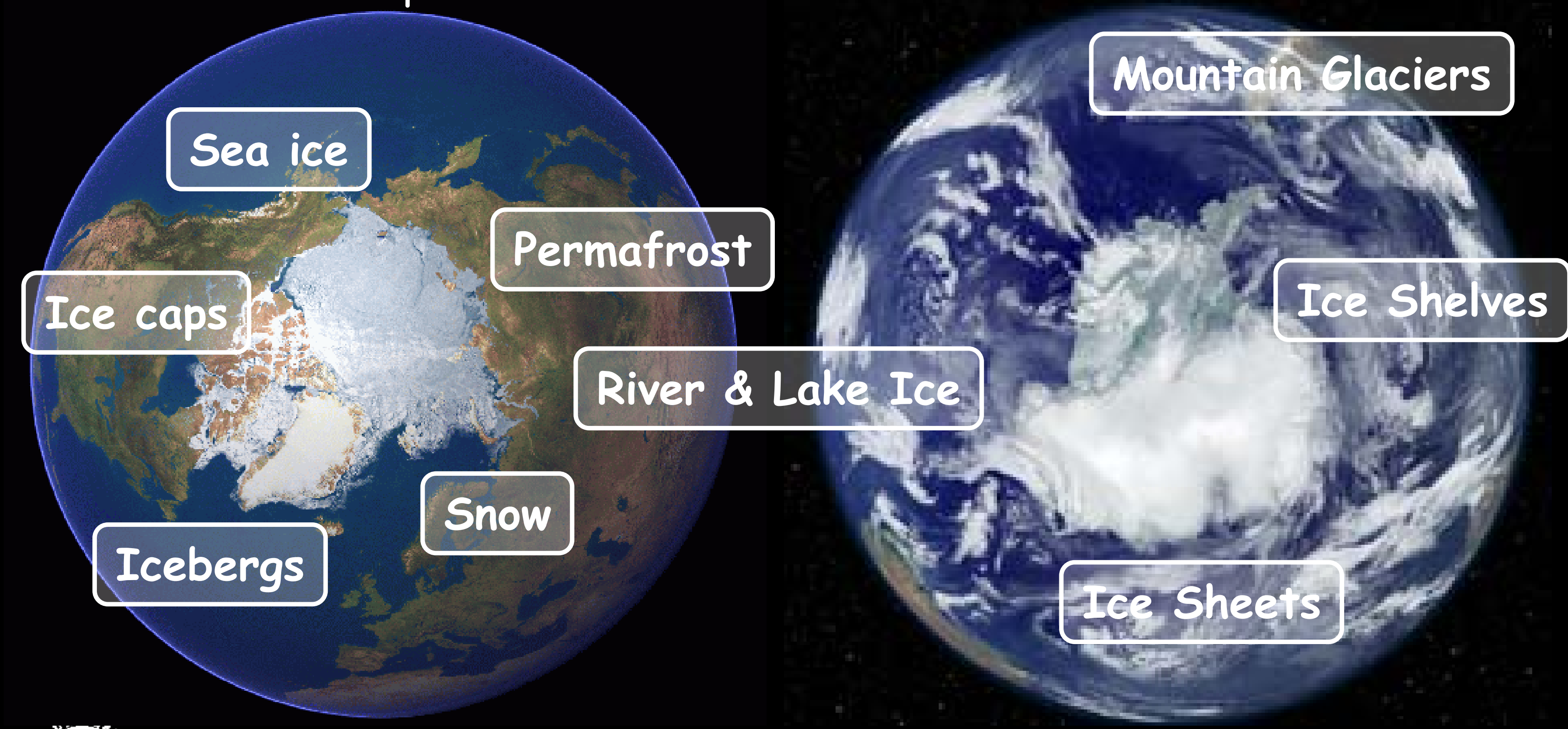
Andrew Shepherd
University of Edinburgh


Ice & Climate

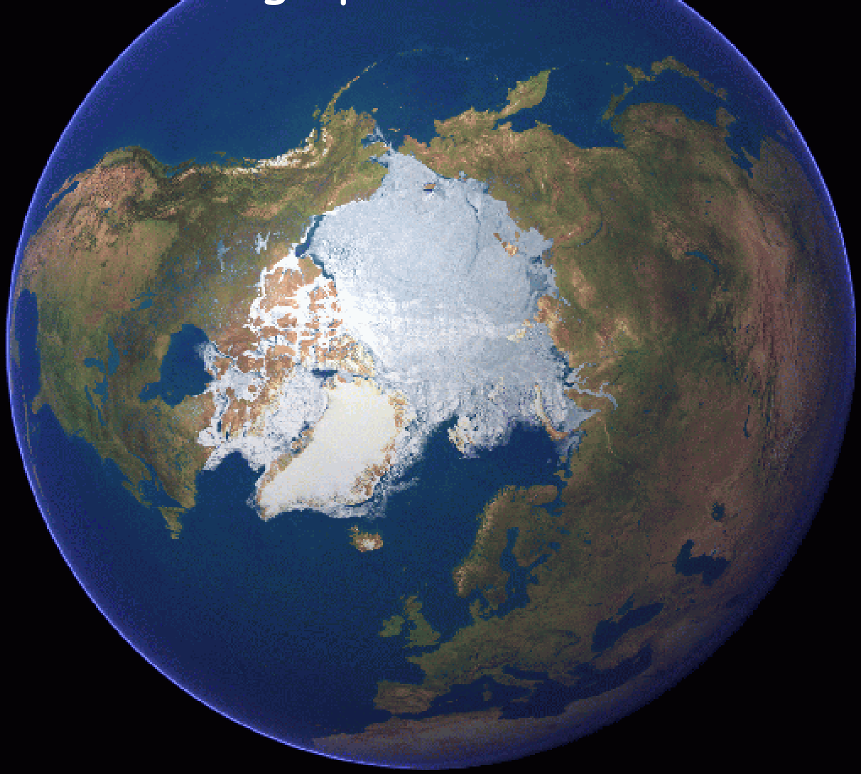
- Planet Earth is characterised by the presence of water. In frozen form, snow and ice cover about a sixth of Earth's surface.
- This lecture provides an introduction to Earth's crysophere, and explains why satellite radar is the modern tool for glaciologists.



- The cryosphere includes all frozen regions of the Earth, such as the polar ice sheets, mountain glaciers, floating sea ice, and the Arctic tundra. It is an important component of the Earth's climate system, because ice is sensitive to changes in temperature such as those that have been predicted for the near future.

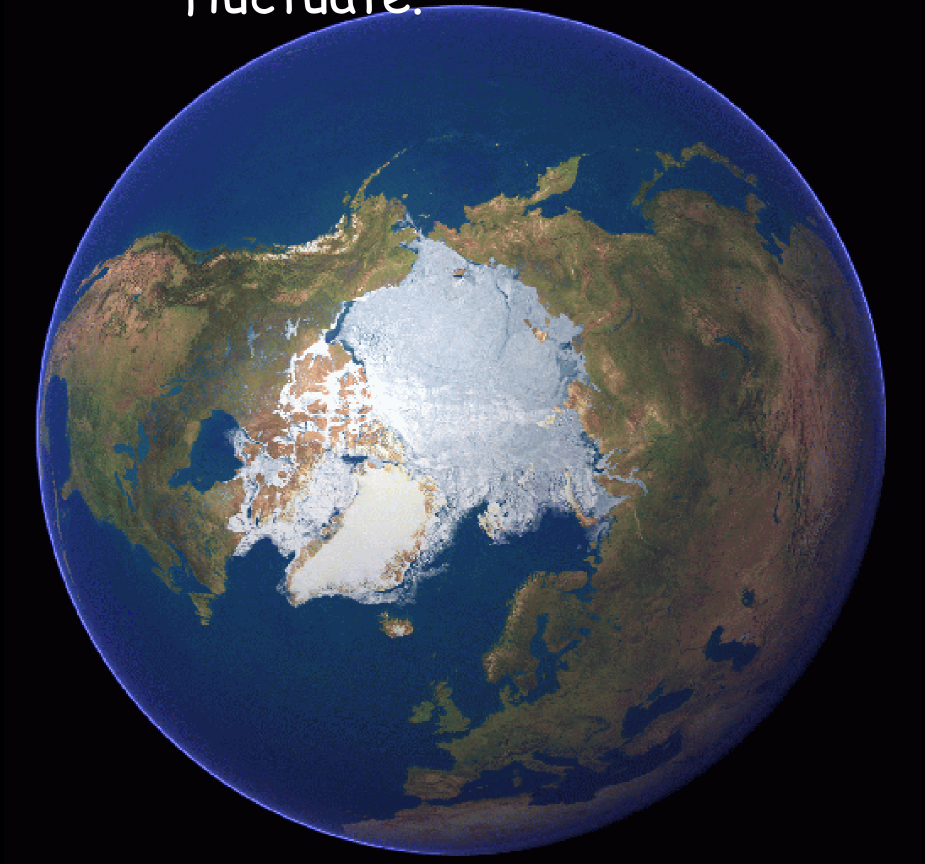


- Frozen regions help us to study climate change in two key ways.
  - Firstly, sub-polar components of the cryosphere (e.g. alpine glaciers) are expected to respond quickly to changes in climate, and their progress can be used as a barometer for climate change predictions.

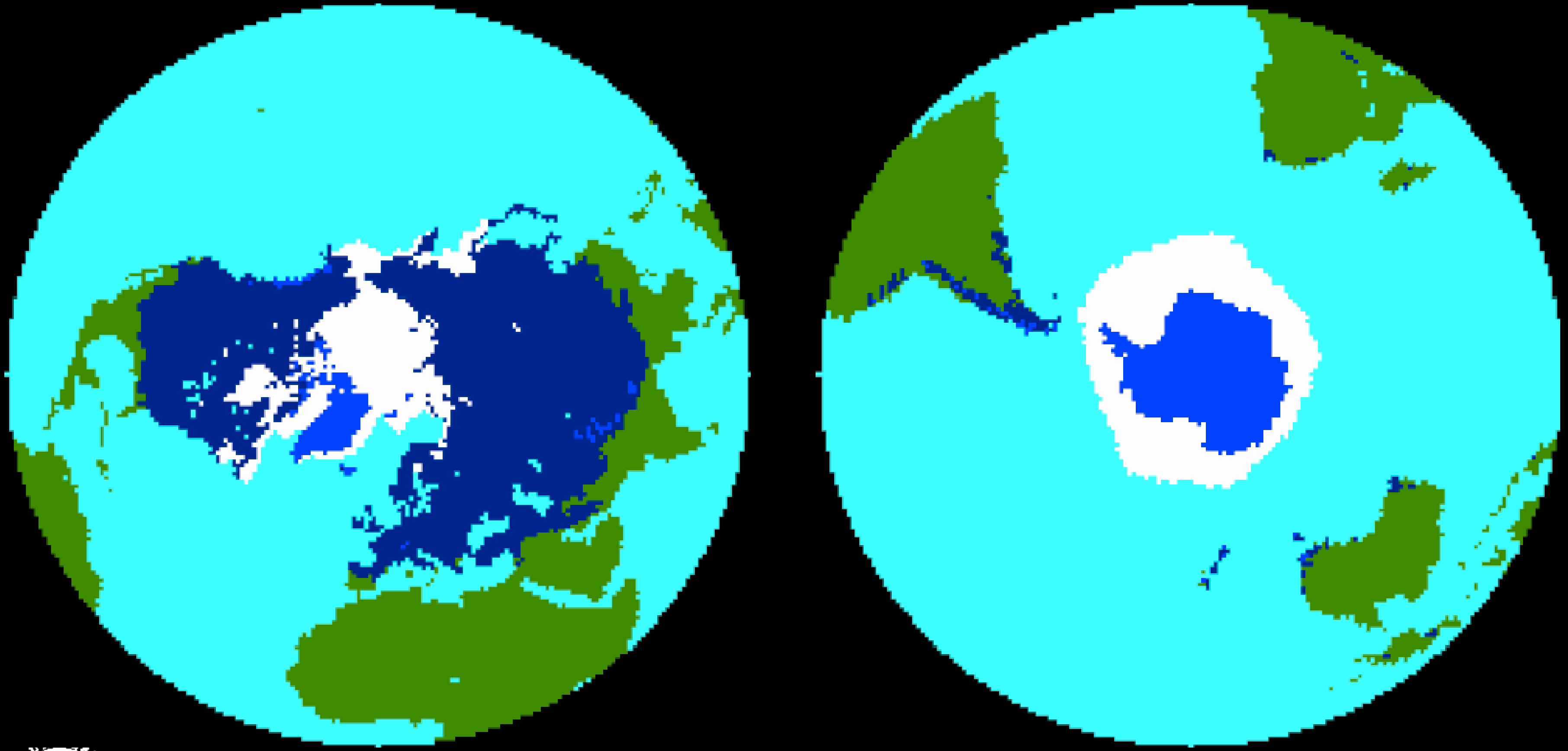


- Frozen regions help us to study climate change in two key ways.

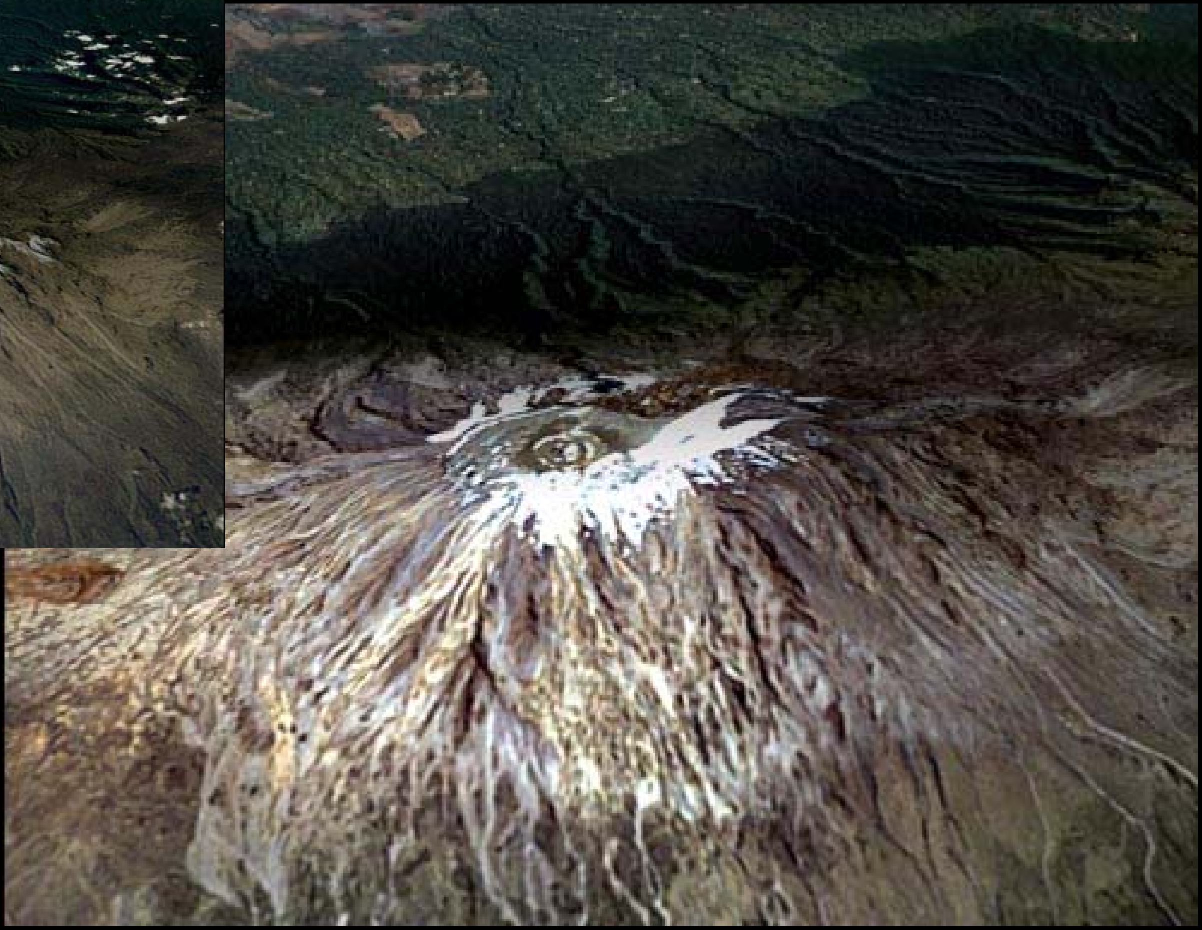
  - Secondly, as climate change occurs, the quantity of water frozen within the cryosphere changes too, causing global sea levels to fluctuate.



- Today, water in solid phase exists on all of Earth's continents at some time of the year.



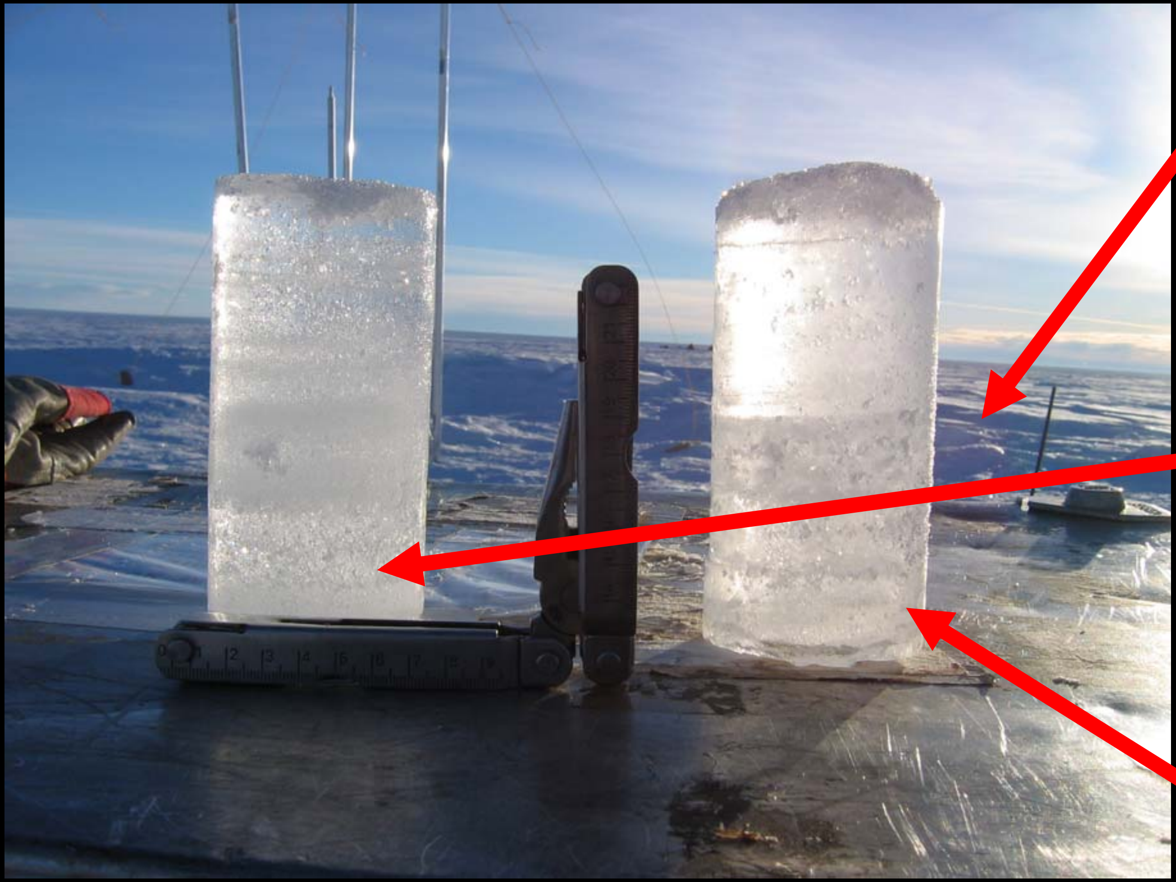
- ... although Africa's ice is set to disappear in the next 20 years.



