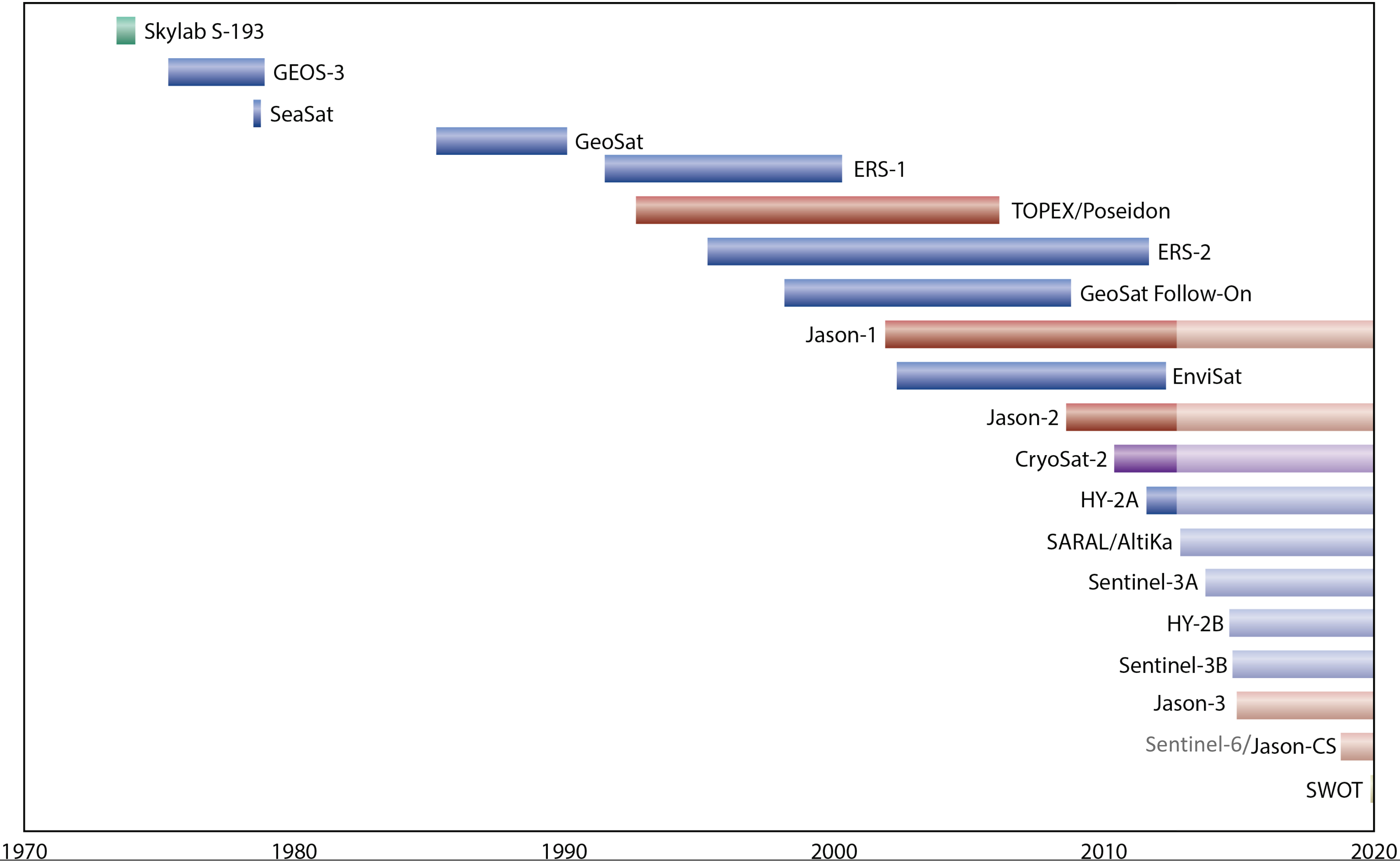
Altimetry: Overview on LR, HR (SAR), SARin, and RDSAR

Mònica Roca and Richard Francis

isardSAT®

Research and services provider enterprise in the Earth Observation Field isardSAT

Altimetry Missions 1970–2020

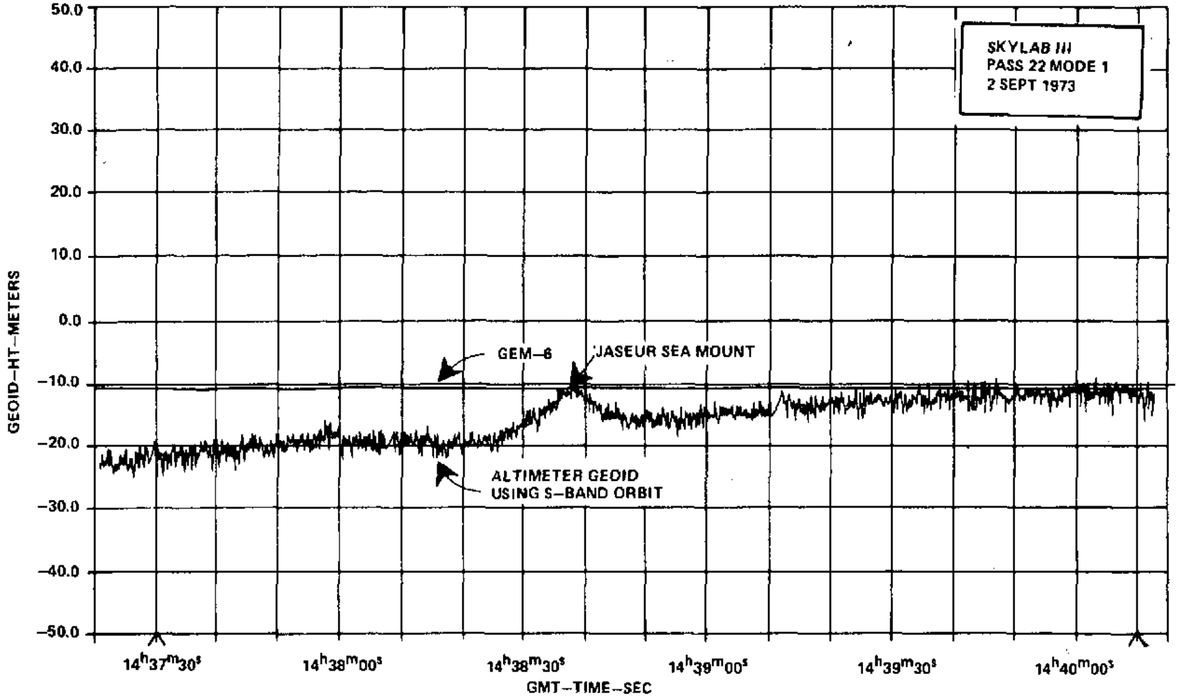


Why measure altitude from space?

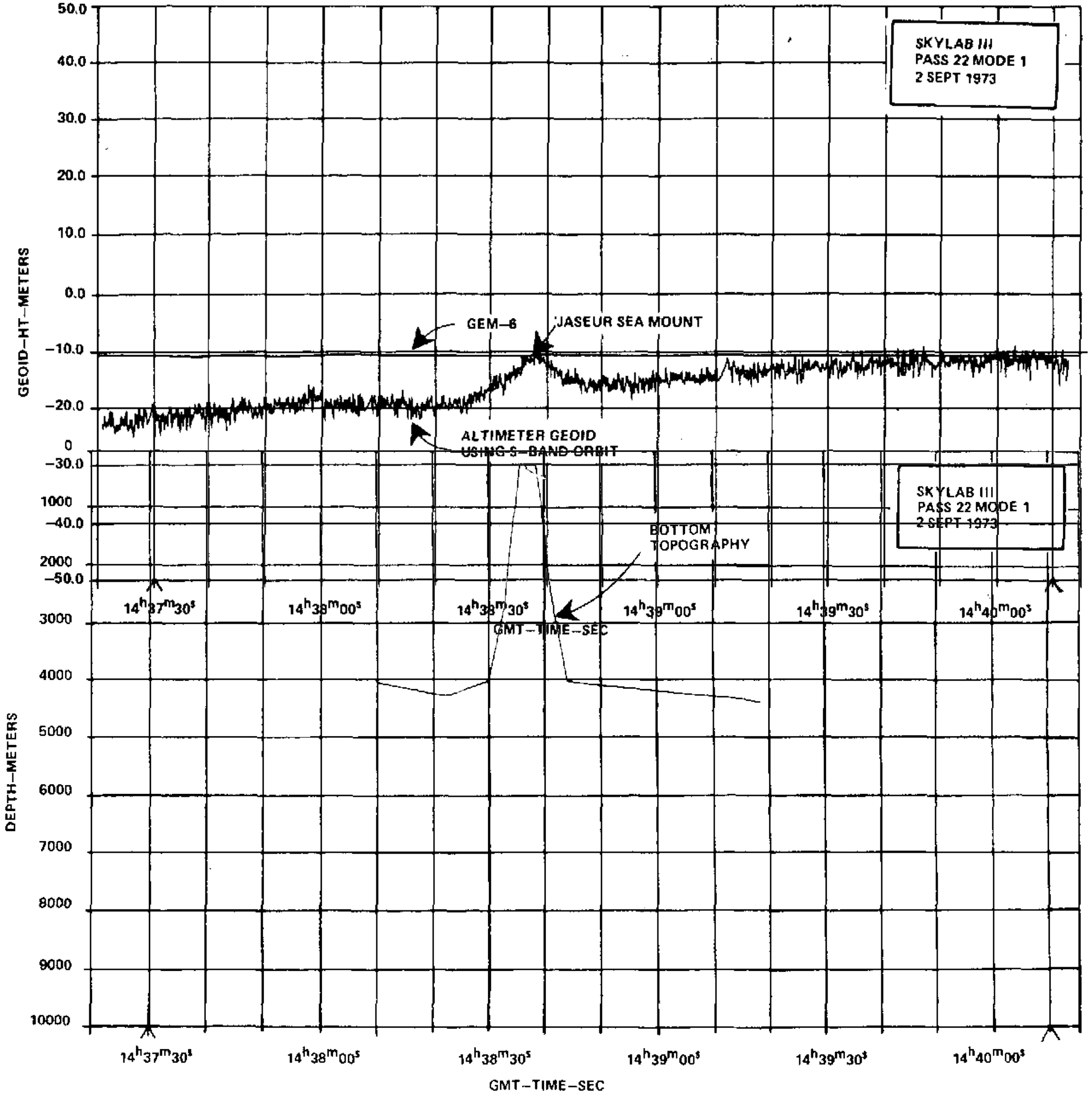
Ocean surface height

- Altimetry first formulated at Williamstown Conference (1969)
- Need was to make measurements over ocean:
  - To measure gravitational geopotential
  - To measure mean sea-level