- Ice area is not a useful parameter for studies of climate change, because it is not generally related to mass.

- For instance, when glaciers surge, their area can double, but their mass remains constant

- Ice volume, however, is directly related to mass through density, and so measuring changes in ice volume tells us directly how sea level is changing.

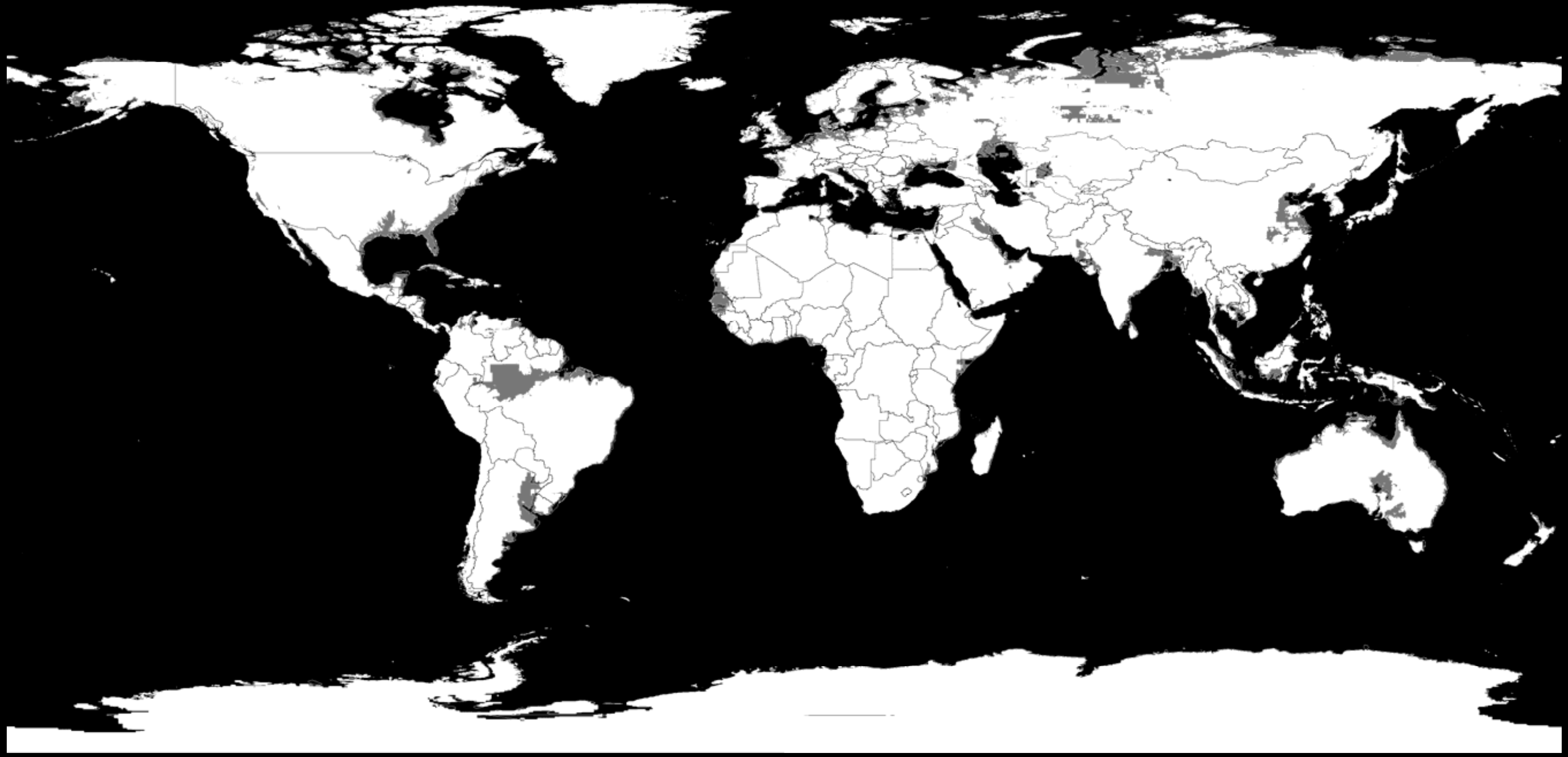


ρ_{SNOW} =350 kg m^{-3}

ρ_{FIRN} =350-917 kg m^{-3}

ρ_{ICE} =917 kg m^{-3}

- If all snow and ice above sea level were to melt, Earth's continents would look very different.



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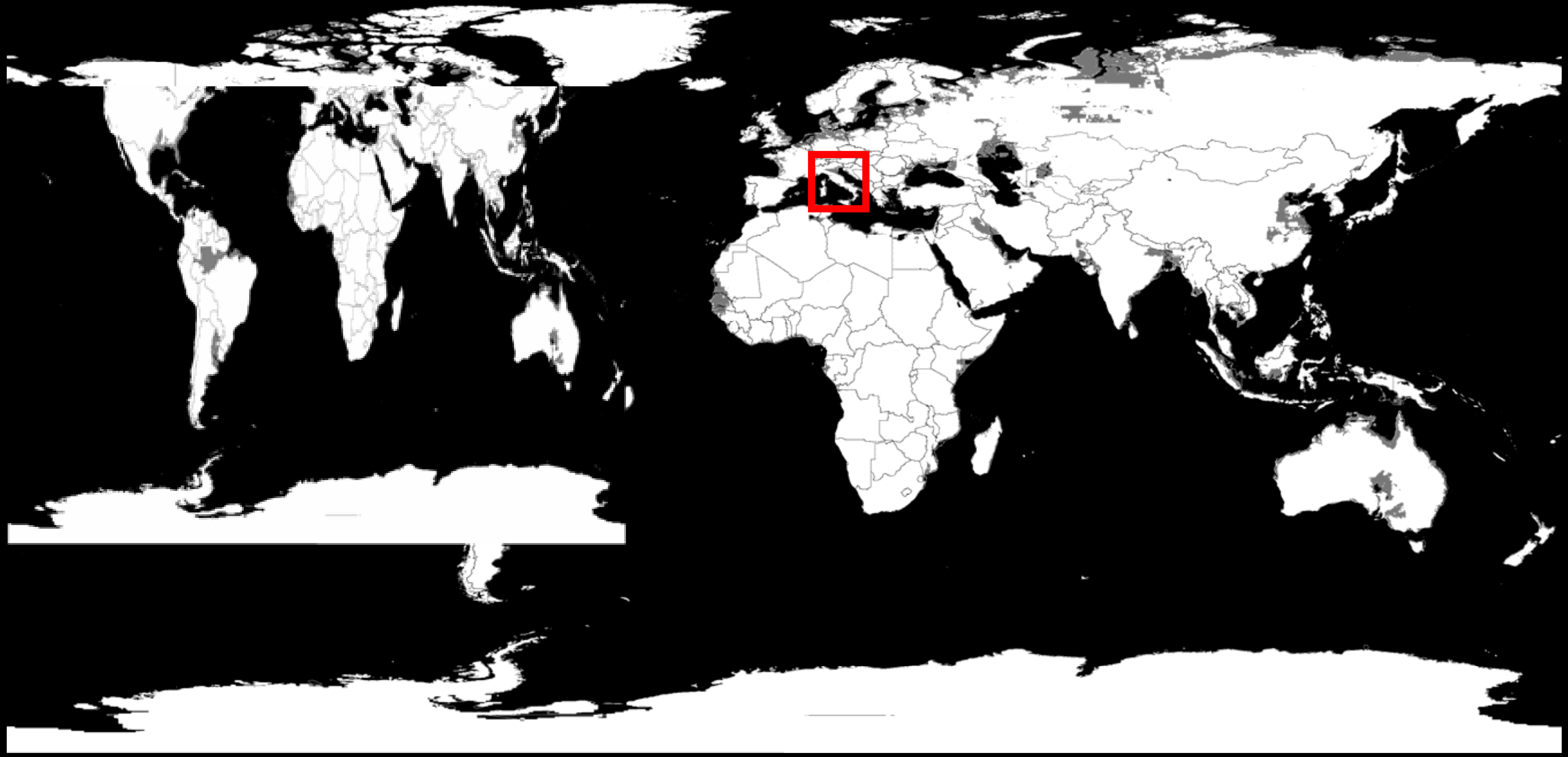

- The vast majority of Earths ice is frozen in Antarctica

Ice	Area (km^2)	Volume (sea level equivalent)
Ice Sheets	14,000,000	80 m
Permafrost	20,000,000	~ 2 m
Glaciers & Ice Caps	5,000,000	0.6 m
Snow	46,000,000	0.01 m
Ice Shelves	1,500,000	2 m*
Sea Ice	33,000,000	0.1 m*

- Because changes in ice volume cannot be realistically measured over large areas by field surveys, remote sensing has moved to the forefront in modern glaciology. Today, satellite remote sensing offers the only practical method to measure changes in ice sheet mass balance.

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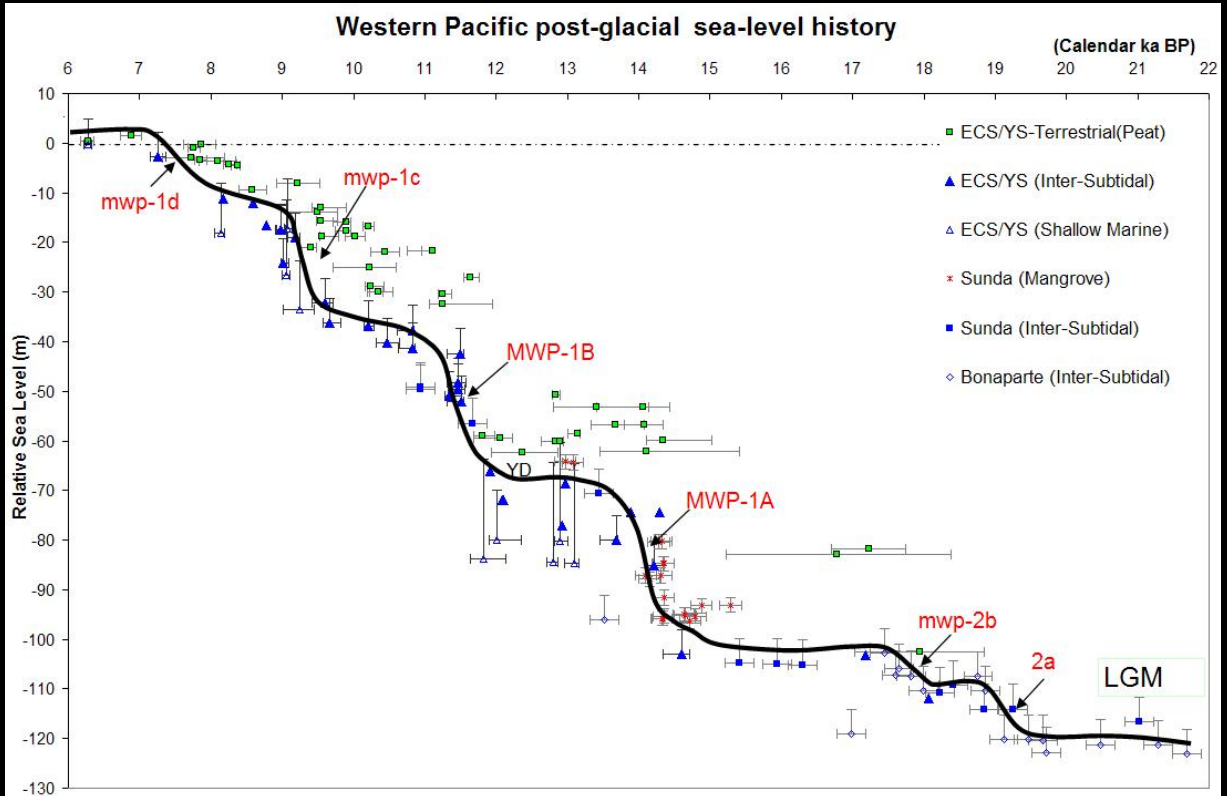
- Changes in ice sheet mass have moderated global sea level throughout the ice age. As Antarctica grows sea levels fall, as Antarctica shrinks sea levels rise.

- Measuring changes in ice sheet mass shows how much they contribute to present sea level change.

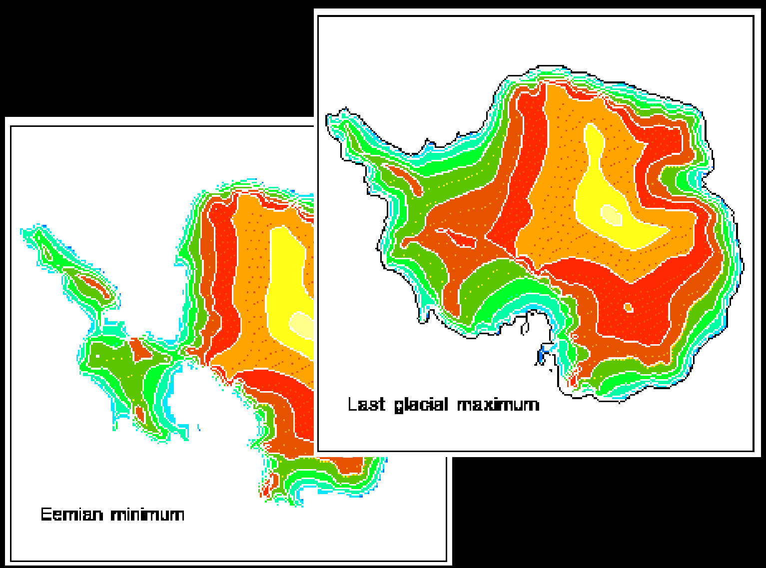


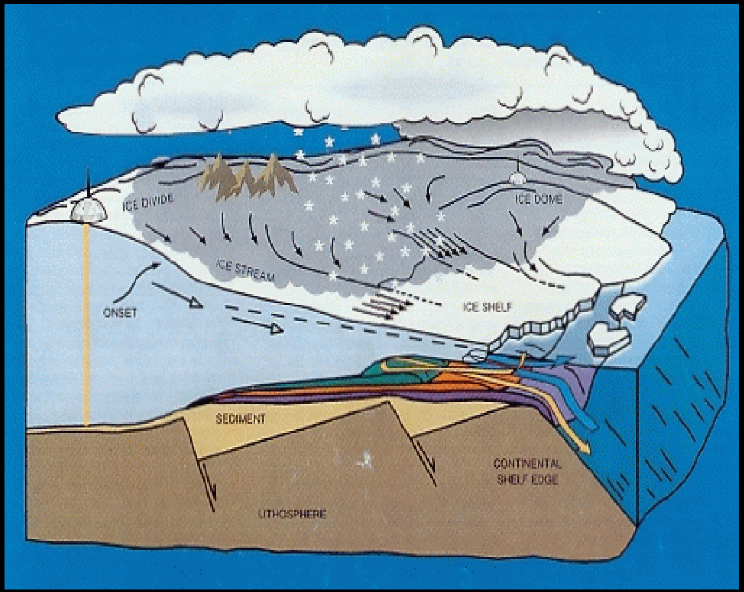
Liu, J.P., Milliman, J.D., Gao, S. and Cheng, P., 2004. Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. Marine Geology, 209(1-4): 45-67.

- Ice sheet mass can be measured in two ways:

(1) By recording changes in total volume, and converting to mass.

(2) By recording the difference between mass input and output





Each approach requires measurements across entire ice sheets

- (1) Volume change (whole ice sheet)

$V_{TODAY} = 26 \times 10^6\ km^3$

$V_{LGM} = 77 \times 10^6\ km^3$

$\Delta V = -51 \times 10^6\ km^3$

$density = 917\ kg\ m^{-3}$

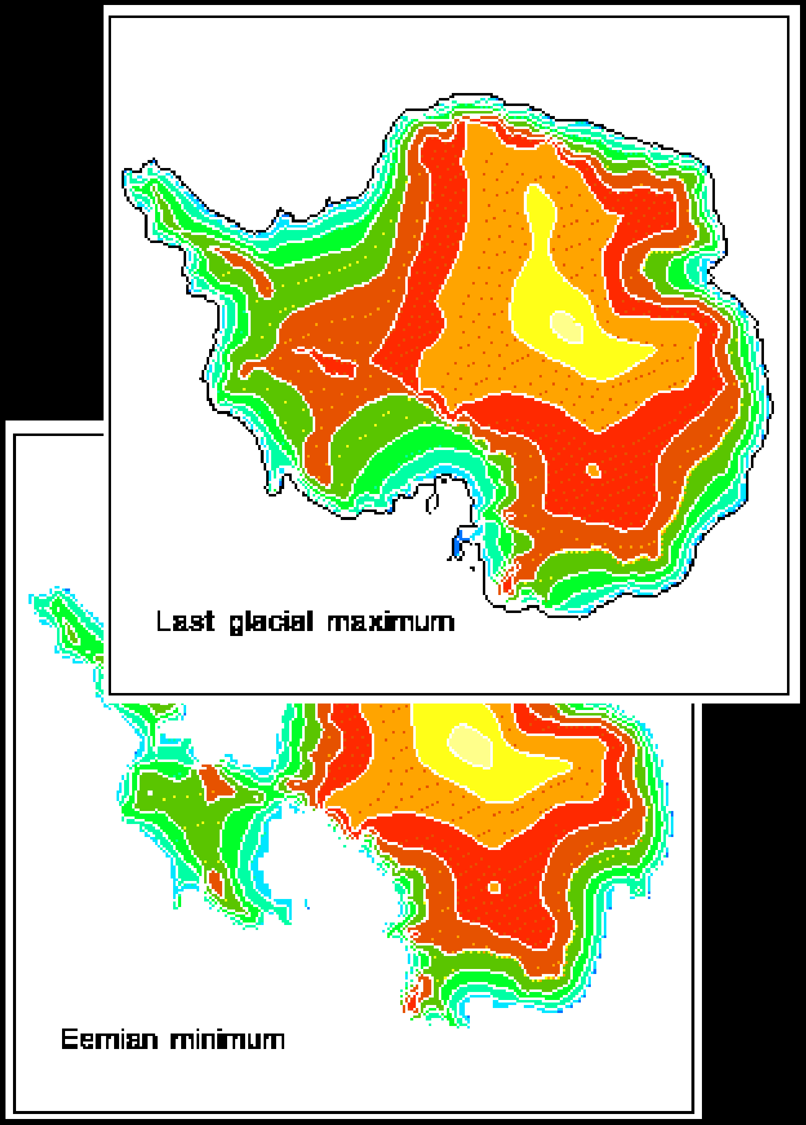
$\Delta M = -47 \times 10^6\ Gt$

$\Delta M / \Delta t = -47 \times 10^6\ Gt / 21{,}000\ yr$

$= -2200\ tonne\ yr^{-1}$

360 Gt = 1 mm ESL

$\Delta ESL / \Delta t = 6\ mm\ yr^{-1}$



- (2) Mass budget (per glacier)