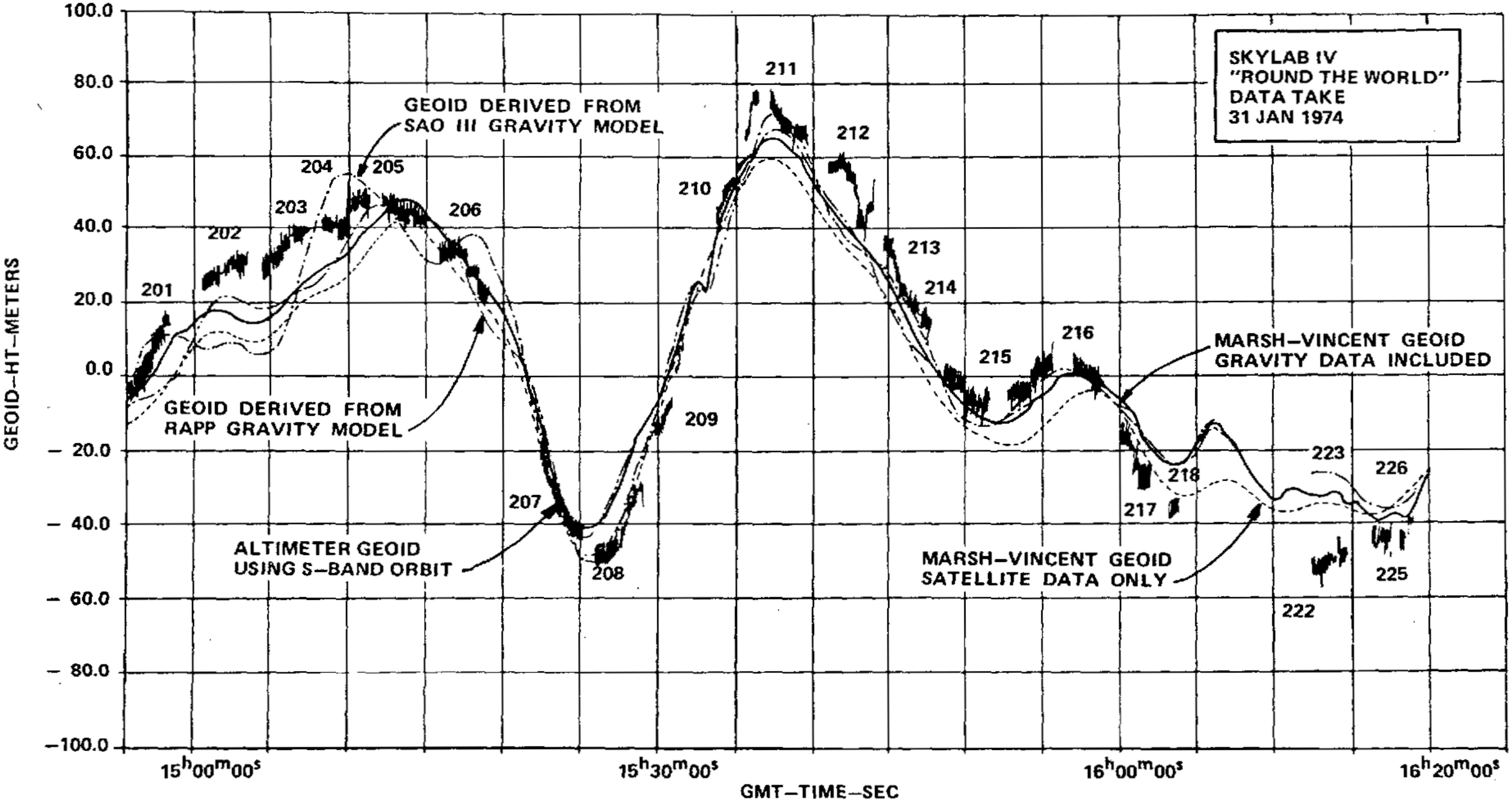
Seamount detected by Skylab S-193



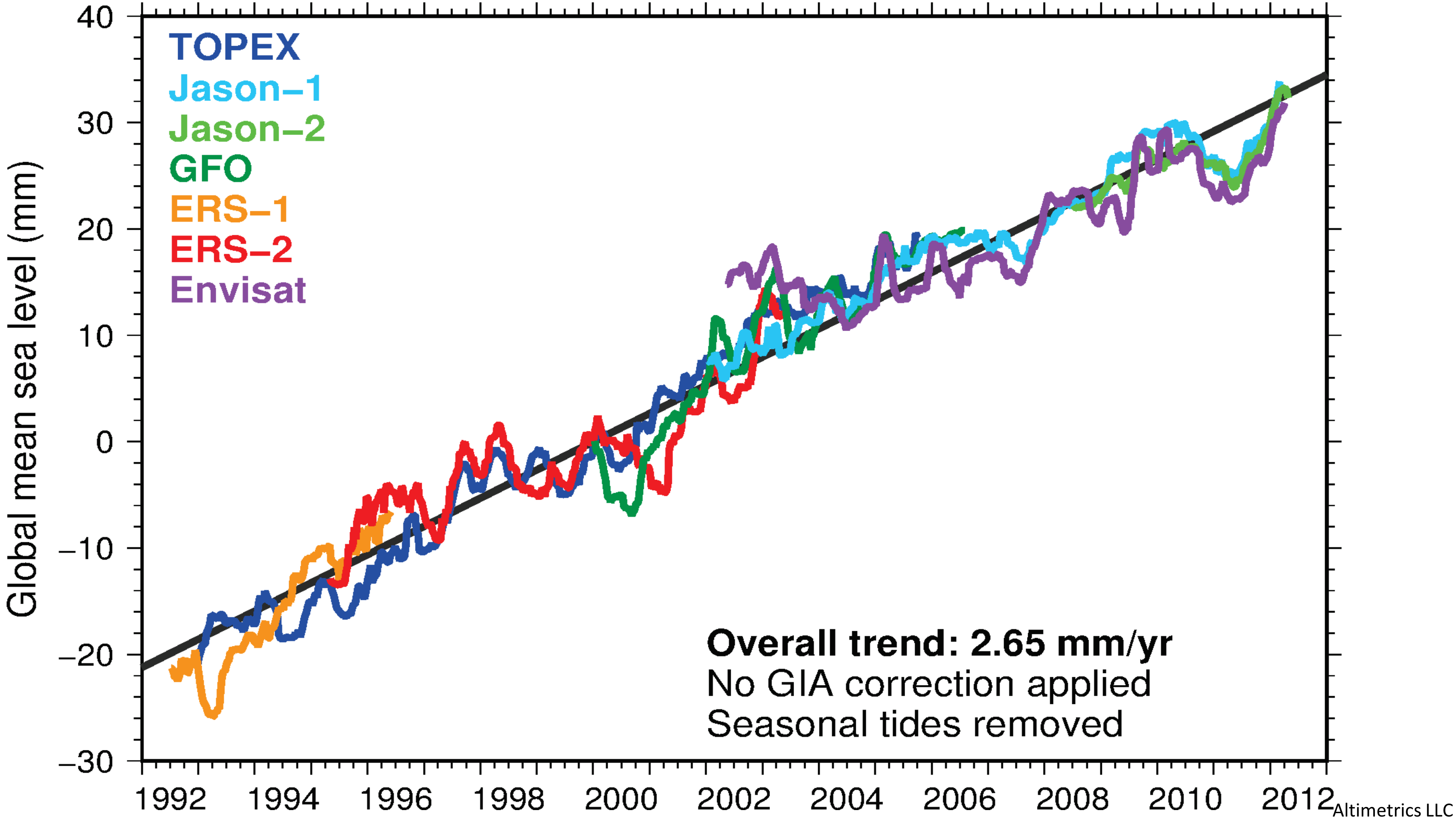
Seamount detected by Skylab S-193

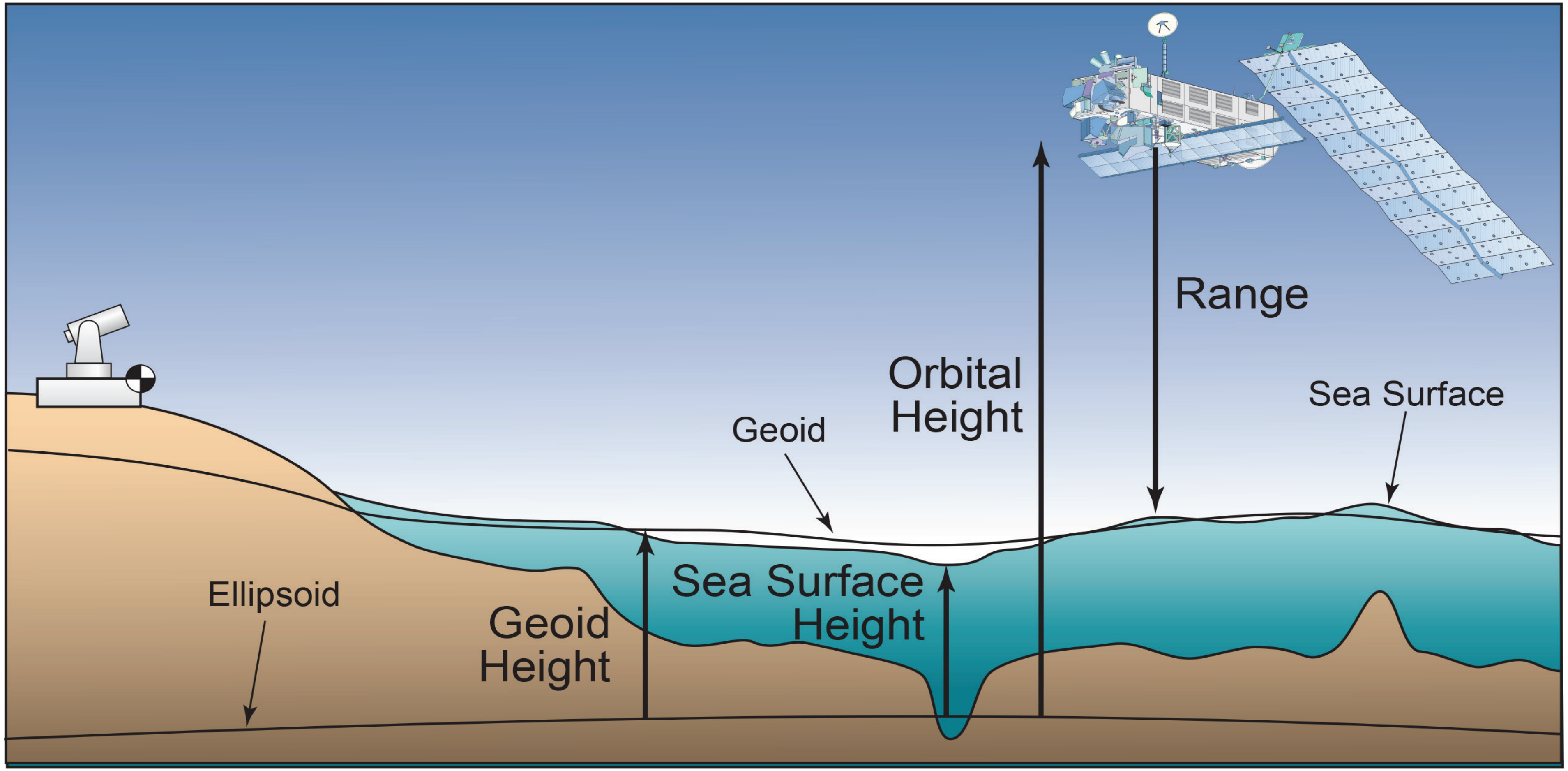


Round the world with Skylab S-193



Sea Level Rise




Range
Orbital
Height
Sea Surface
Geoid
Sea Surface
Height
Ellipsoid
Geoid
Height

How accurate do we need?

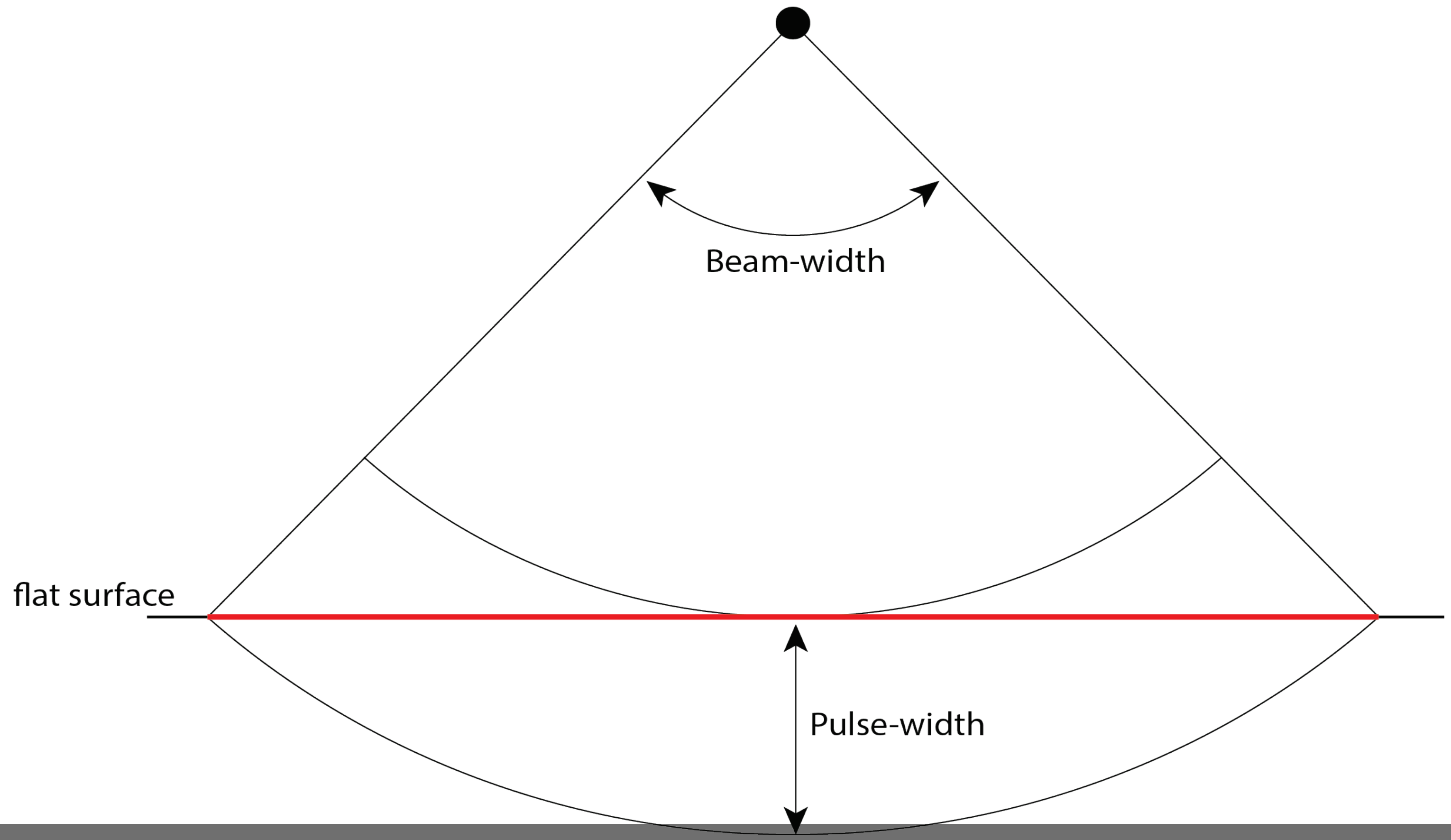
- Williamstown Conference (1969) identified 10 cm as requirement
- Skylab S-193 (1972-74) height noise ~1 m
- Gravitational features in the sea surface visible, but no ocean circulation
- More accuracy needed!