<u>Input (snowfall)</u>

<Snowfall rate> = 373 mm yr^{-1}

Area = 1.2 x 10^6 km^2

Density = 350 kg m^{-3}

Mass input = 153 Gt yr^{-1}

<u>Output</u> (glacier discharge)

Glacier speed = 2.5 km yr^{-1}

Width = 50 km

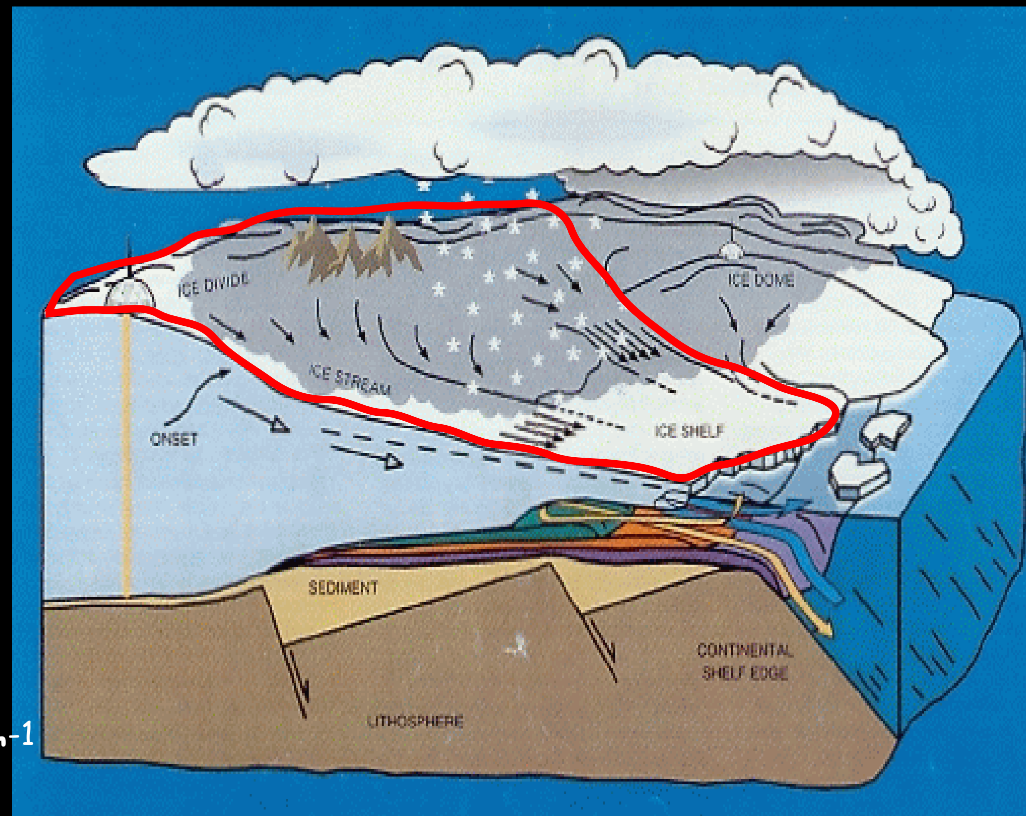
<Thickness> = 1.5 km

density = 900 kg m^{-3}

Mass output = 169 Gt yr^{-1}

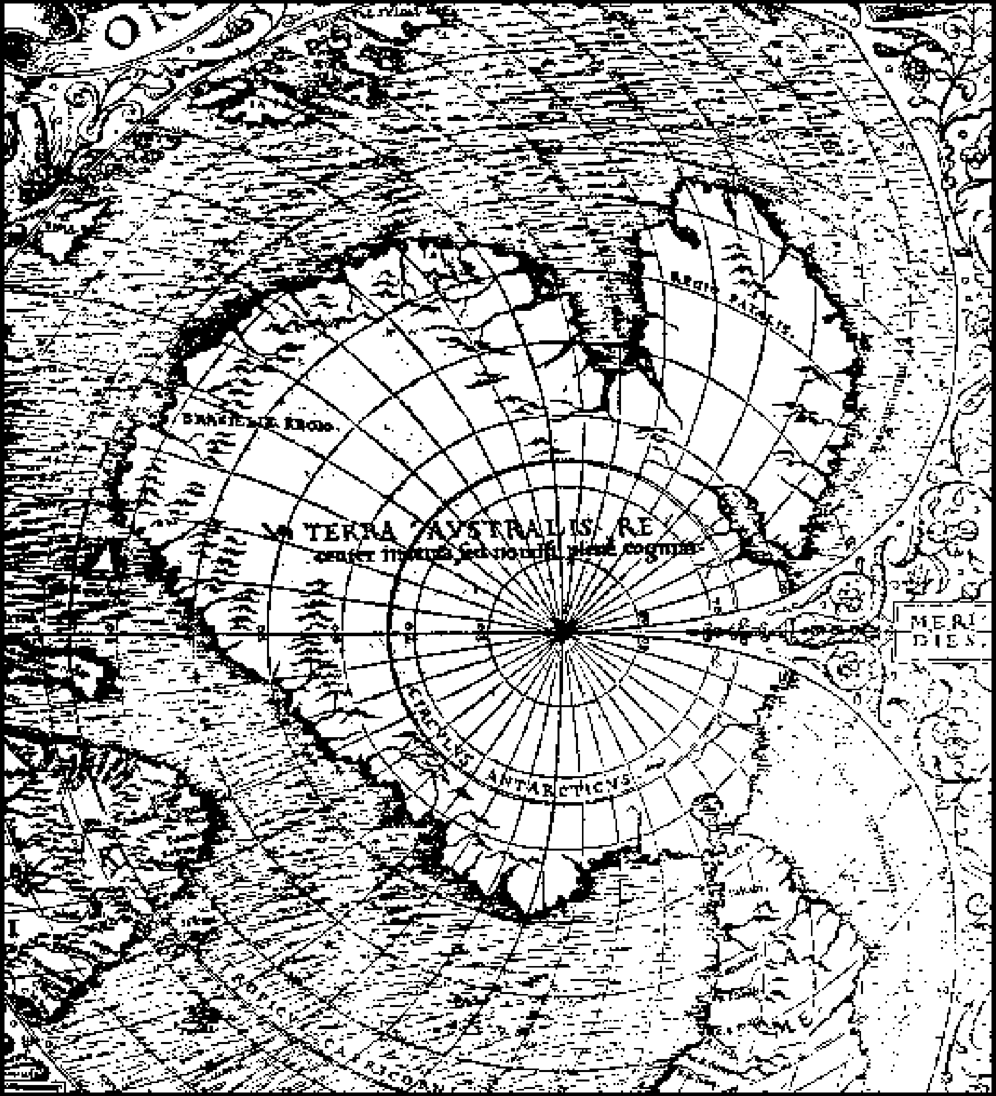
$\Delta M / \Delta t$ = 153 – 169 = -16 Gt yr^{-1}

$\Delta ESL / \Delta t$ = -0.04 mm yr^{-1}




Observing Antarctica

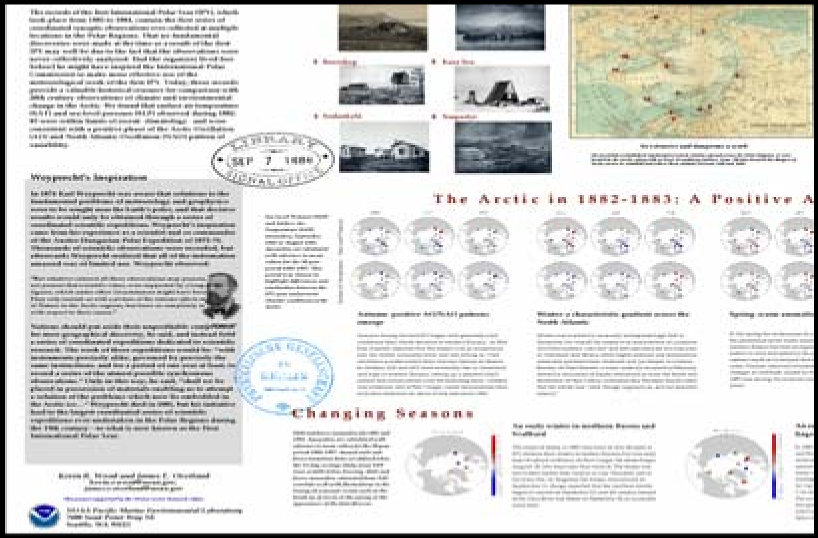
- 1531: First map of Antarctica?



- 1882: First International Polar Year.

  The fundamental concept of the first IPY was that geophysical phenomena could not be surveyed by one nation alone; rather, an undertaking of this magnitude would require a global effort.

- 12 countries
- 15 expeditions
- 13 to the Arctic
- 2 to the Antarctic



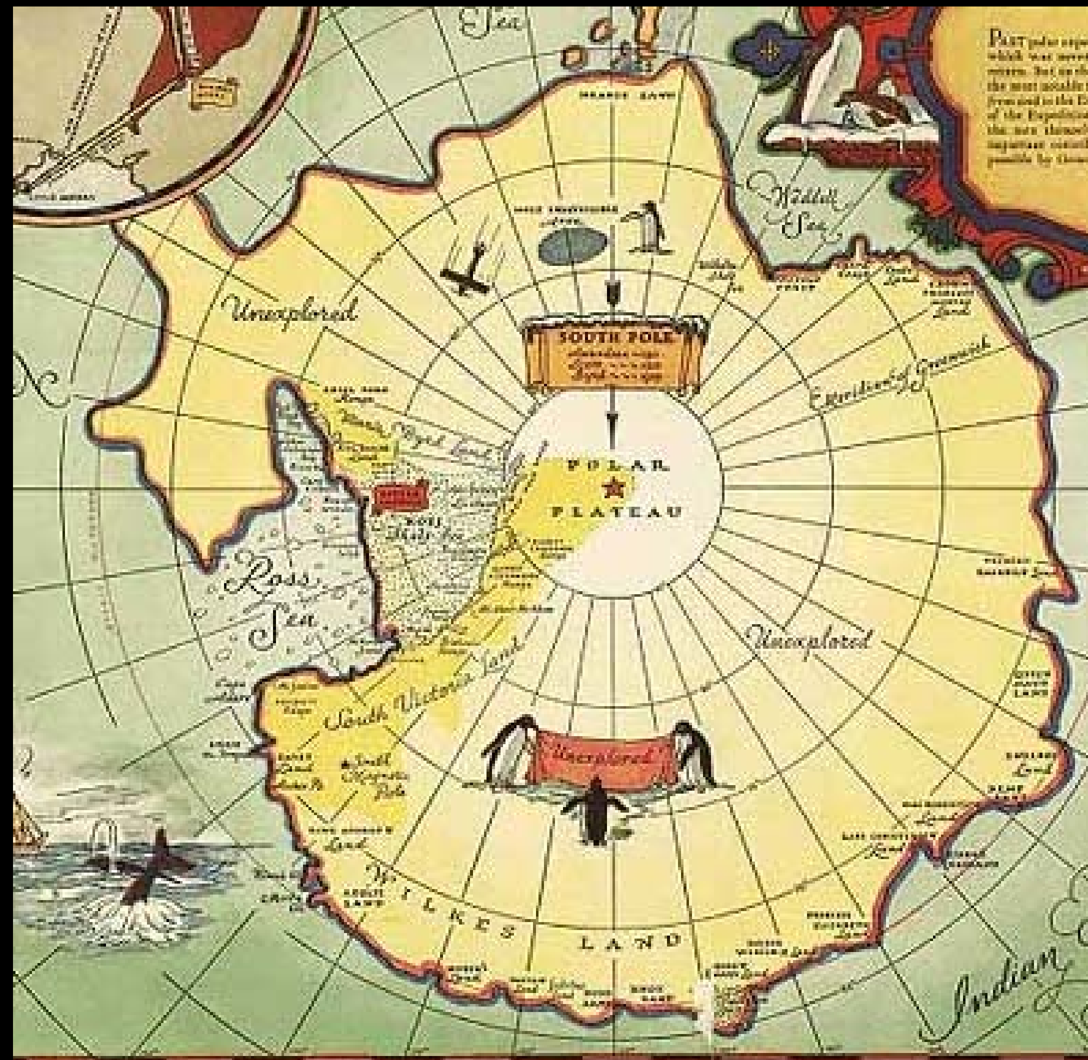
- 1914: Shackleton shipwrecks at Antarctic Peninsula

- 1932: Second International Polar Year.

- The International Meteorological Organization proposed and promoted the Second IPY (1932–1933) as an effort to investigate the global implications of the newly discovered "Jet Stream."

- 40 nations
- Atmospheric science
- 40 Arctic stations
- First inland Antarctic station

- 1946: Byrd maps Antarctica by air



- 1957: The International Geophysical Year

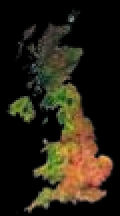
  Conceived to exploit technology developed during WWII (for example, rockets and radar)

- Continental drift, confirmed
- First satellites launched
- Van Allen Radiation Belt discovered
- Antarctica's ice mass quantified
- Antarctic Treaty ratified

- 2002: Satellite mosaic of Antarctica

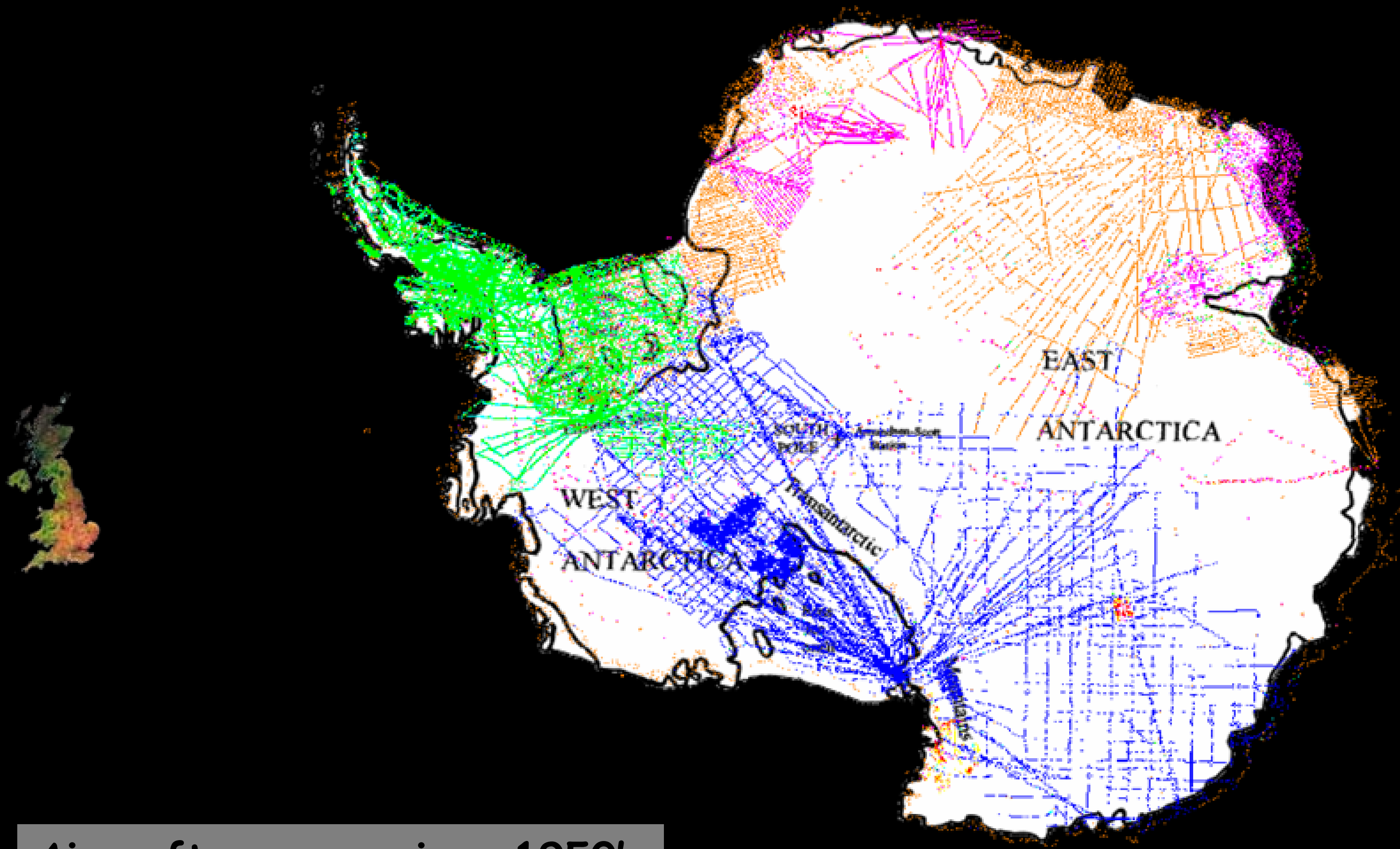
- 2007: Third International Polar Year.
  IPY 2007 will expand upon the legacy of scientific achievement and societal benefits from past examples.

Observing Antarctica



Field sites visited since 1920's

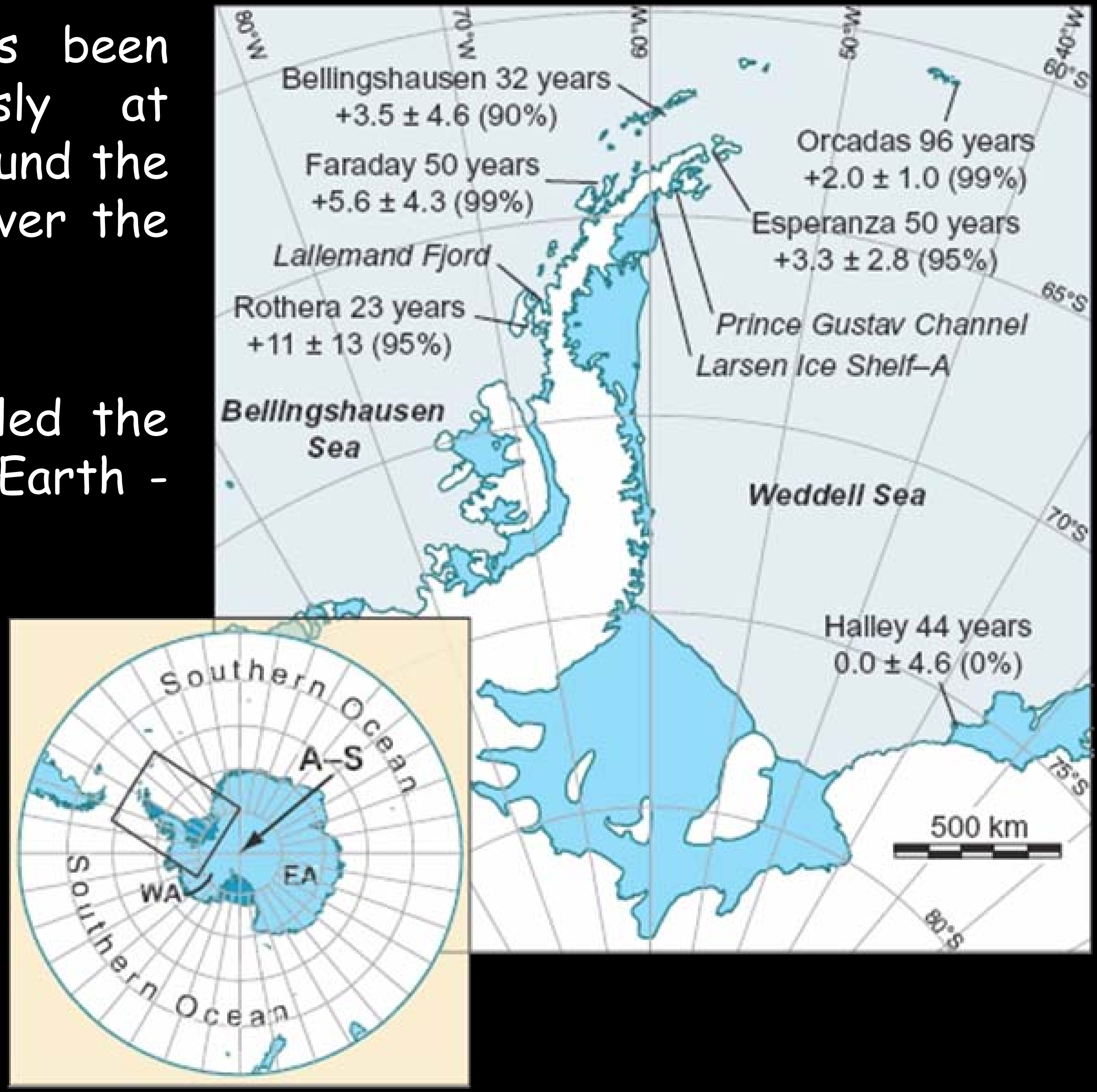
Field stations occupied since 1940's



Aircraft surveys since 1950's

- Air temperature has been recorded continuously at research stations around the Antarctic Peninsula over the past century.