How it works

Geometrical Considerations (1)

- Beam-width limited geometry (for a flat surface):
  - all surface within beam illuminated simultaneously
  - stringent pointing: pointing errors directly affect footprint location and echo shape
  - narrow antenna beam
  - full echo
  - the laser case

Geometrical Considerations (1)

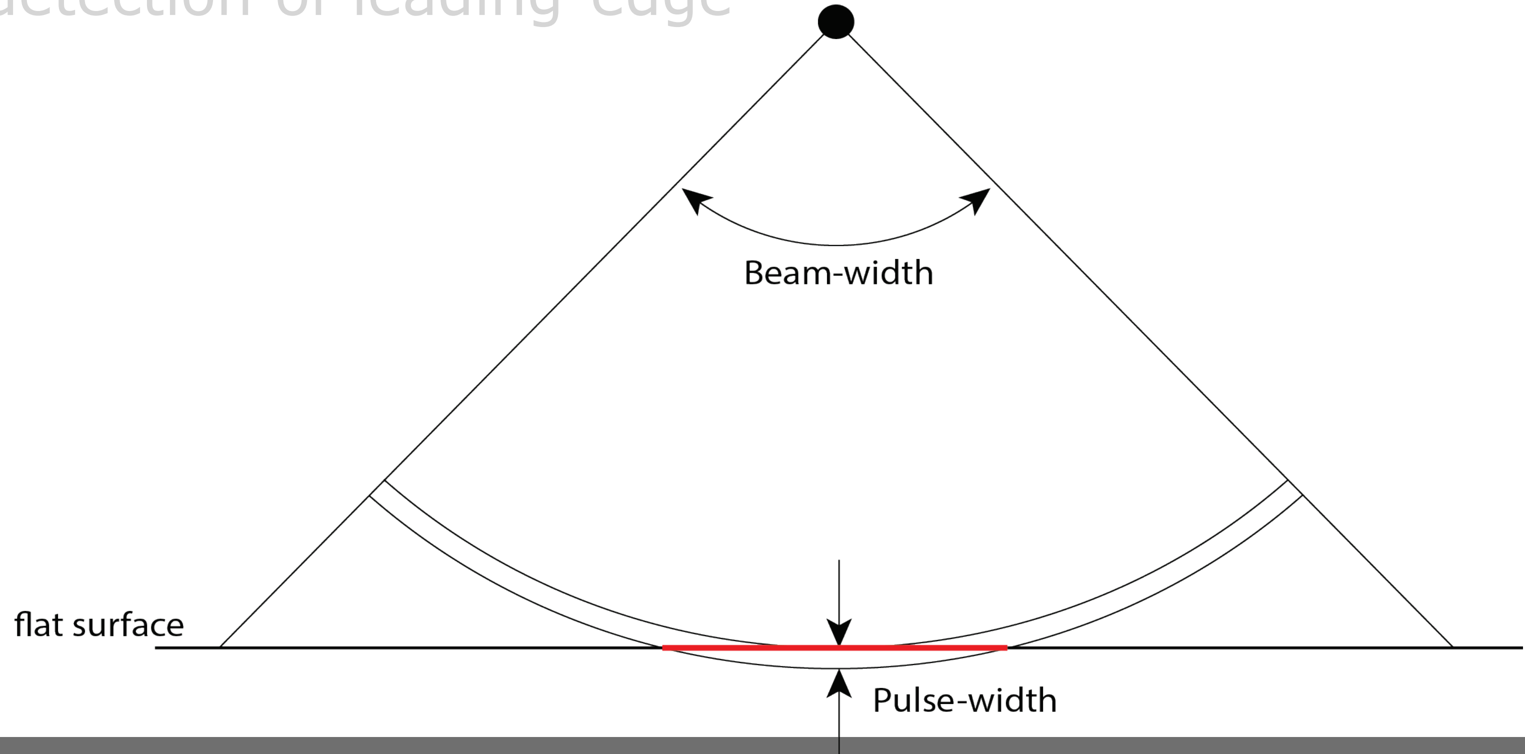


Geometrical Considerations (2)

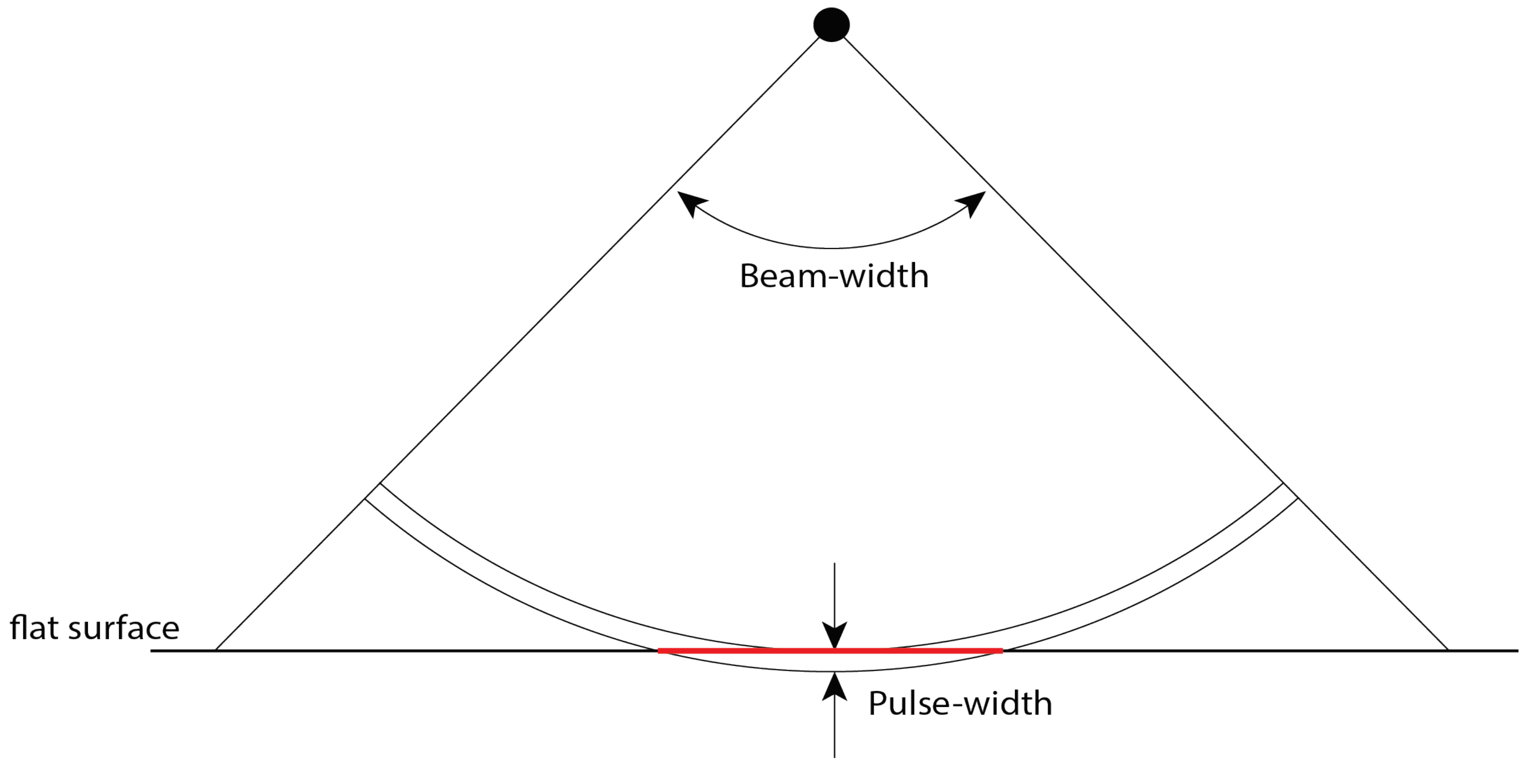
- Pulse-width limited geometry (for a flat surface):
  - "wide" antenna beam: illuminated surface defined by pulse-width
  - pointing errors affect echo shape but not location
  - sensitive to surface geometry
  - detection of leading-edge

Geometrical Considerations (2)

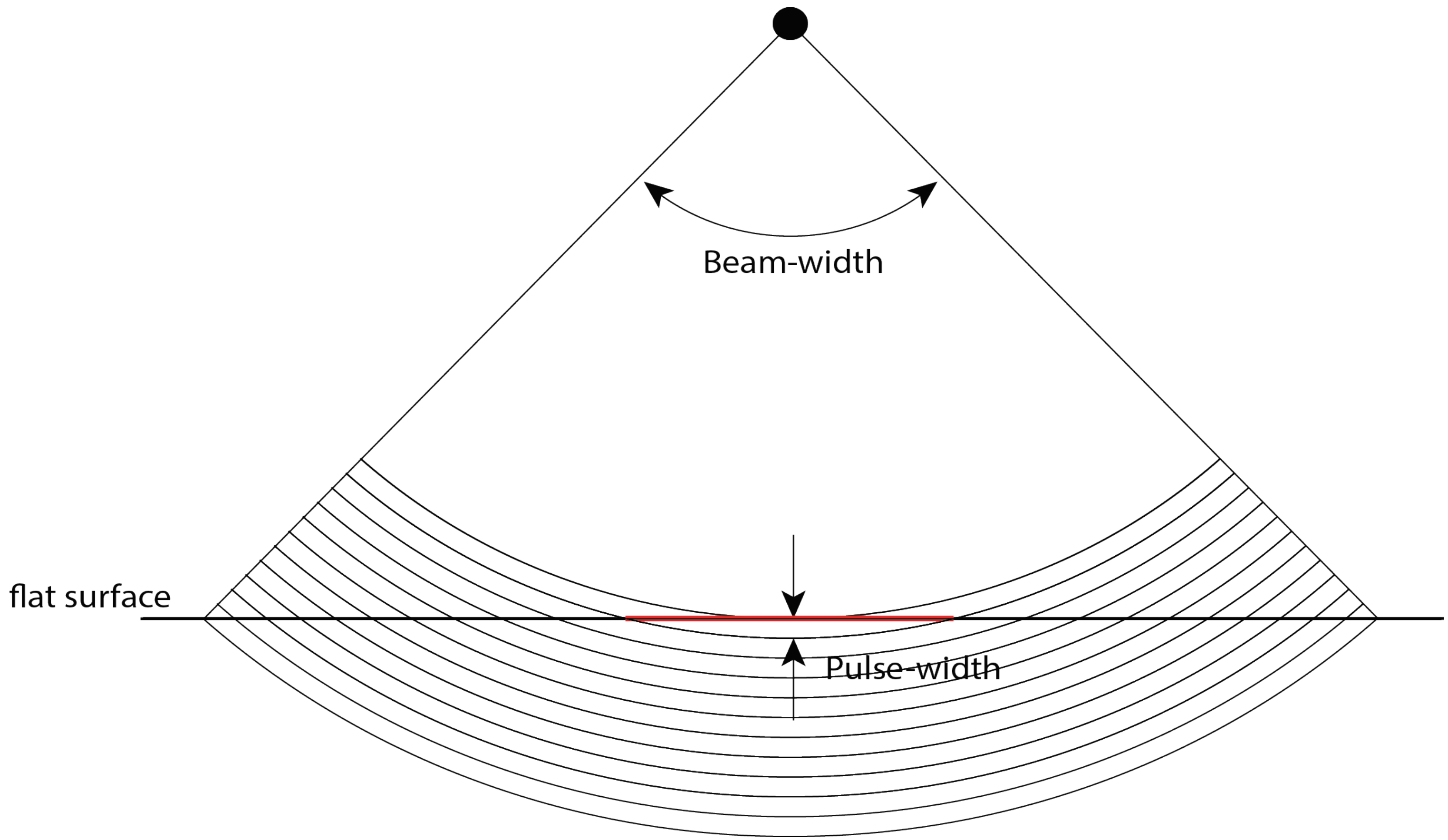
- Pulse-width limited geometry (for a flat surface):
  - "wide" antenna beam: illuminated surface defined by pulse-width
  - pointing errors affect echo shape but not location
  - sensitive to surface geometry
  - detection of leading-edge