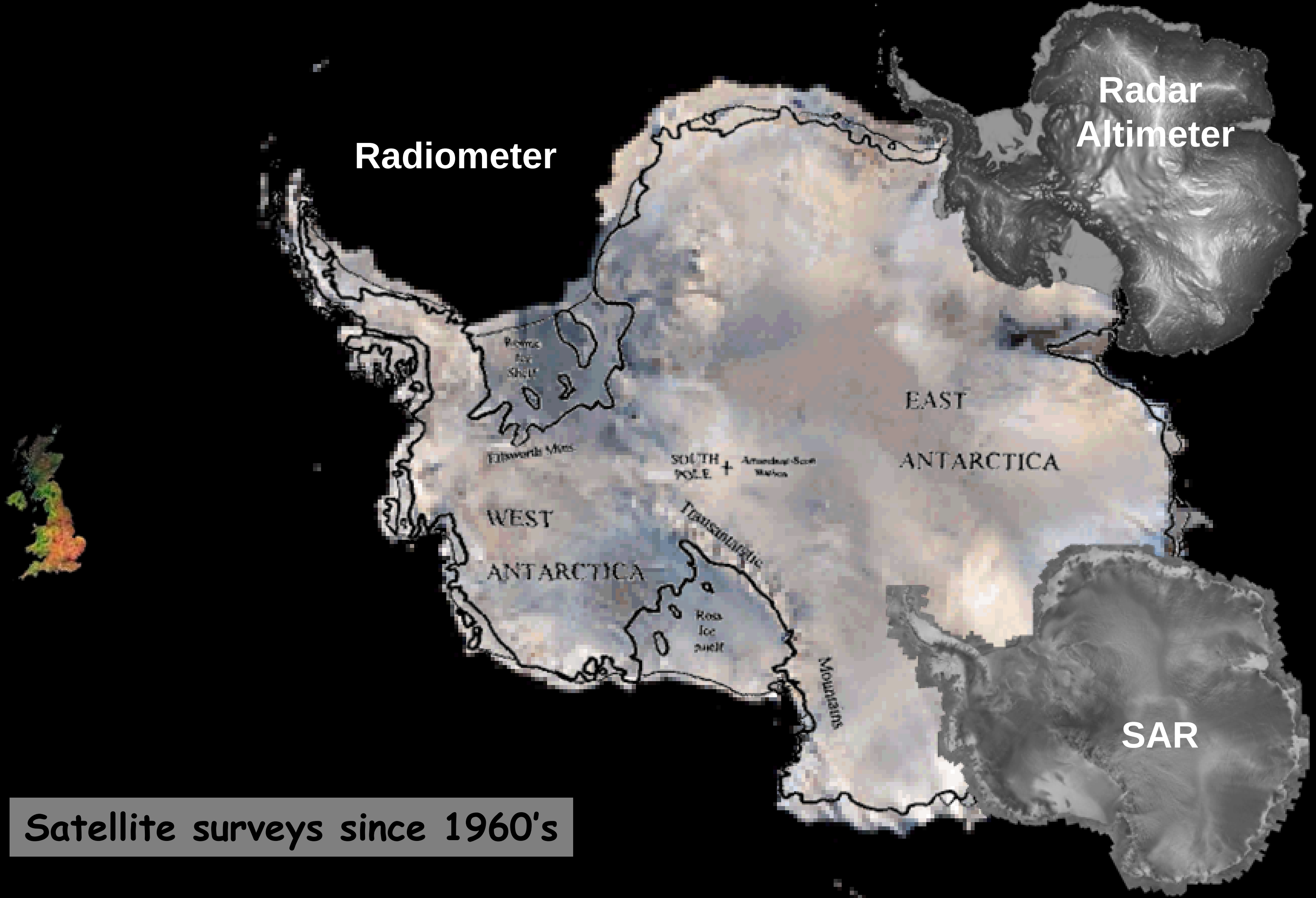
- These records revealed the greatest warming on Earth - over 10 C in places.



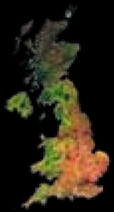
- Glaciological estimates of Antarctic mass balance (360 Gt = 1mm slr)

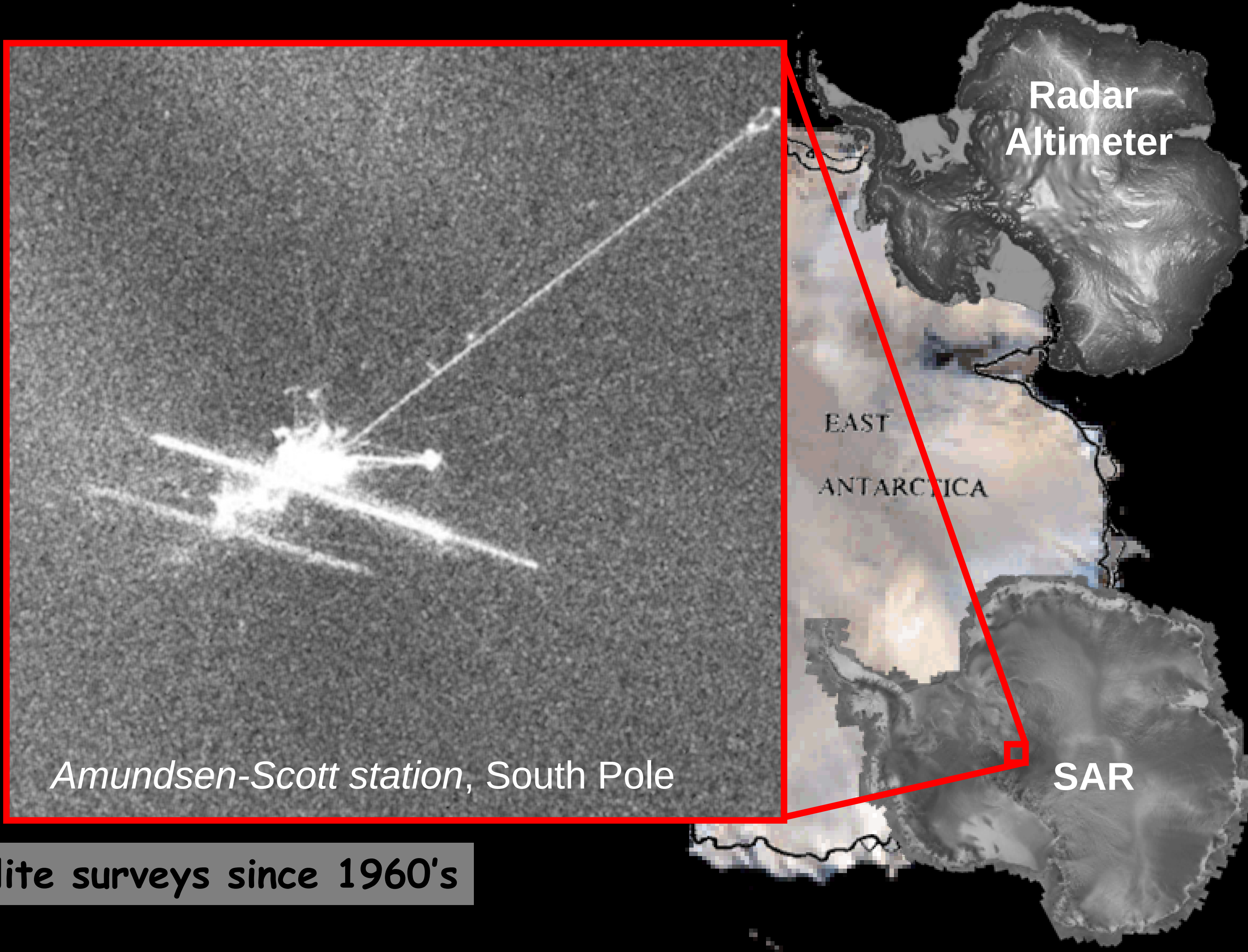
Study	Mass input (Gt)	Mass output (Gt)	Mass Balance (Gt)
Losev, 1963	2000	2400	-400
Bull, 1971	2080	1660	+420
Kotlyakov, 1978	2000	2720	-720
Meir, 1983	1749	1262	+487
Budd, 1985	2000	1800	+200
Bentley, 1991	2200	2010	190
Jacobs, 1992	2144	2613	-469
			-40 ± 480

Satellite Remote Sensing



Satellite surveys since 1960's





Amundsen-Scott station, South Pole

Satellite surveys since 1960's

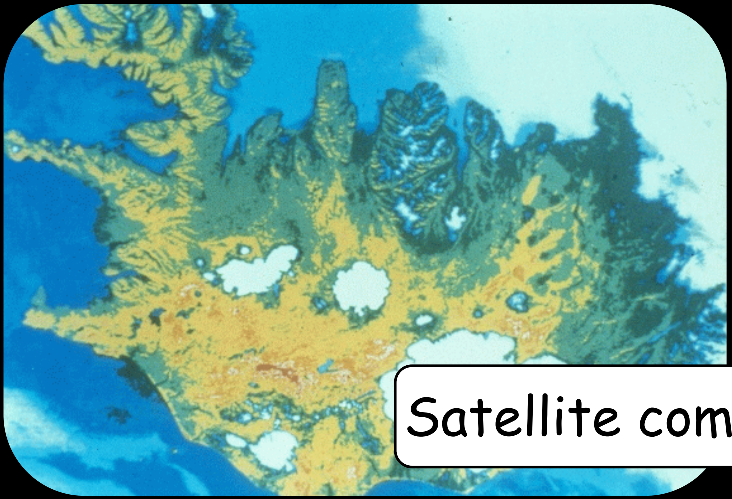
- The first satellites were cameras in space. They were placed in orbit before telecommunications were possible, and so their film had to be physically ejected down to Earth.

- A C-119 aircraft recovers a film capsule ejected from the DMSP satellite program.

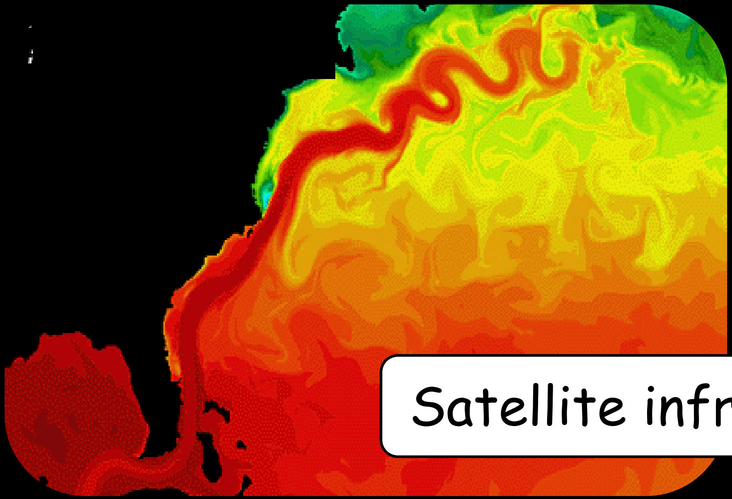
- Modern instruments are far more sophisticated.
- In 2009, the CryoSat-2 satellite will be launched, carrying an interferometric synthetic aperture radar altimeter
- CryoSat-2 will record fluctuations in the volume of the polar ice sheets to a far greater precision than has been previously possible.

- Unlike photography, RADAR is a quantitative remote sensing technique. It can be used to measure distance and speed precisely

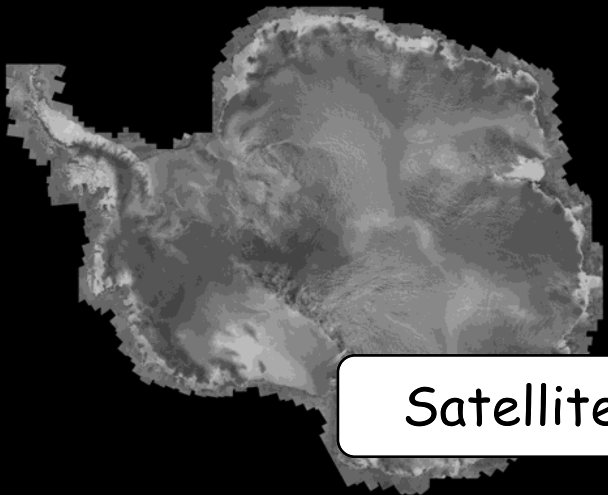
Oblique Photo



Satellite composite

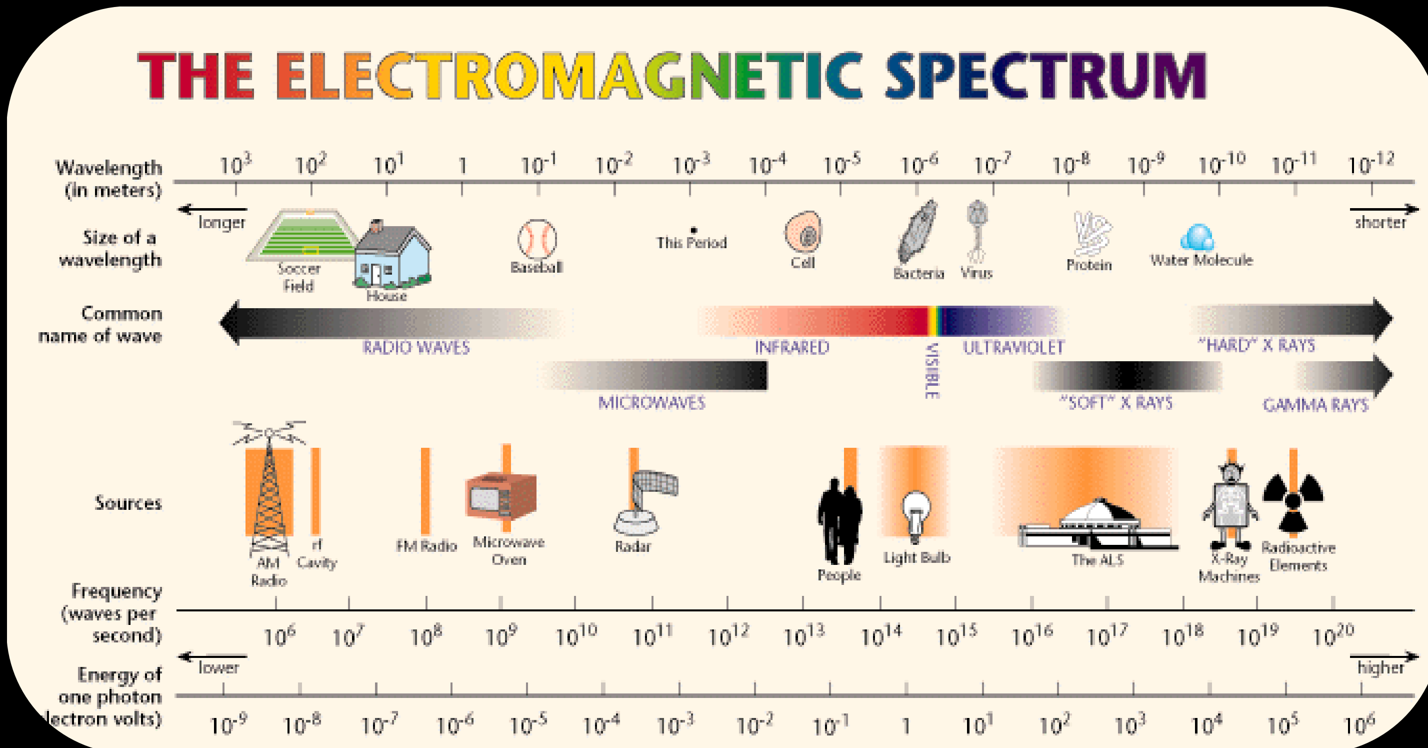


Satellite infrared



Satellite radar

- Radio waves have the longest wavelengths (0.1 to 1000 m), followed by microwaves (0.1 to 100 mm), infrared, visible, UV and X-rays.



- The Earth's atmosphere (including clouds) is transparent to electromagnetic radiation with wavelengths from 1 mm to 20 m – which includes radio and microwaves. This is why TV and radio stations are able to broadcast over long distances.

- RADAR echoes are used to measure distances (range). Radars are active sensors

- Aircraft use radar altimeters to measure their elevation above the Earths surface (altitude) for navigation purposes.
- Police use doppler radar to record vehicle speeds.

- The principals of radar operation are straightforward, and are equally applicable to aircraft altimeters, satellite sensors and even police speed traps (not cameras).

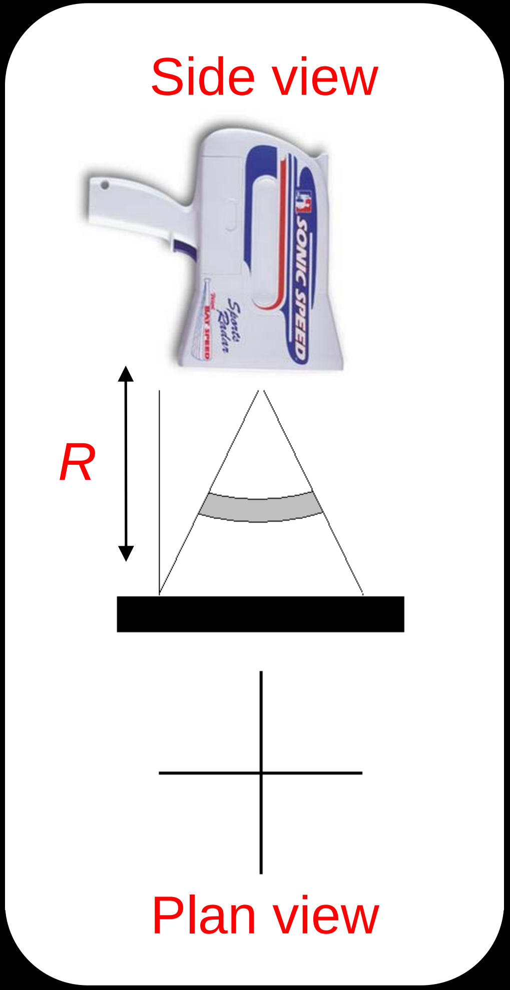
(1) Radars transmit pulses of electromagnetic radiation at radio frequencies

(2) The radar pulse is scattered or reflected by solid surfaces.

(3) The backscattered pulse (echo) is detected by the radar receiver

(4) The pulse travel time is recorded.

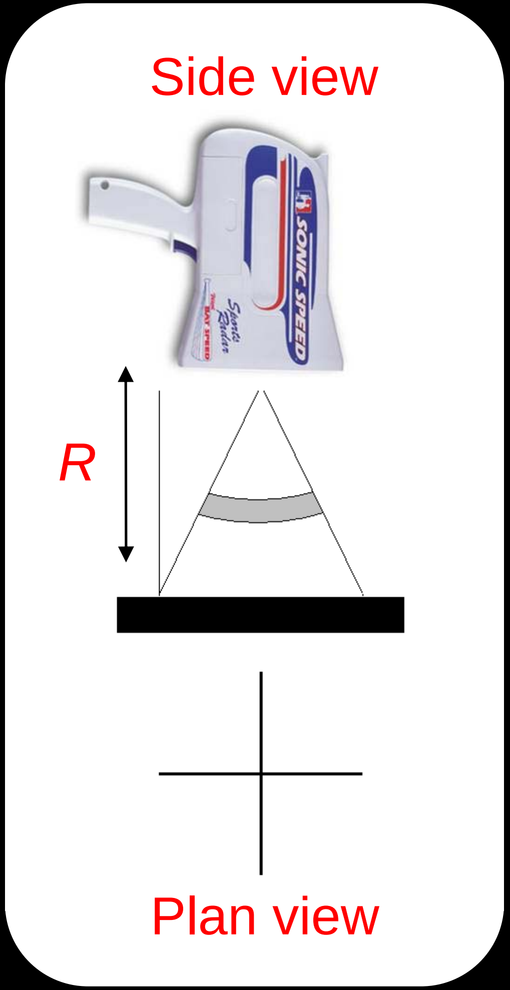
(5) The travel time is converted into the distance (range) separating the radar and the surface.



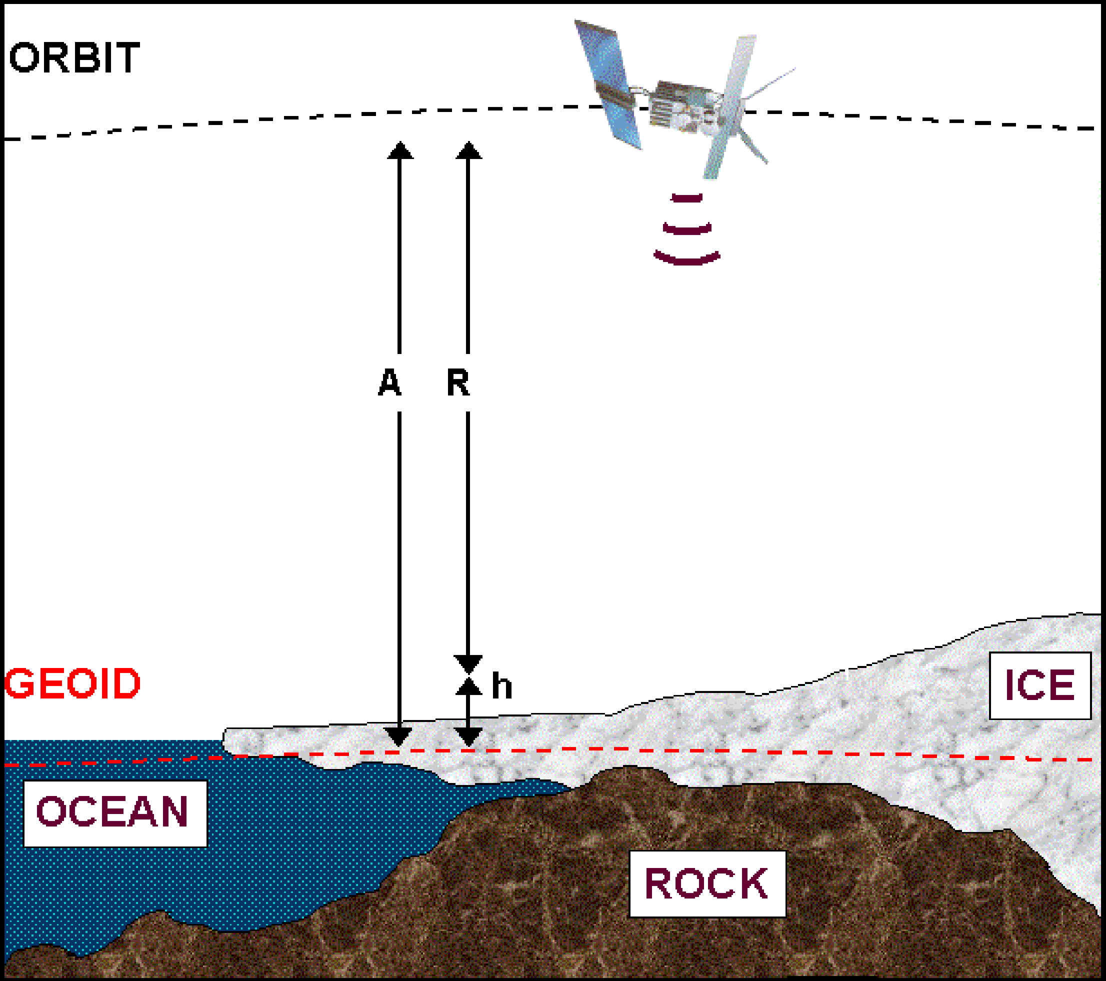
- The radar equation is very simple, and relates the travel time (T) to the distance travelled (range, R):

$$R = \frac{1}{2} cT$$

where c is the speed of light. Note the factor ½ to account for the fact that the radar pulse travels to the surface and back again in the time T.



- Altimeters are radars (e.g. on aircraft or satellites) pointed towards Earth to measure altitude.

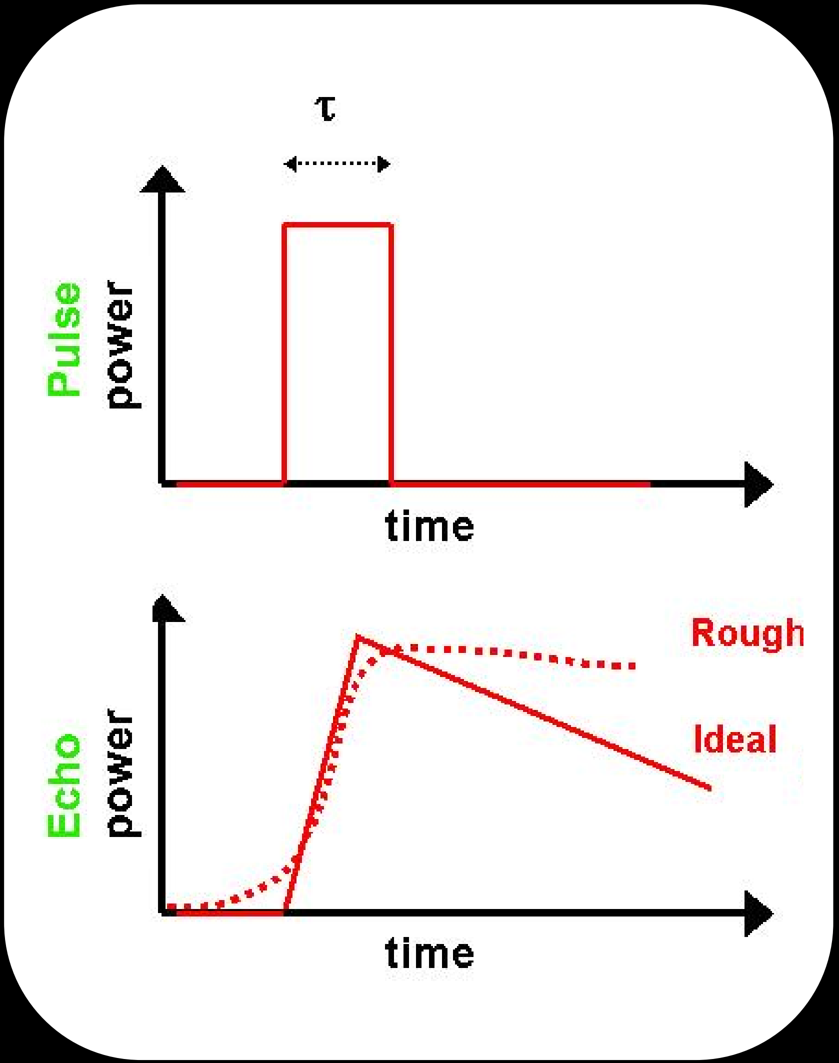


Altimeters transmit a single pulse of electromagnetic radiation, and measure the range and power of the echo from one reflecting point

- Radar altimeters typically transmit at microwave wavelengths, as these are short enough (0.1 to 100 mm) to be easily reflected from Earth surfaces.

- The radar pulse is a burst of electromagnetic radiation of constant power. This provides a characteristic top-hat shaped signal.

- Radar pulses are distorted by interactions with reflecting surfaces. Echo shapes contain useful information as to the surface roughness, e.g. wave height.



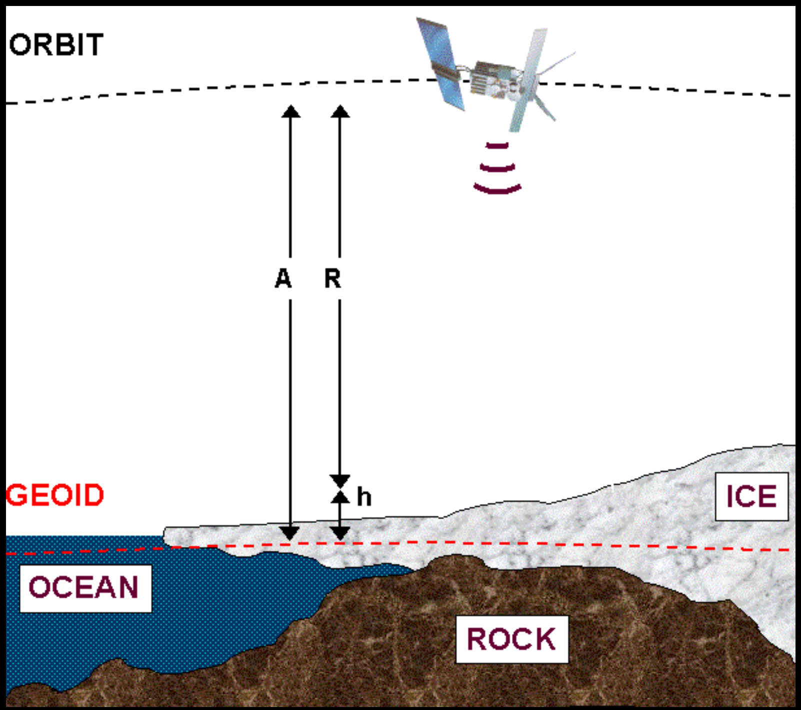
- Satellite altitude is precisely determined relative to the Earth's geoid using gyroscopes to measure the gravity from space.

- The geoid is a hypothetical reference level used to describe a surface close to mean sea level where the strength of gravity is constant. Mountains are above the geoid, and sea floors are below.

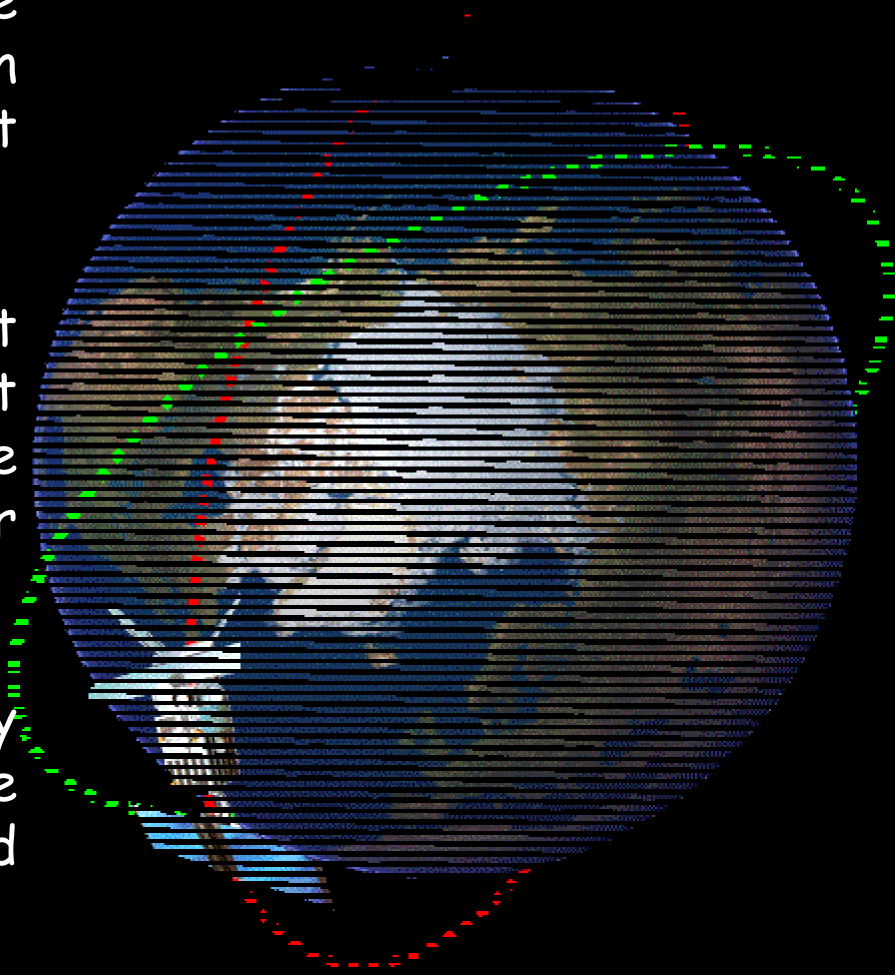
- Satellite altimeters can be used to measure the height of Earth's surface relative to the geoid, for instance to create accurate digital elevation models (DEM's).

- The surface height (h) is simply the altitude (A) minus the radar range (R)

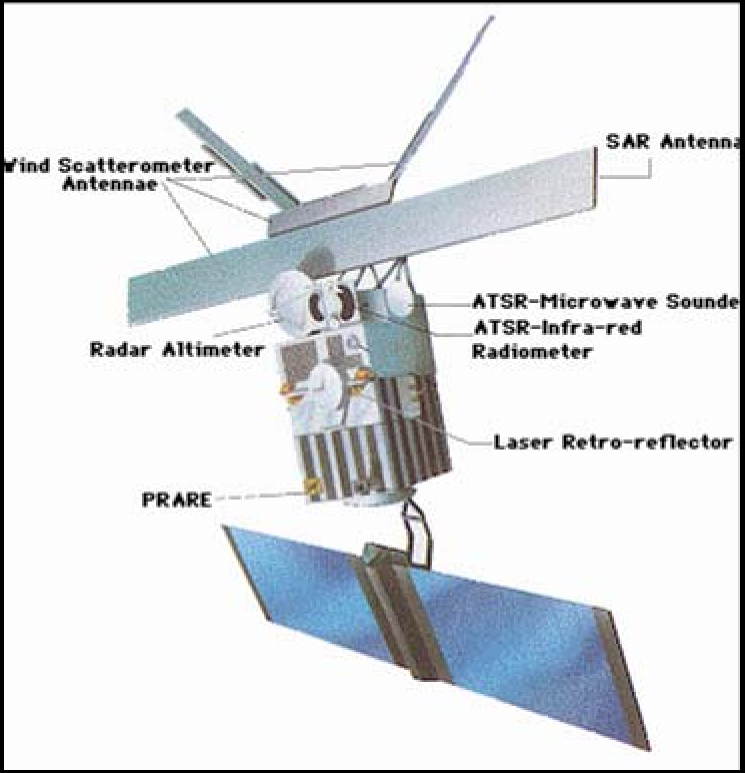
$$h = A - R$$

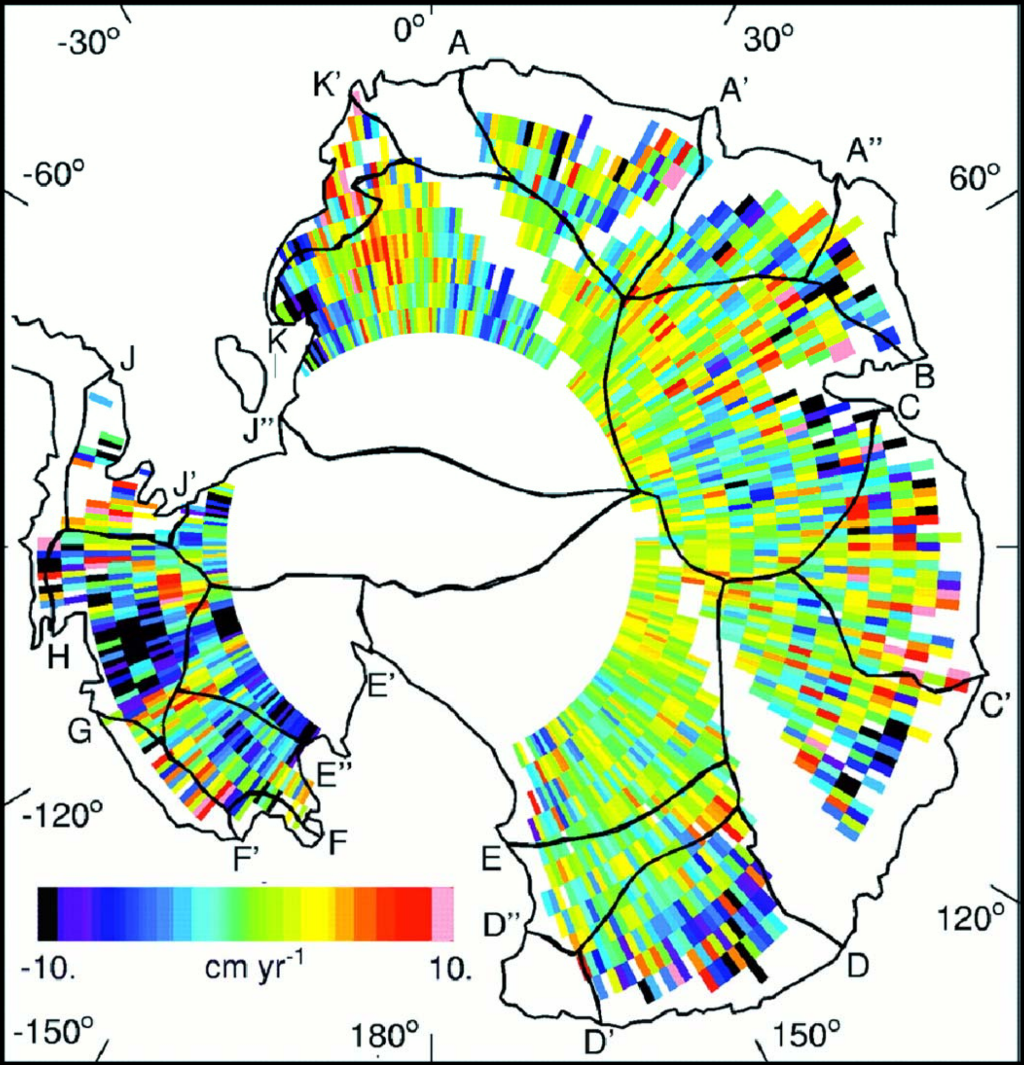


- Satellite radar altimeters are flown in near-polar orbits to repeatedly measure the Earth's surface elevation.
- This allows us to determine surface height changes, such as ocean waves, lava flows, or ice sheet growth and decay.
- Height change is determined at crossing points of the satellite orbit to allow for slight variations in the orbit trajectory, and for greater measurement precision.
- Crossing point locations are closely spaced at high latitudes, where the orbits converge, and widely spaced at the equator.