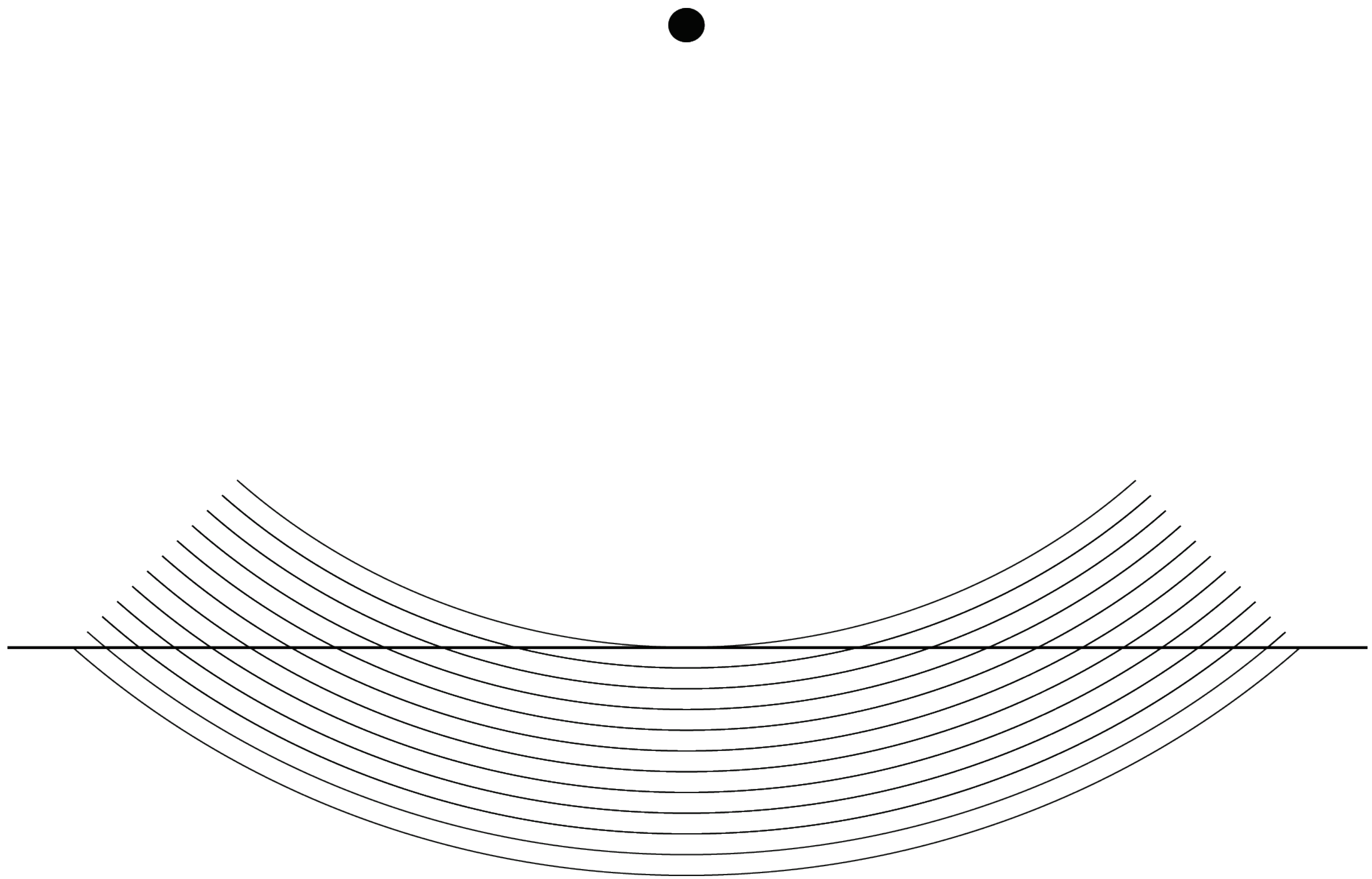
Flat surface response



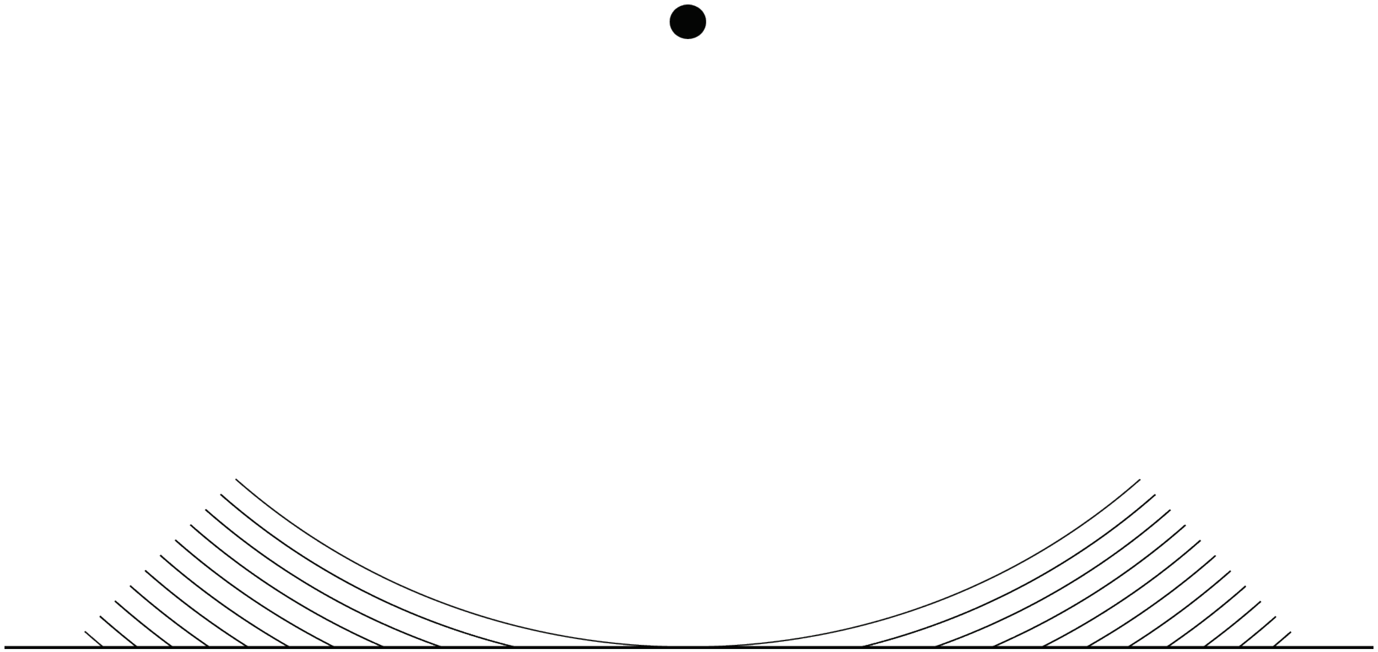
Flat surface response



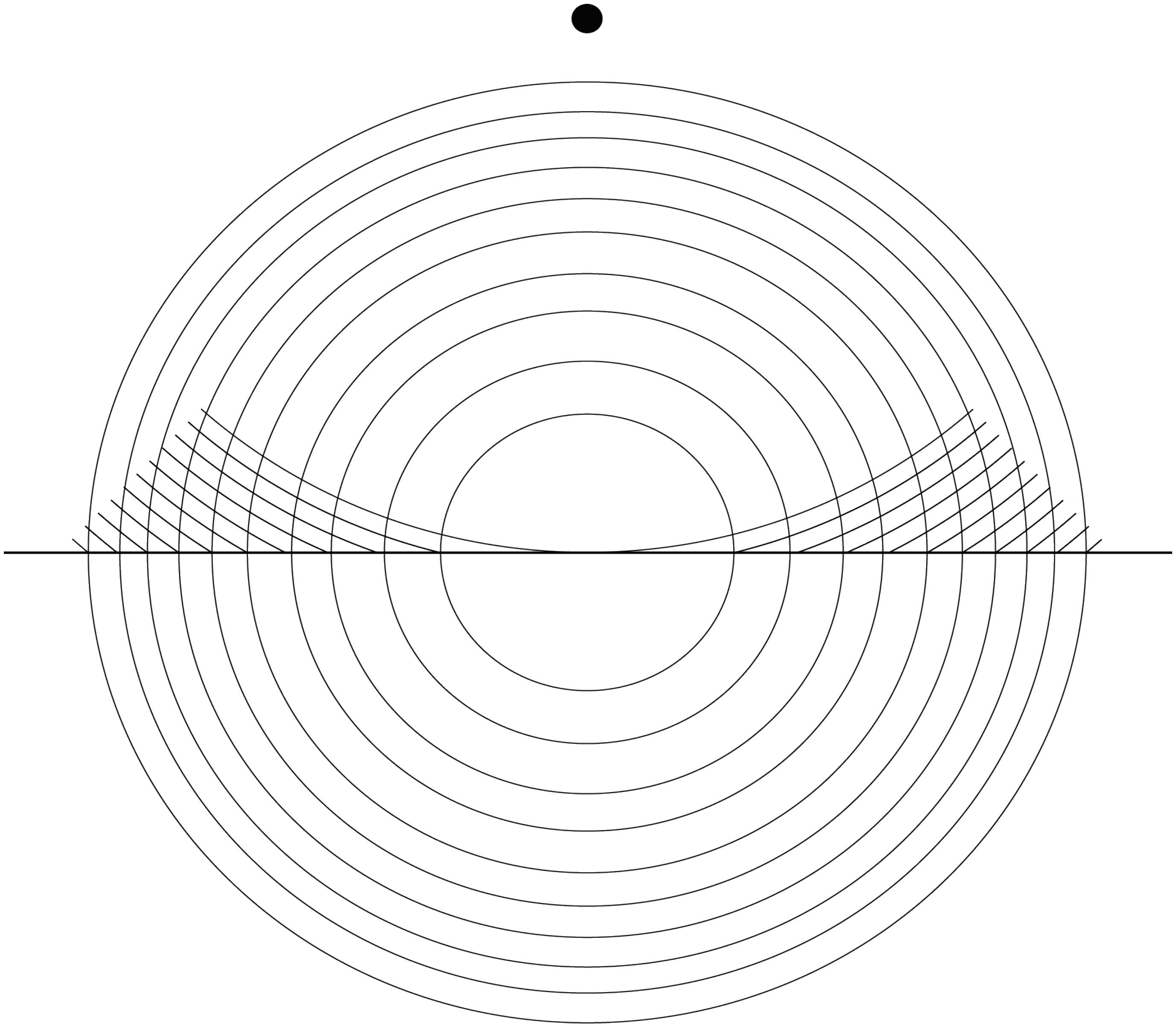
Flat surface response



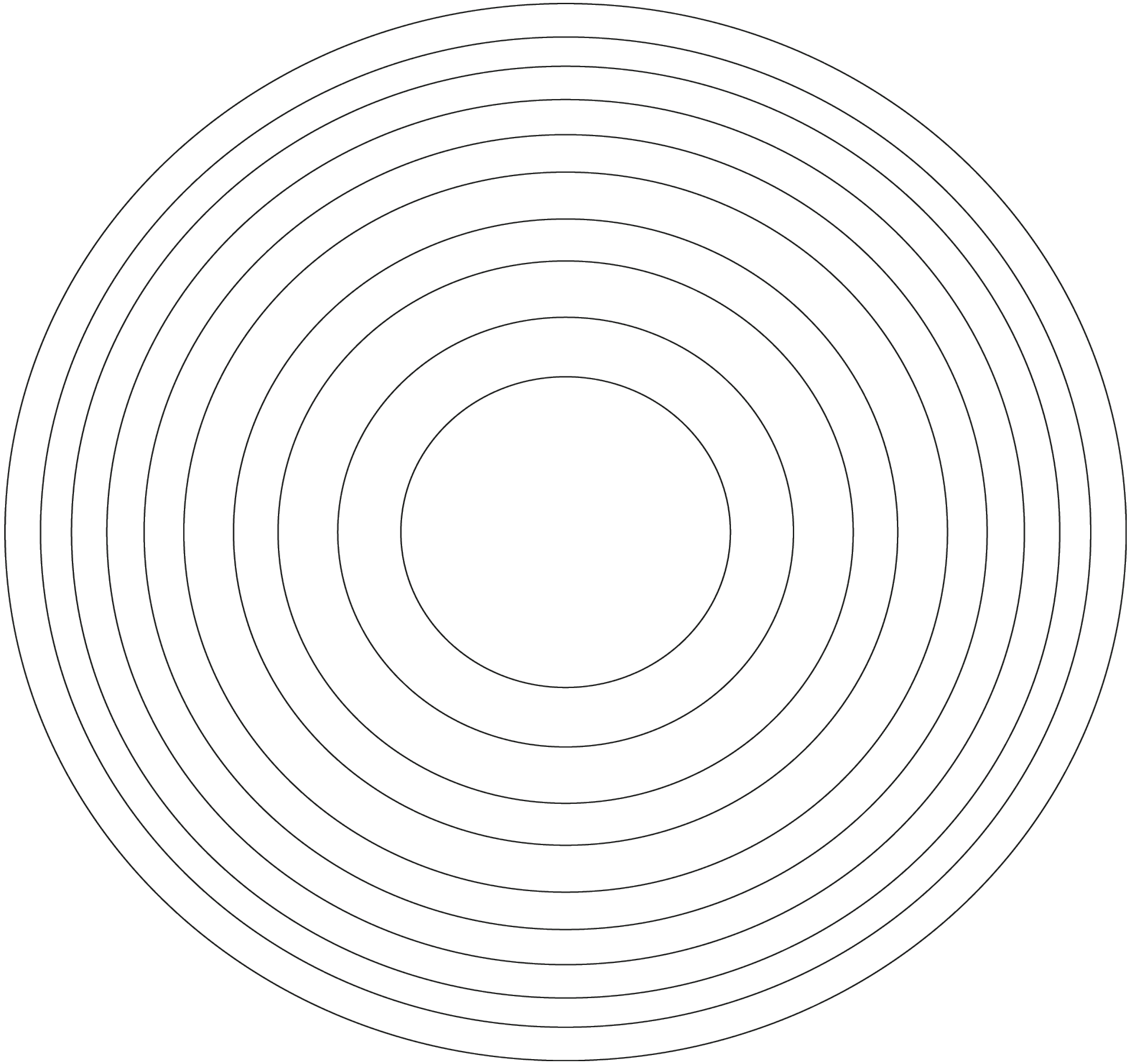
Flat surface response



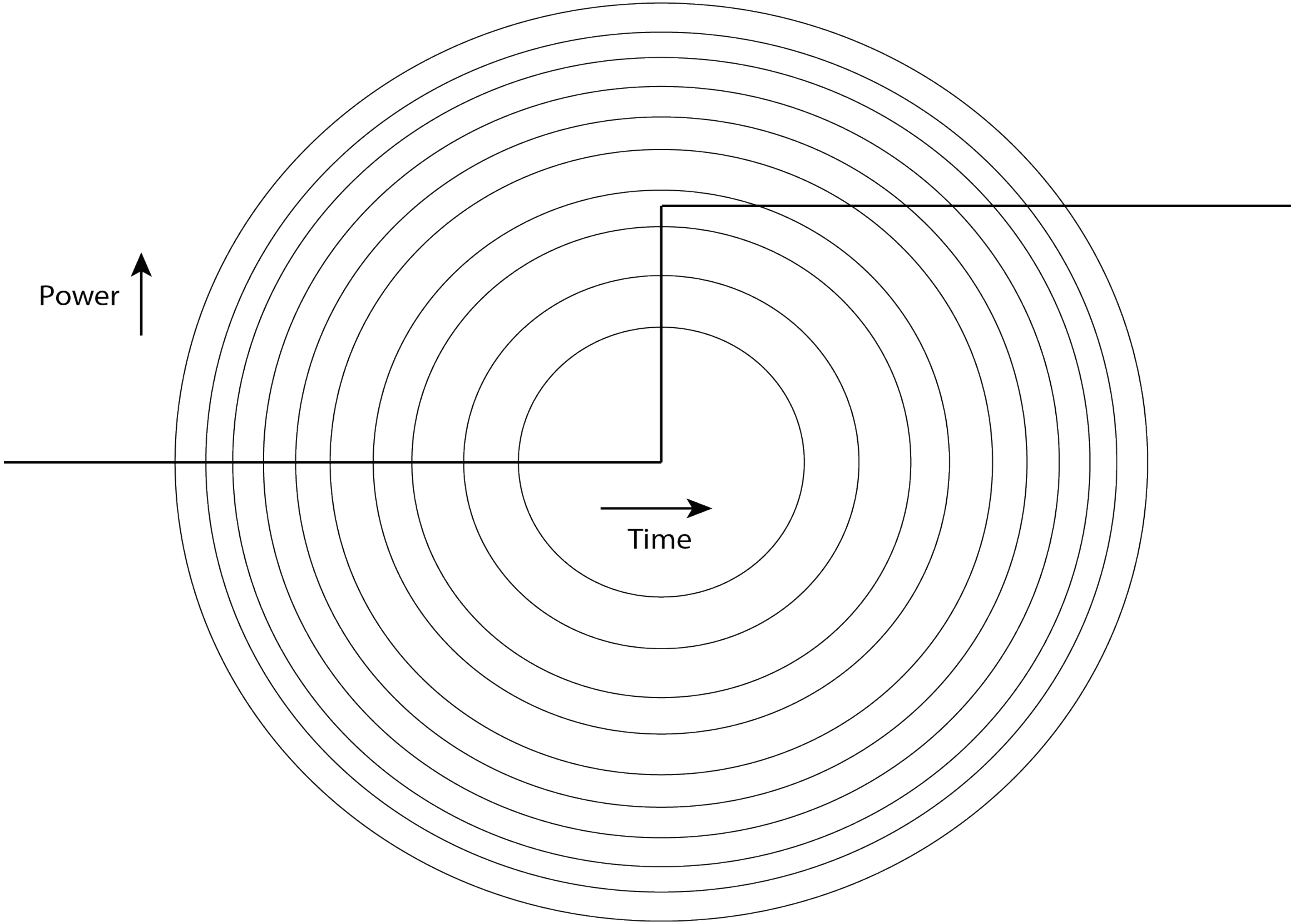
Flat surface response



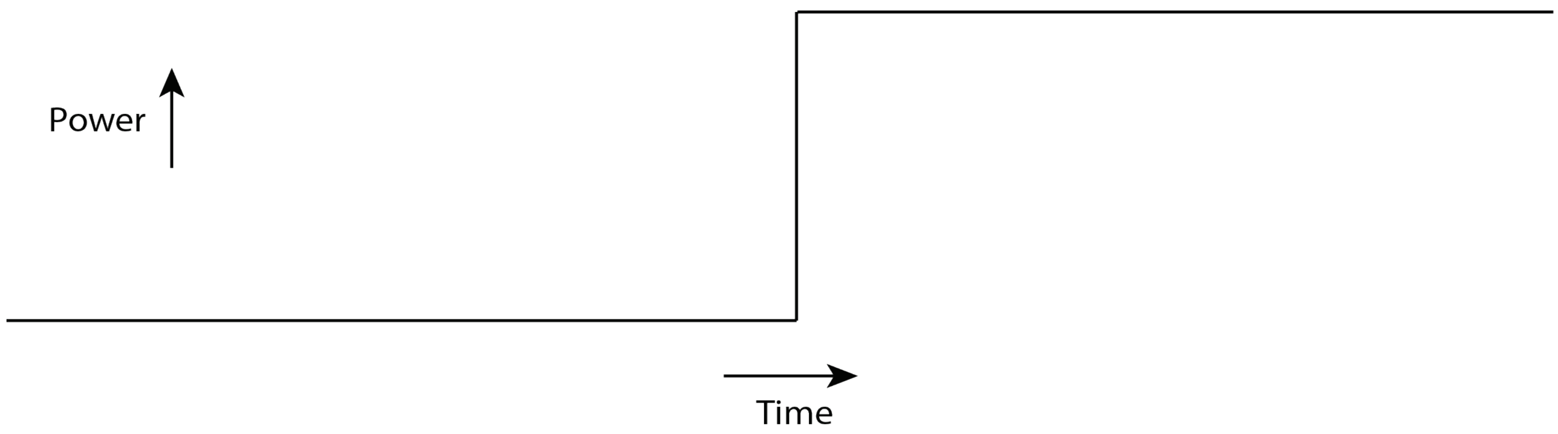
Flat surface response



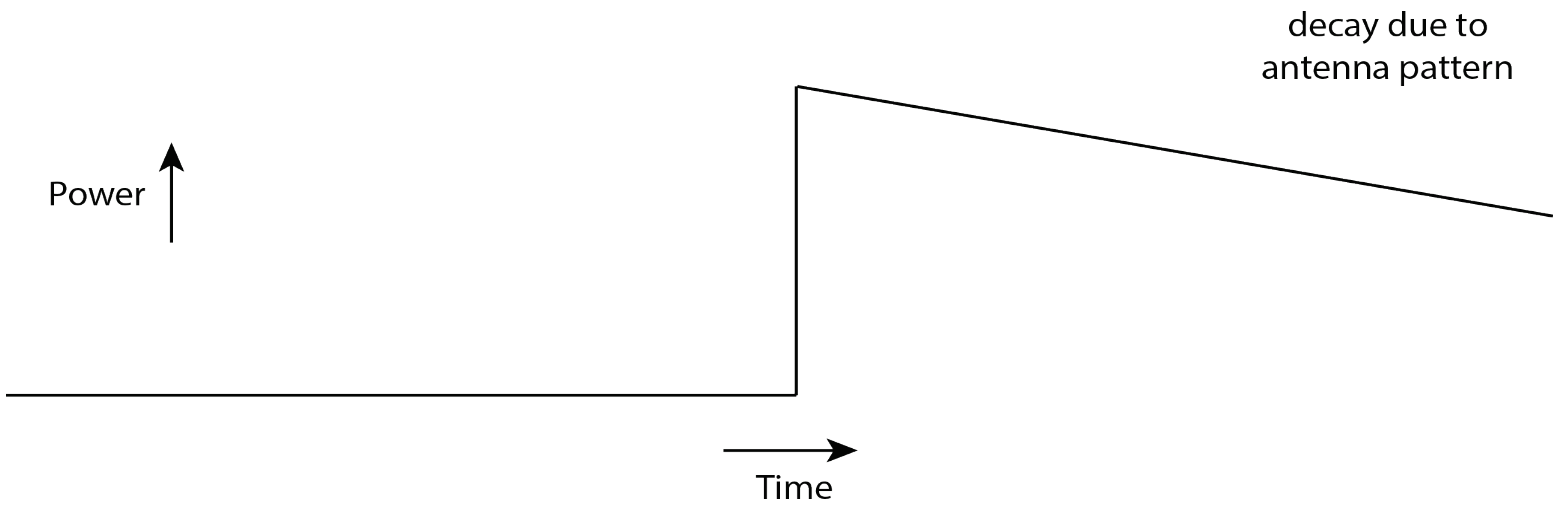
Flat surface response



Flat surface response