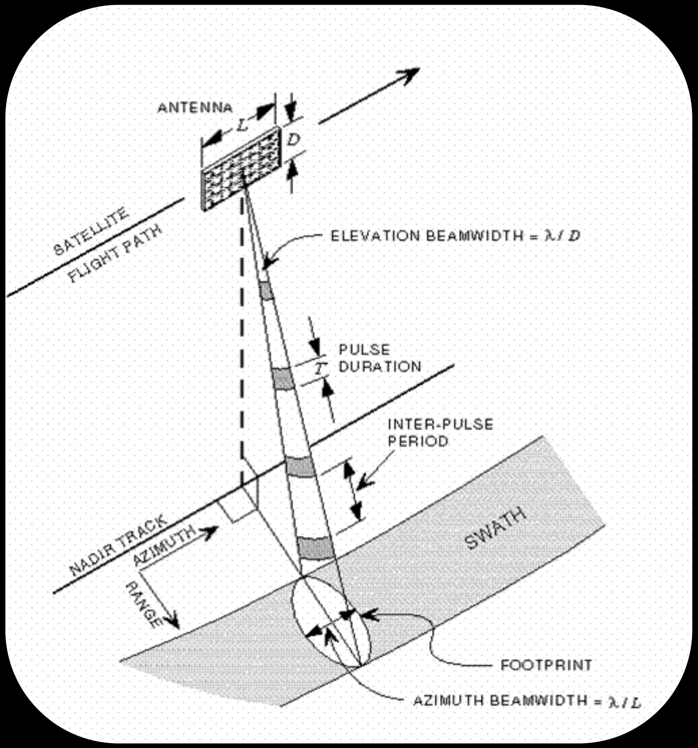
- The European Remote Sensing (ERS-1 and ERS-2) satellites have the same radar altimeter onboard. ERS-1 was launched in 1991 and retired in 2000, ERS-2 was launched in 1995 still operates.
- ERS orbits are inclined at 8° to the pole, fly at 782 km altitude, complete a single Earth revolution in 90 minutes, and principally follow 35 day repeat cycles.
- ERS satellites have provided by far the most comprehensive dataset of ice sheet elevation change.
- This includes $^2/_3$ of the Antarctic ice sheet and the entire Greenland ice sheet, allowing precise estimates of their growth or decay and the resultant contribution to global sea level over the past decade.

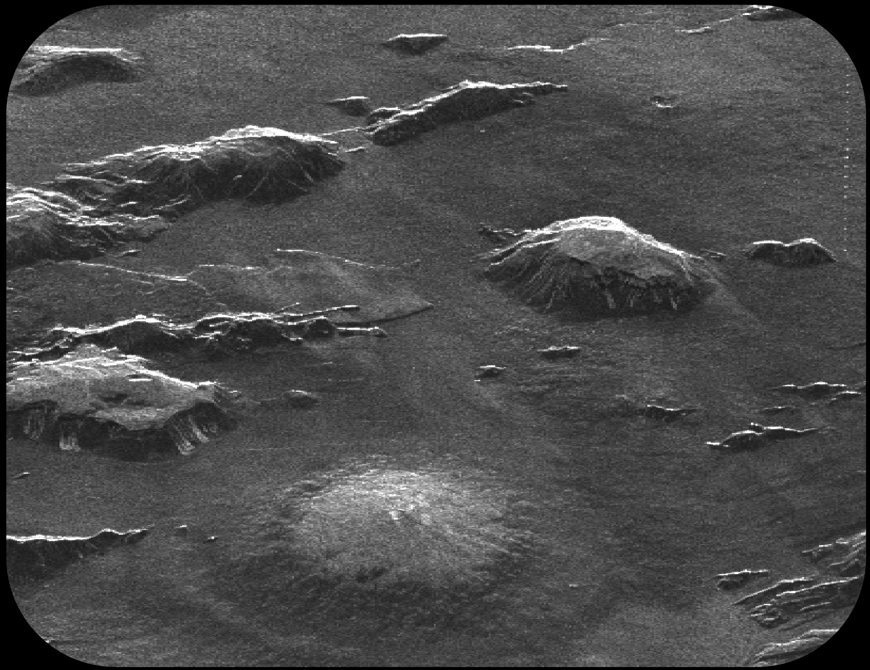




- Wingham et al (1998) measured the volume change of 66% of the Antarctic ice sheet using ERS radar altimetry.
- They calculated the ice sheet was losing 60 ± 76 Gt yr^{-1}.

- Synthetic Aperture Radars transmit fast repetitions (chirps) of microwave pulses across a wide ranging swath.
- As the satellite travels forwards, data are collected both along and across the ground track.





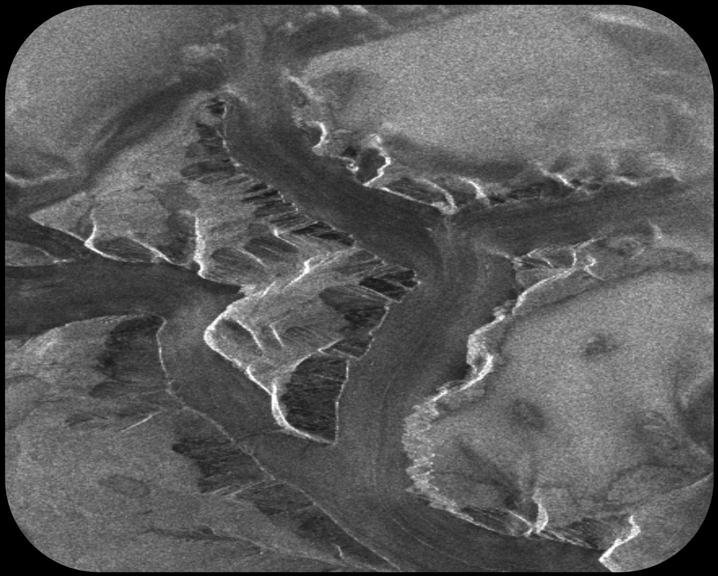
- The power of backscattered echoes reflects the degree of radar wave penetration of the Earth's surface. SAR images are formed from the backscattered power.

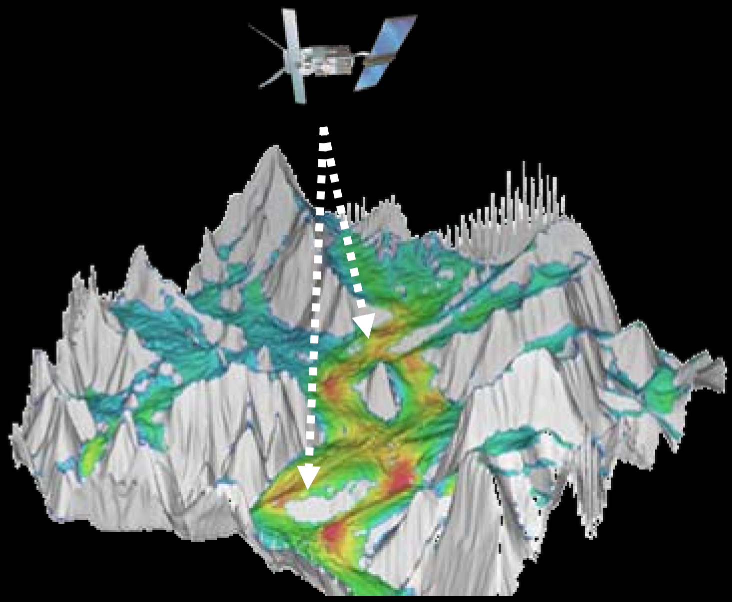
- SAR uses an active source of illumination, and so images can be obtained at night.

- SAR operates at microwave frequencies, and so images can be recorded through clouds.

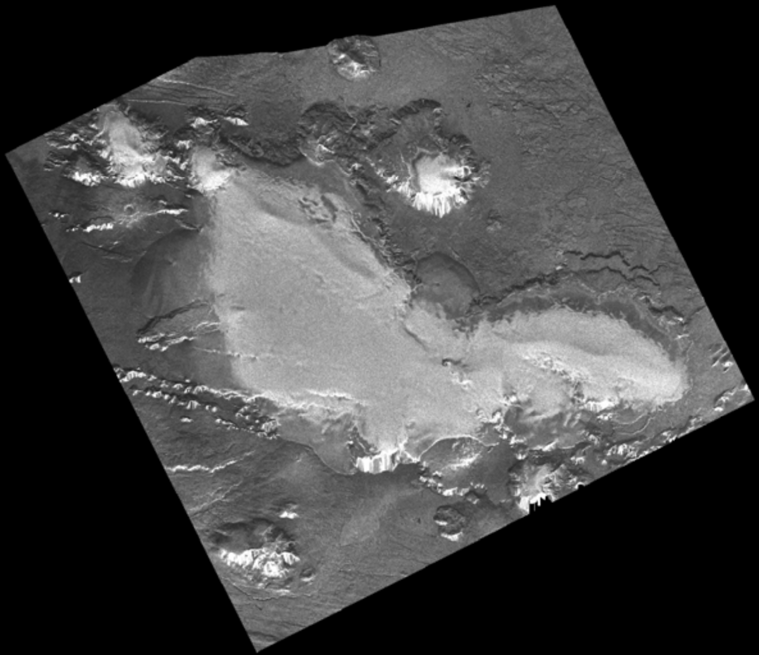
- SAR instruments look sideways, and so raw images appear skewed.

- Side-looking SAR sensors cannot view areas of steeply sloping terrain (> 24°) that fall in the radar beam shadow.



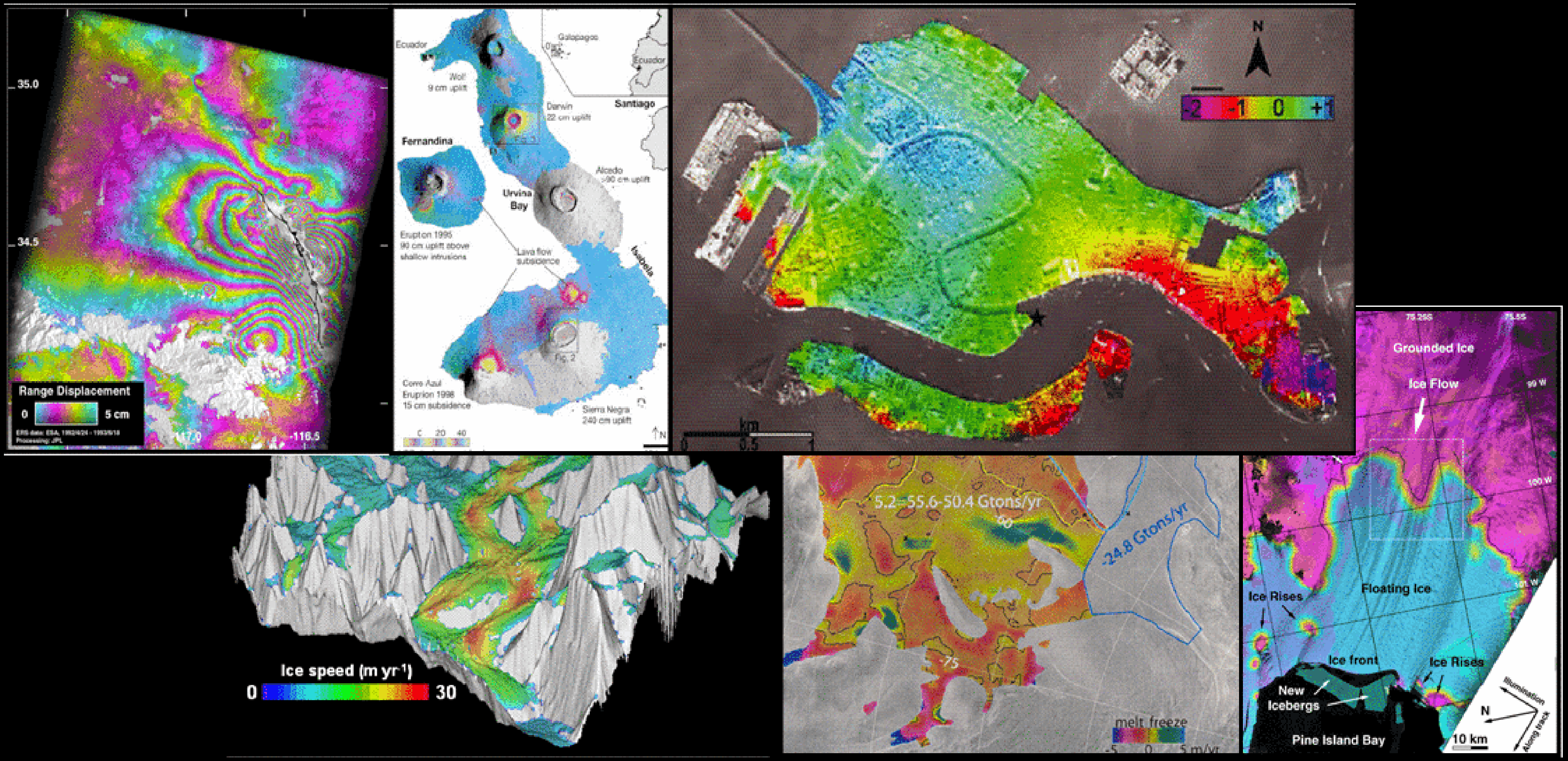


- All radar echoes suffer from a signal distortion called speckle. This arises because the echo is in reality a complicated (incoherent) sum of scattering across the ground pixel. The impact of speckle is to make radar images appear noisy.



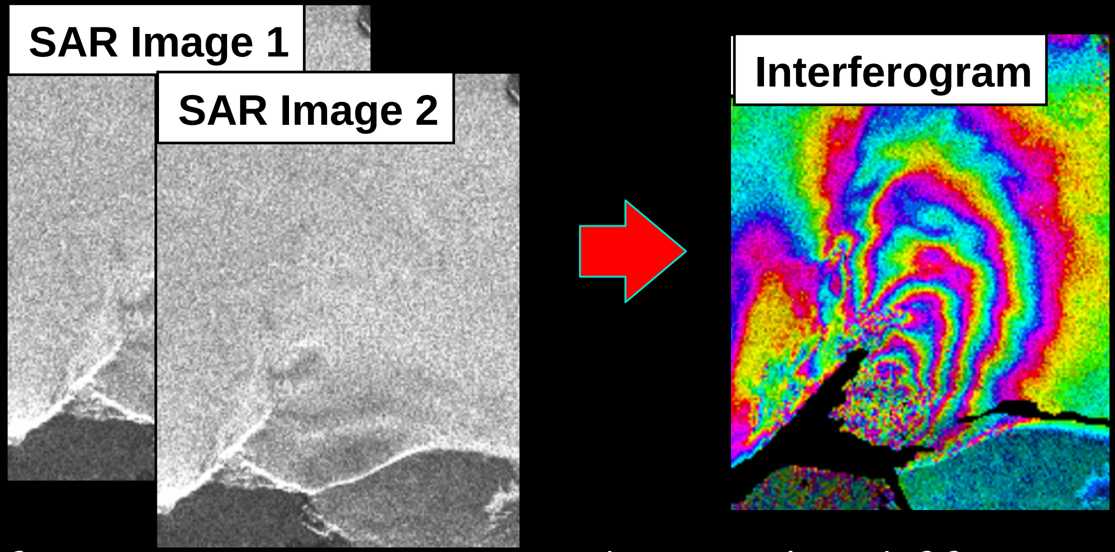
- Surfaces that are highly reflective appear bright in radar images (e.g. ice) and surfaces that transmit radio frequencies appear dark (e.g. fresh snow).

- SAR interferometry (InSAR) is a technique for measuring minute movements of the Earth's surface from space.



- Applications of InSAR include recording earthquakes, volcanic uplift, subsidence ice motion, ice melting and ocean tides.

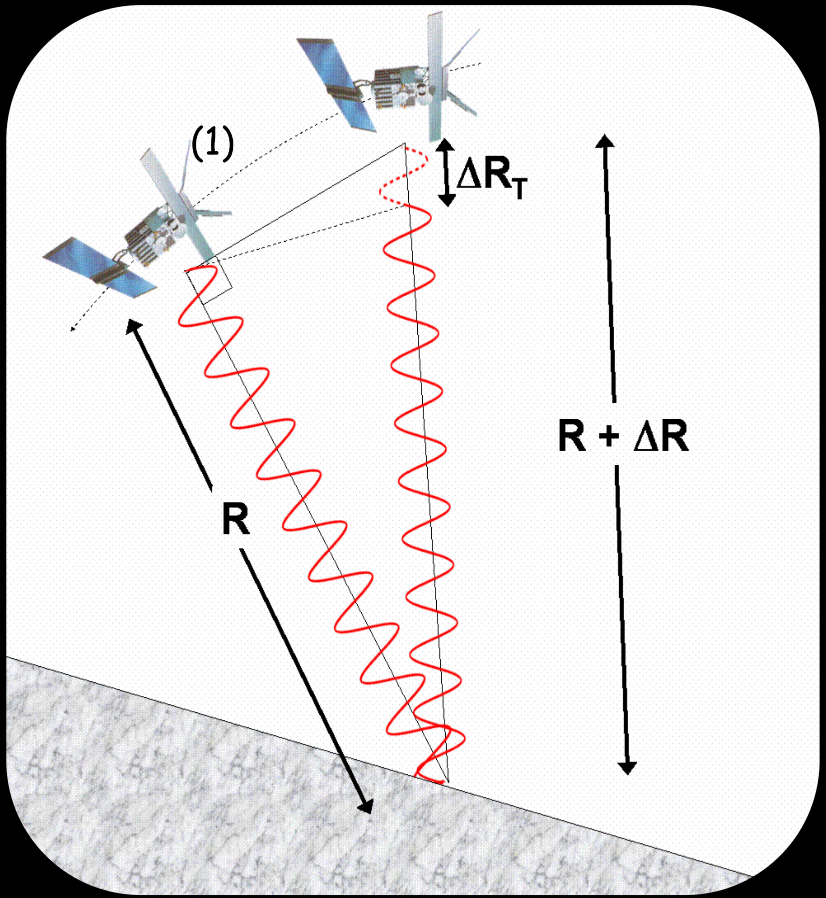
- The principal of InSAR is that two SAR images of the same area taken at separate times can be combined to produce an interference pattern (interferogram) related to surface movement and elevation during the time interval.

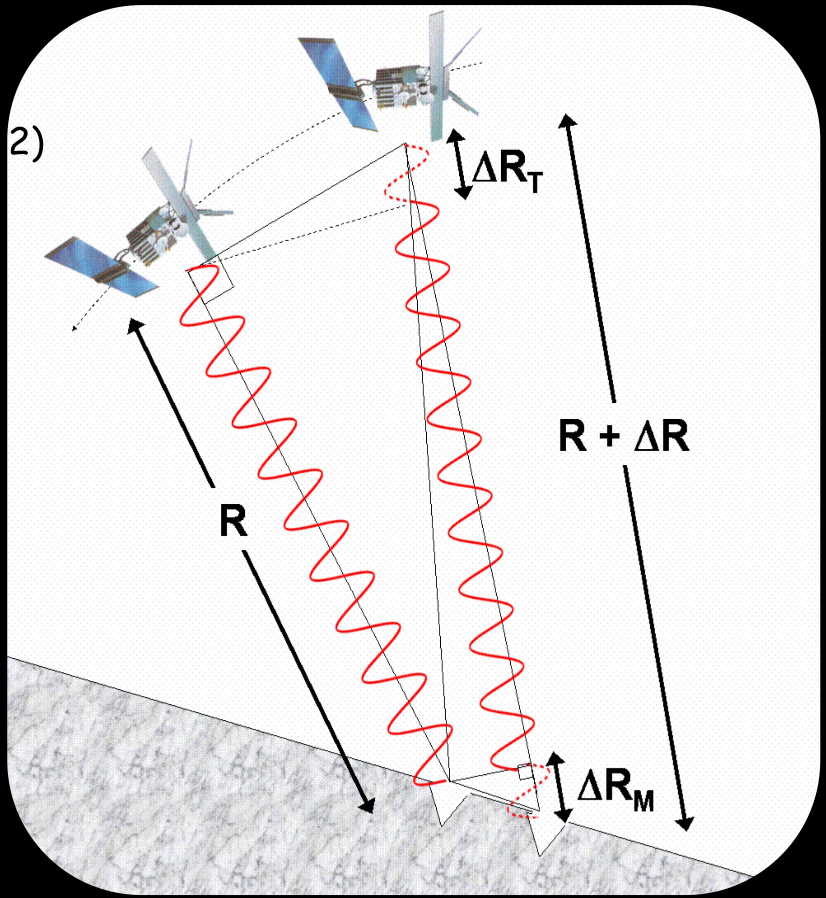


- The interference pattern arises due to the difference in radar range to each reflecting point between images.

- This difference is expressed as a phase angle (0 to 360°), equal to the fraction of a complete radar wavelength.

- The range difference (ΔR) can arise in two ways:
  (1) The satellite does not return to the same location on repeat
  (2) The surface can move during the intervening period.





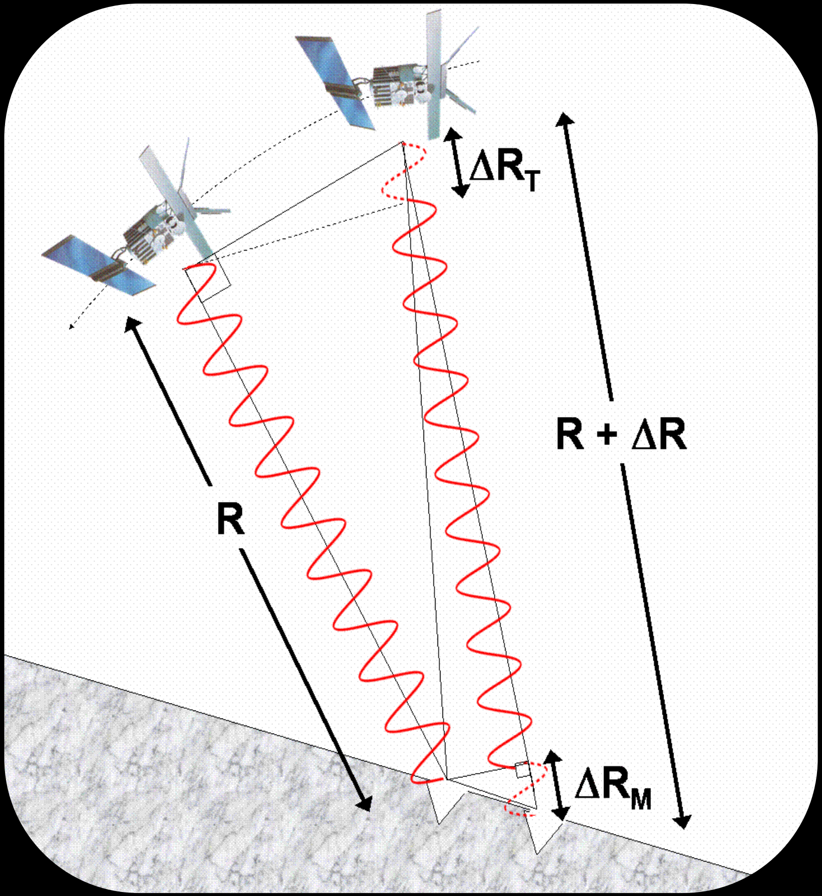
- The range difference (ΔR) is related to the interferogram phase (ϕ) using the interferogram equation:

$$\Delta R = \frac{1}{2} N\lambda = \frac{1}{2} \times \frac{\phi}{2\pi} \times \lambda = \frac{\lambda\phi}{4\pi}$$

where N is the number of wavelengths within the range difference and λ is the radar wavelength (5.6 cm for ERS).

- ΔR can then be partitioned into components due to surface topography (ΔR_T) and motion (ΔR_M) :

$$\Delta R = \Delta R_T + \Delta R_M = \frac{\lambda}{4\pi}(\phi_T + \phi_M)$$



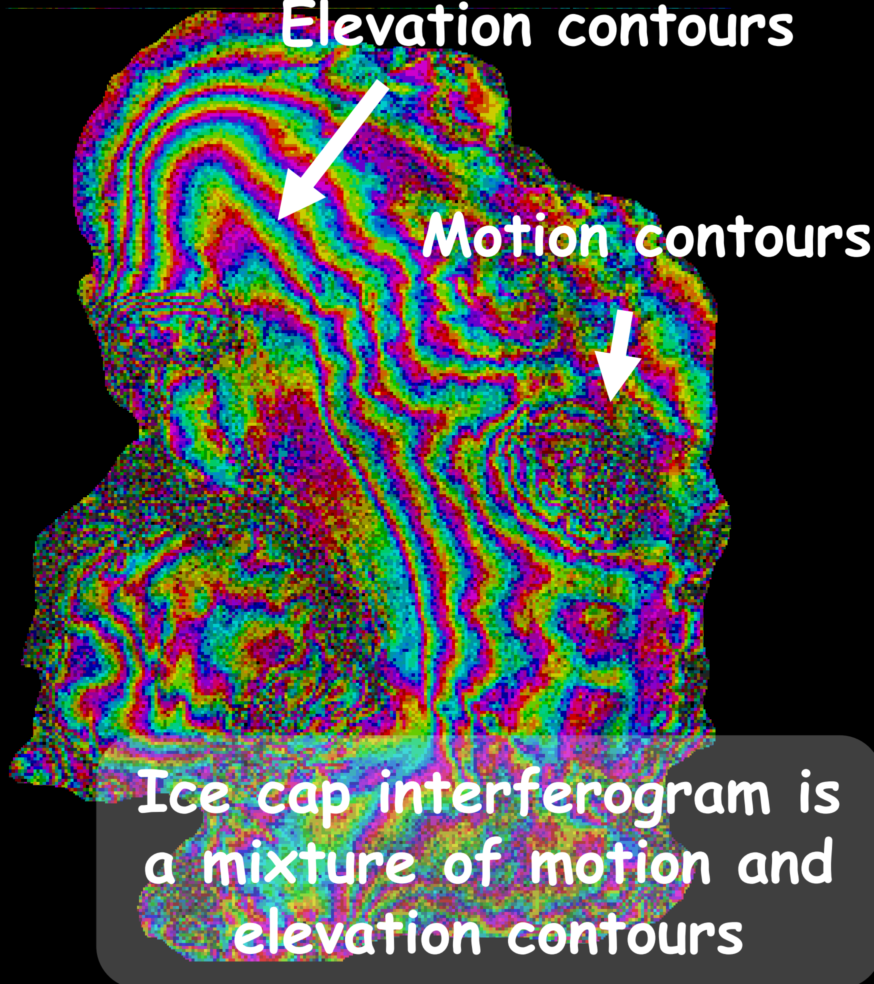
- The range difference (ΔR) is related to the interferogram phase (ϕ) using the interferogram equation:

$$\Delta R = \frac{1}{2} N\lambda = \frac{1}{2} \times \frac{\phi}{2\pi} \times \lambda = \frac{\lambda\phi}{4\pi}$$

where N is the number of wavelengths within the range difference and λ is the radar wavelength (5.6 cm for ERS).

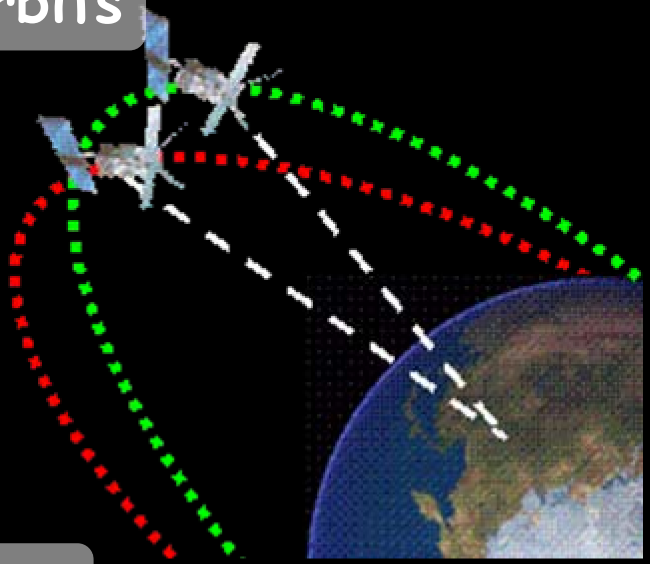
- ΔR can then be partitioned into components due to surface topography (ΔR_T) and motion (ΔR_M) :

$$\Delta R = \Delta R_T + \Delta R_M = \frac{\lambda}{4\pi}(\phi_T + \phi_M)$$

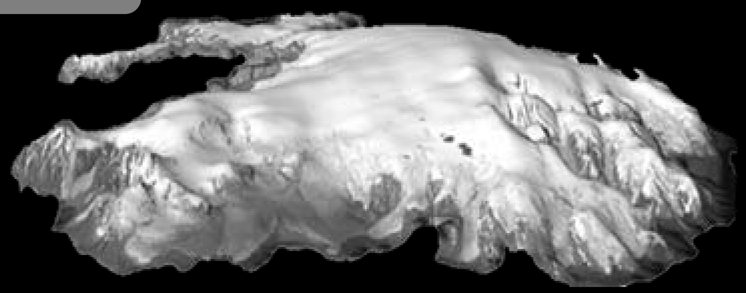


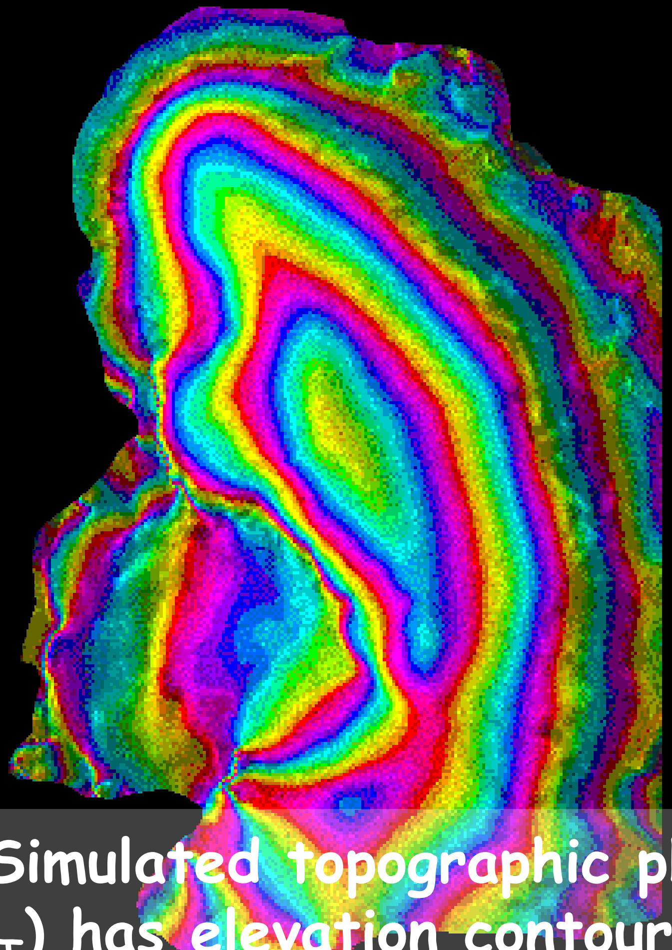
- The topographic phase ϕ_T can be calculated from the satellite orbits and a digital elevation model (DEM) of the surface.

Orbits



DEM

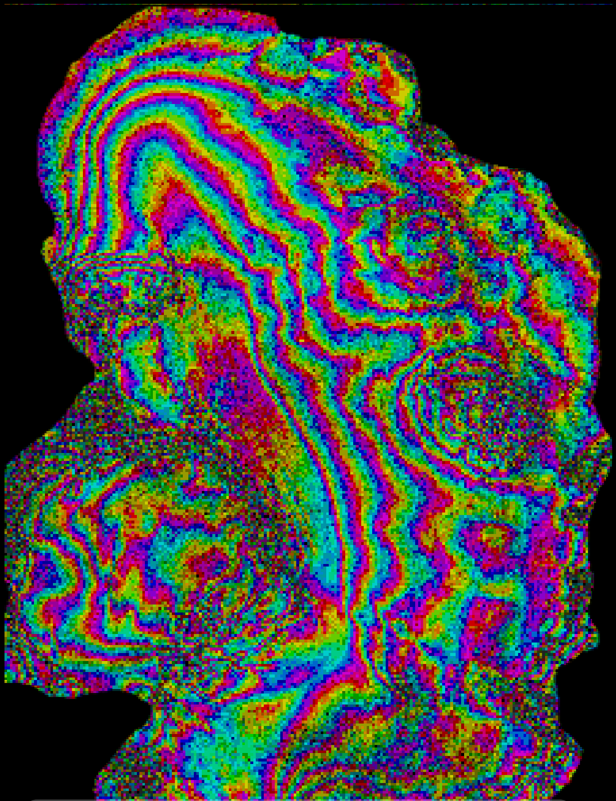




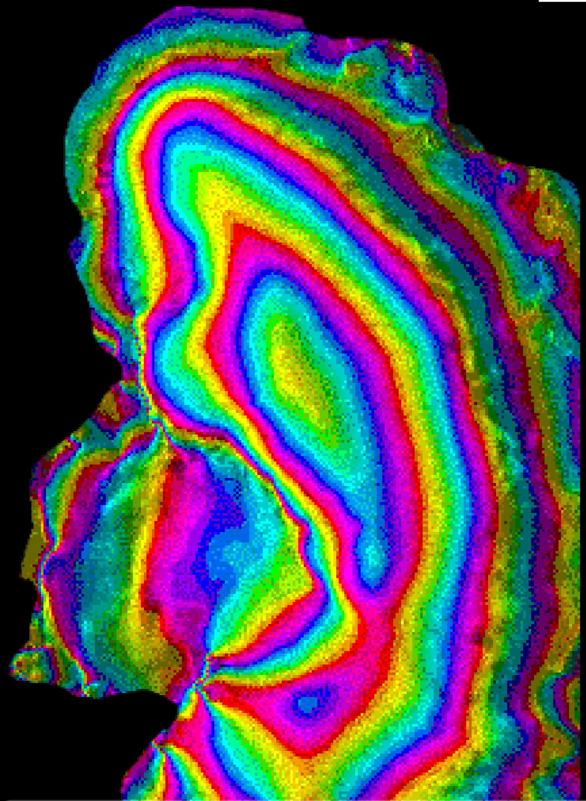
Simulated topographic phase (ϕ_T) has elevation contours only

- Range due to surface motion is calculated by subtracting simulated topographic phase from an interferogram:

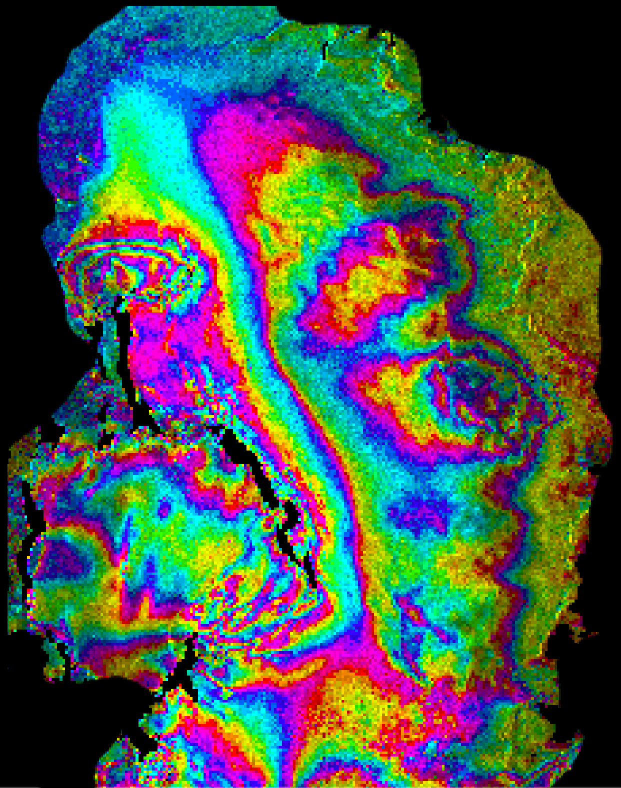
$$\Delta R_M = \frac{\lambda}{4\pi}\phi_M = \frac{\lambda}{4\pi}(\phi - \phi_T)$$



Interferogram (ϕ)