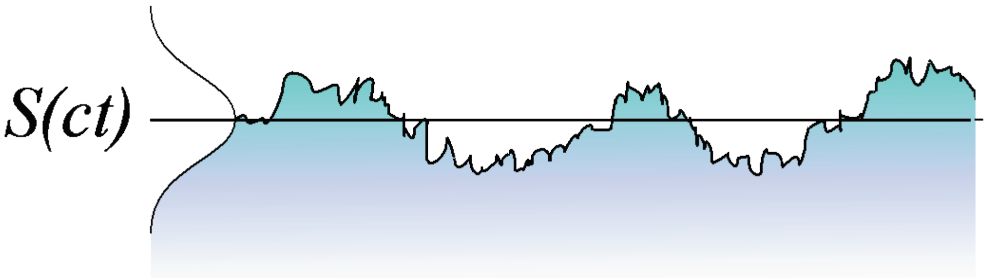


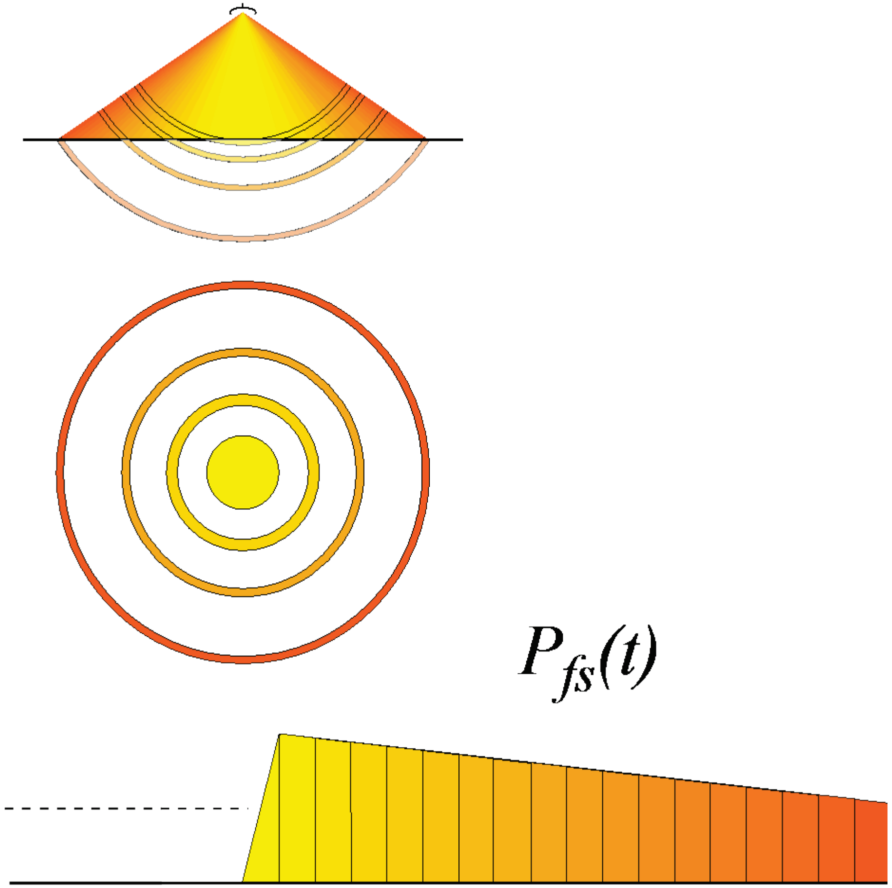
Flat surface response



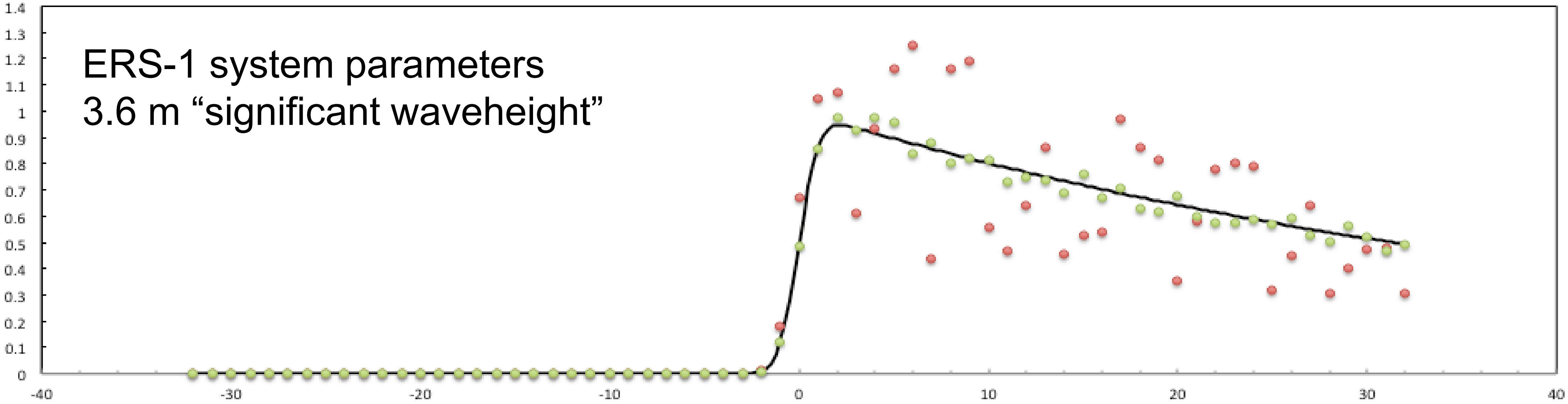
Return Averaged Echo

$$P_r(t) = I(t) * S(ct) * P_{fs}(t)$$



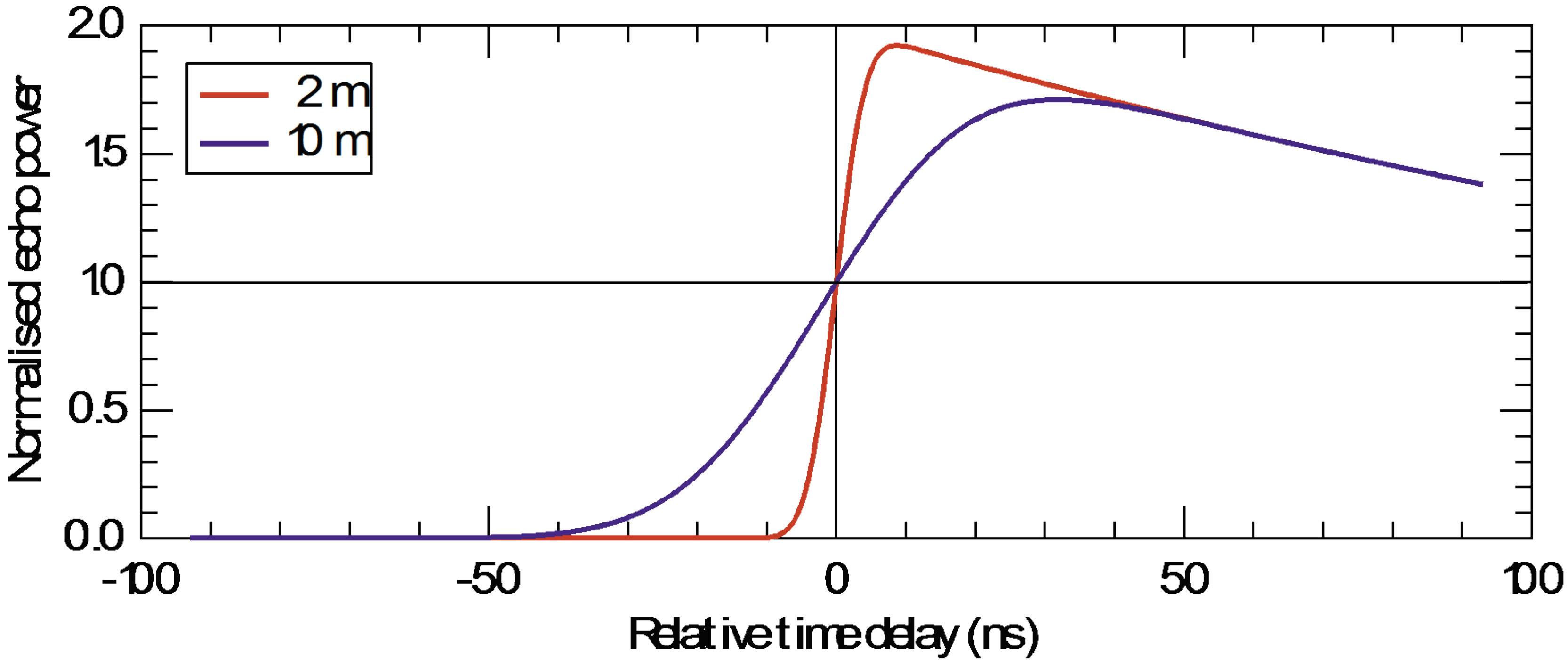


Average Echo



- Black line: average echo
- Red points: individual echo shows **speckle**
- Green points: on-board average of 50 echoes

Return Echo: Average Waveform



- A given power point (e.g. 50%, 87%) is related to the echo delay time.