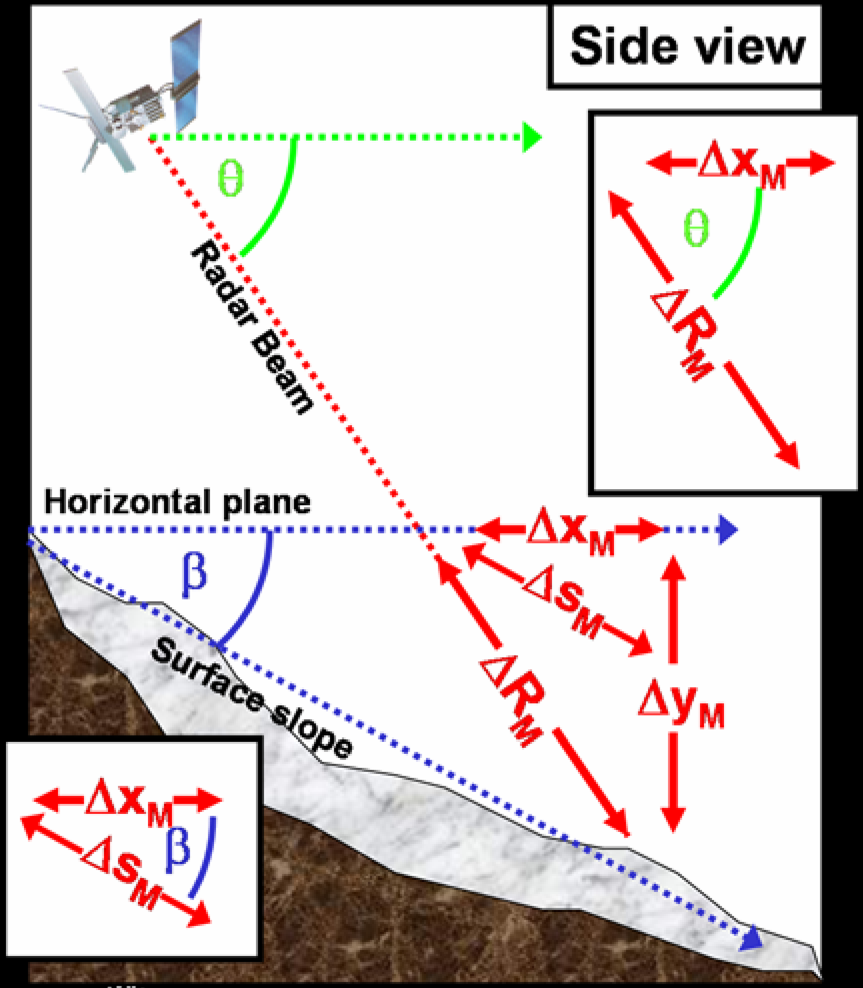


Topographic phase (ϕ_T)



Motion phase (ϕ_M)

- The range difference due to motion (ΔR_M) can be converted into horizontal motion using the surface slope (β) using trigonometry:



The horizontal component of ΔR_M is

$$\Delta x_M = \Delta R_M \cos\theta$$

The surface plane component of ΔR_M is

$$\Delta s_M = \frac{\Delta x_M}{\cos\beta}$$

The surface plane velocity is

$$v_{SURF} = \frac{\text{distance}}{\text{time}} = \frac{\Delta s_M}{\Delta T}$$

and so

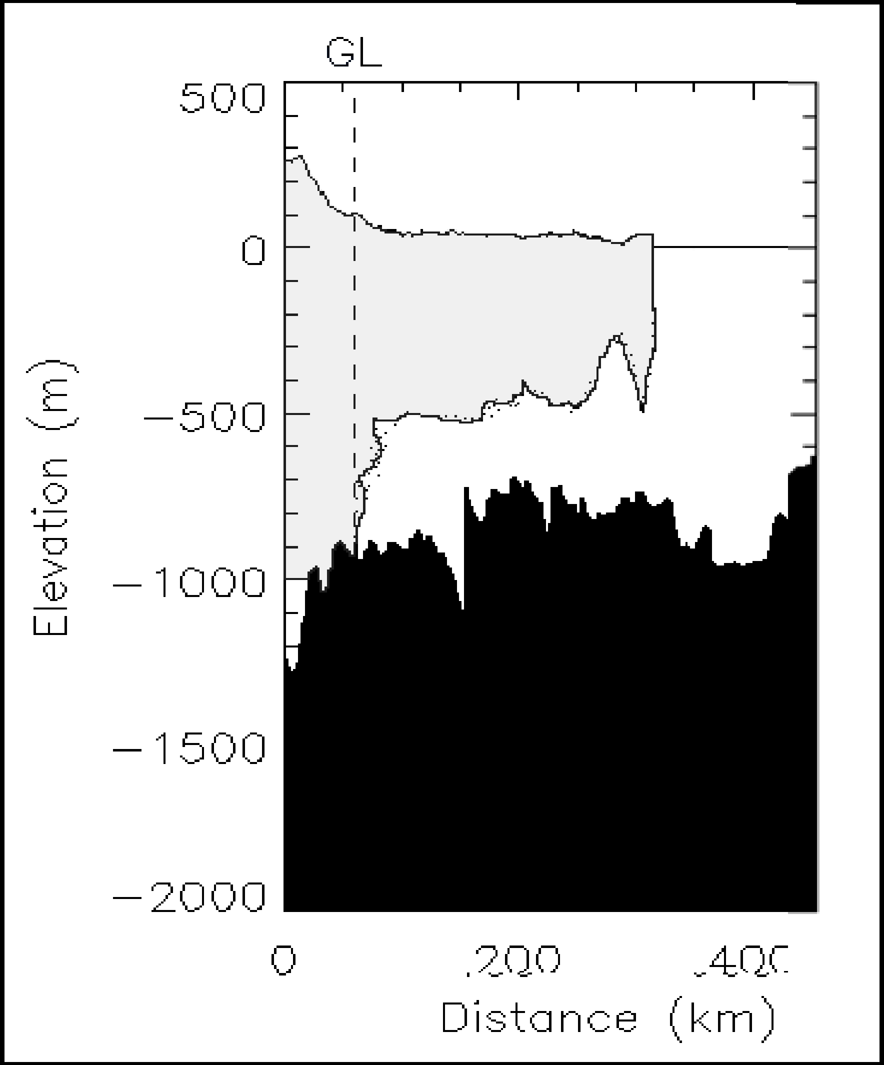
$$v_{SURF} = \frac{\lambda(\phi - \phi_T)\cos\theta}{4\pi\Delta T\cos\beta}$$

- A single interferogram measures surface motion in one direction only (scalar speed). The SAR look direction is perpendicular to the satellite flight path.

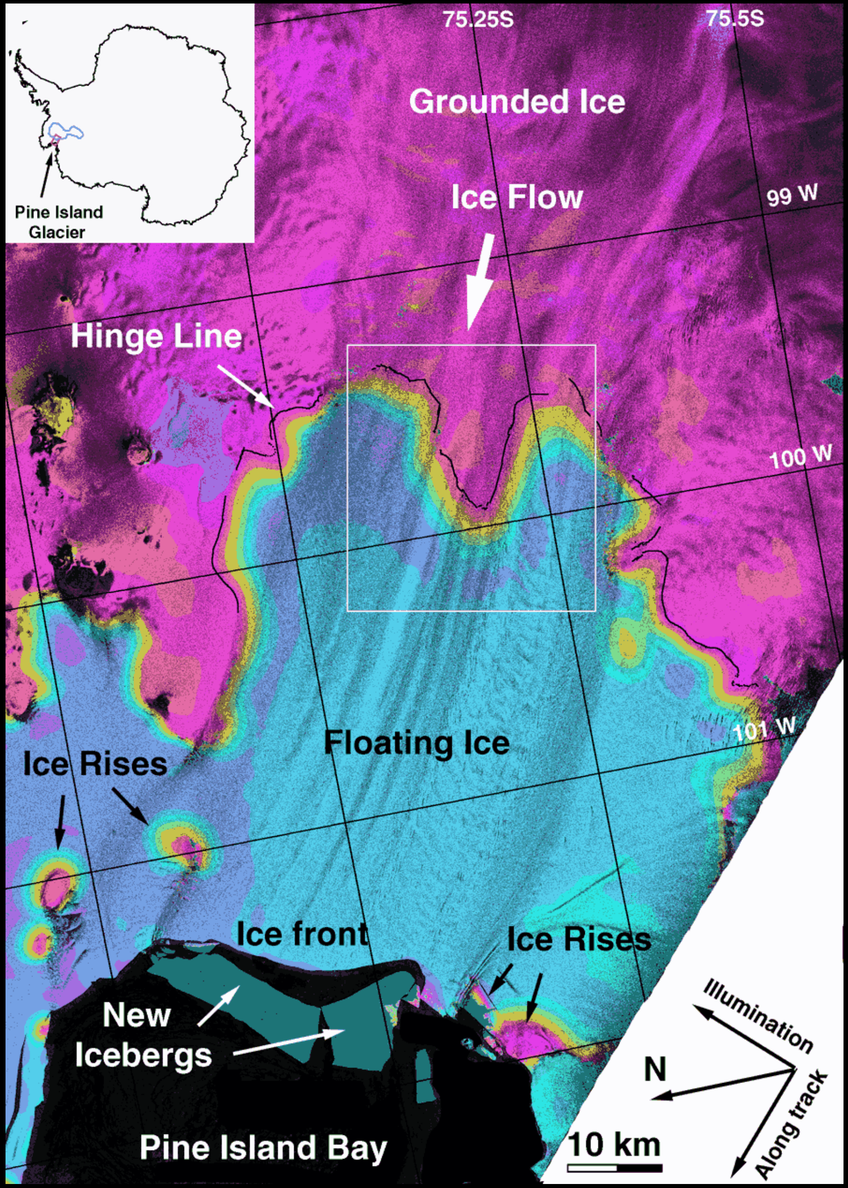
- To calculate ice flow in three dimensions (vector velocity) requires knowledge of the flow direction. A good approximation is that ice flows parallel, and in the direction of the maximum surface:

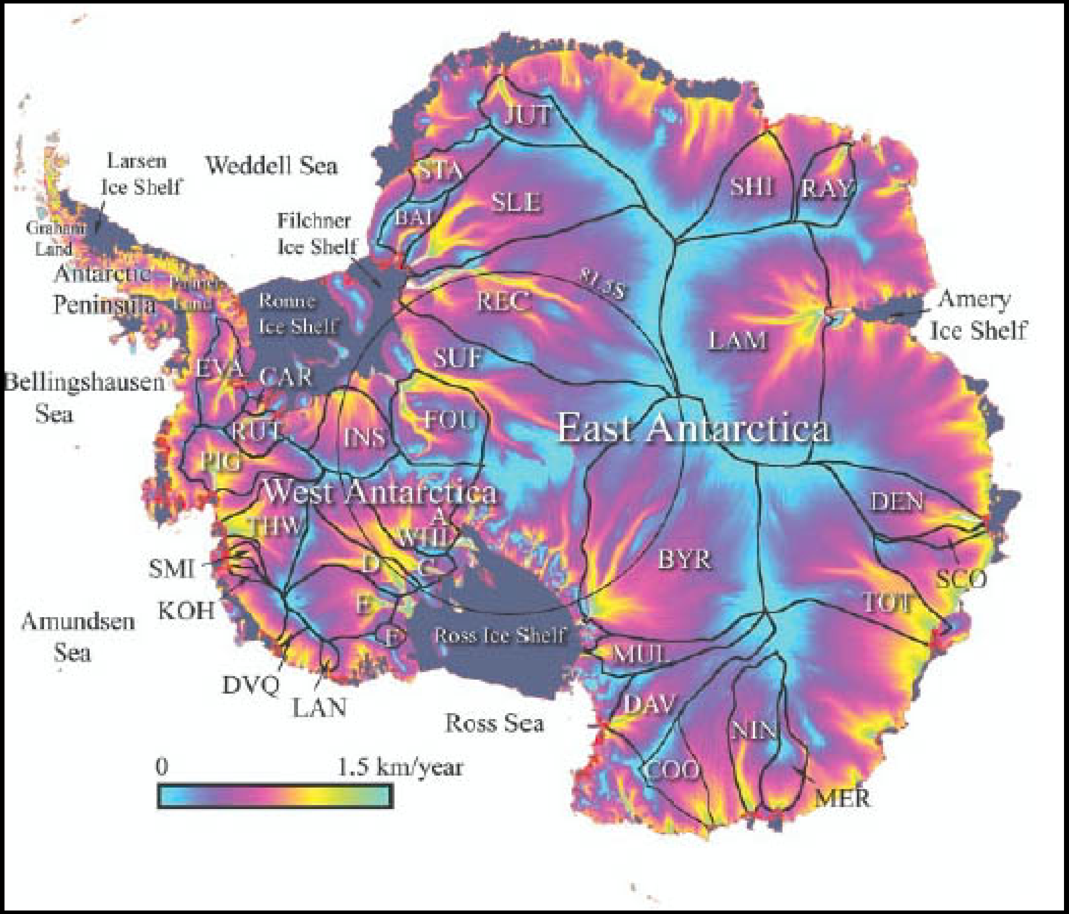
$$v_{SURF} = \frac{v_{HORIZ}}{\cos\alpha} = \frac{\lambda(\phi - \phi_T)\cos\theta}{4\pi\Delta T\cos\beta\cos\alpha}$$

- An advanced application of InSAR is to measure the location of ice sheet grounding lines.
- Seaward of the grounding line glacier floating sections flex with the raising and lowering ocean tide.



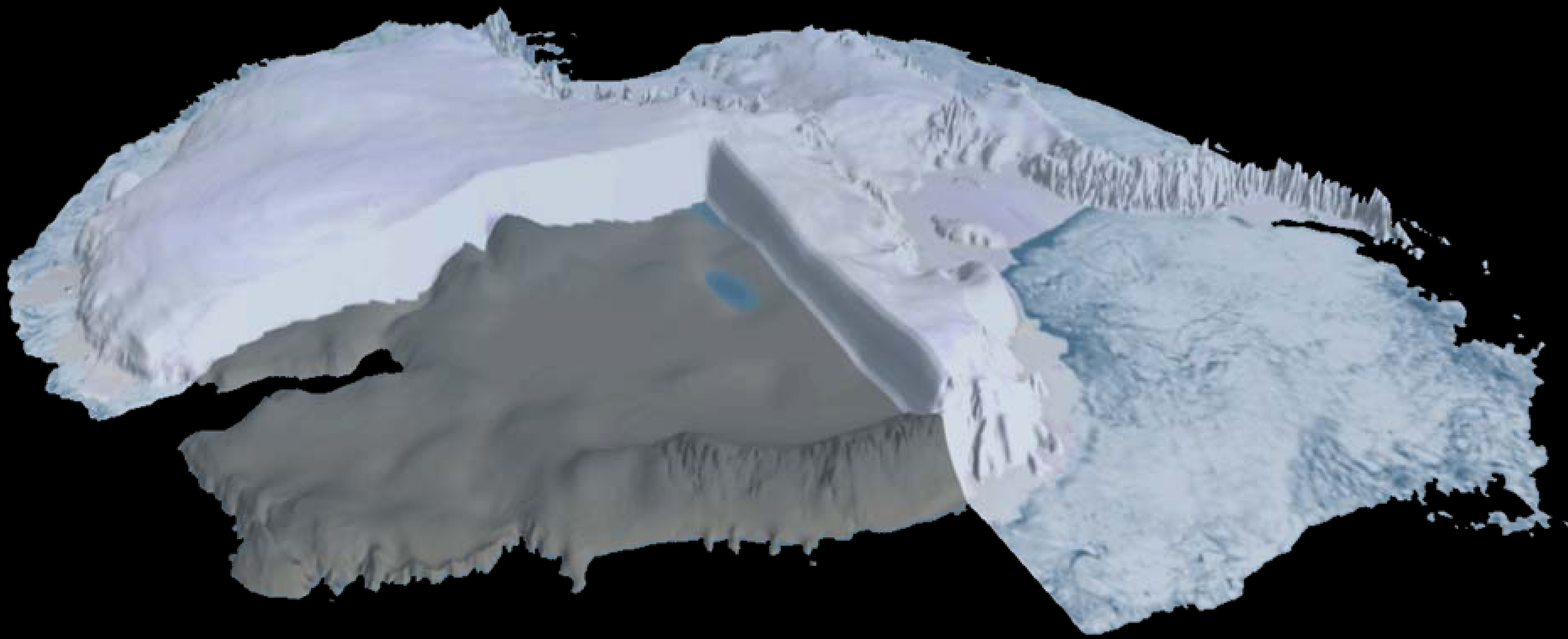
- Differencing four interferograms eliminates ice motion and fixed topography to reveal tidal motion.
- The tidal flexure hinge line (close to the grounding line) is clearly visible in quadruple-difference interferograms.
- The major application of this technique is to monitor migration of glacier grounding lines over time, to determine their retreat or advance.



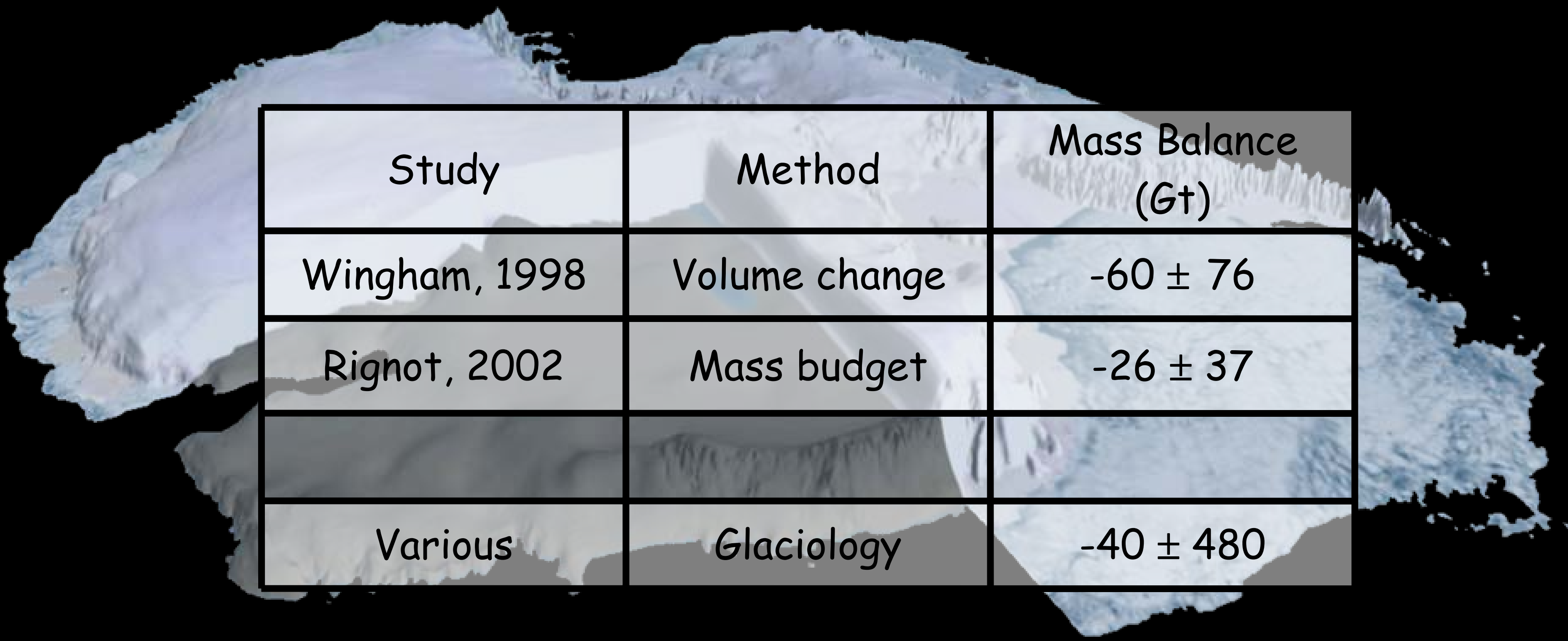


- Rignot et al (2002) computed the mass budget of 60% of the Antarctic ice sheet using InSAR.
- They calculated the ice sheet was losing 26 ± 37 Gt yr^{-1}.

- Estimates of Antarctic mass balance



- Estimates of Antarctic mass balance



Study	Method	Mass Balance (Gt)
Wingham, 1998	Volume change	-60 ± 76
Rignot, 2002	Mass budget	-26 ± 37
Various	Glaciology	-40 ± 480

- Satellite RADAR has brought about a factor 10 improvement in the precision of the Antarctic ice sheet sea level contribution