- Leading edge slope is related to Significant Waveheight.
- Integrated echo power is related to surface σ°.

System Design: PRF

- Coherent radiation illuminating a surface which is rough at the wavelength scale produces *speckle* (multiplicative noise).
- Effect of speckle can be reduced by averaging **decorrelated** echoes.
- Height noise normally characterised by averages 1 second for low resolution, 1/20 seconds for high resolution.
- Height noise reduces as more echoes are averaged in a given time.

System Design: PRF

Pulse Repetition Interval (PRI)
Pulse Repetion Frequency (PRF)
PRF = 1/PRI

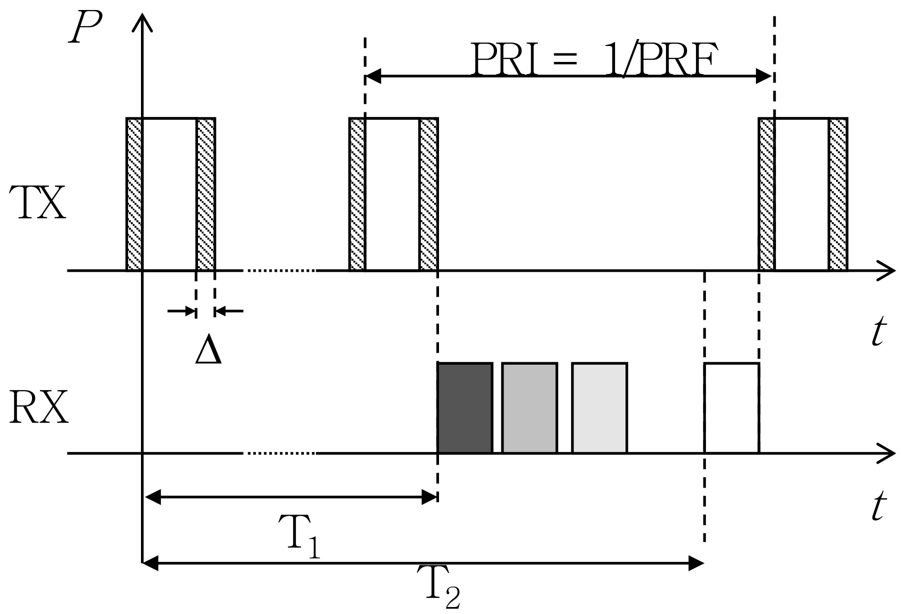
- Higher PRF provides more echoes in a given time.
- limit when echoes become correlated (~ 2 kHz PRF)

Decorrelation time:

$$\mathrm{PRF} \leq \frac{f \cdot v \cdot \sqrt{\tau_c}}{0.305 \cdot \sqrt{ch} \cdot \left(\frac{R+h}{R}\right)}$$

f = radar carrier frequency
v = satellite ground-track velocity
R = Earth radius
h = satellite height

Ambiguity:

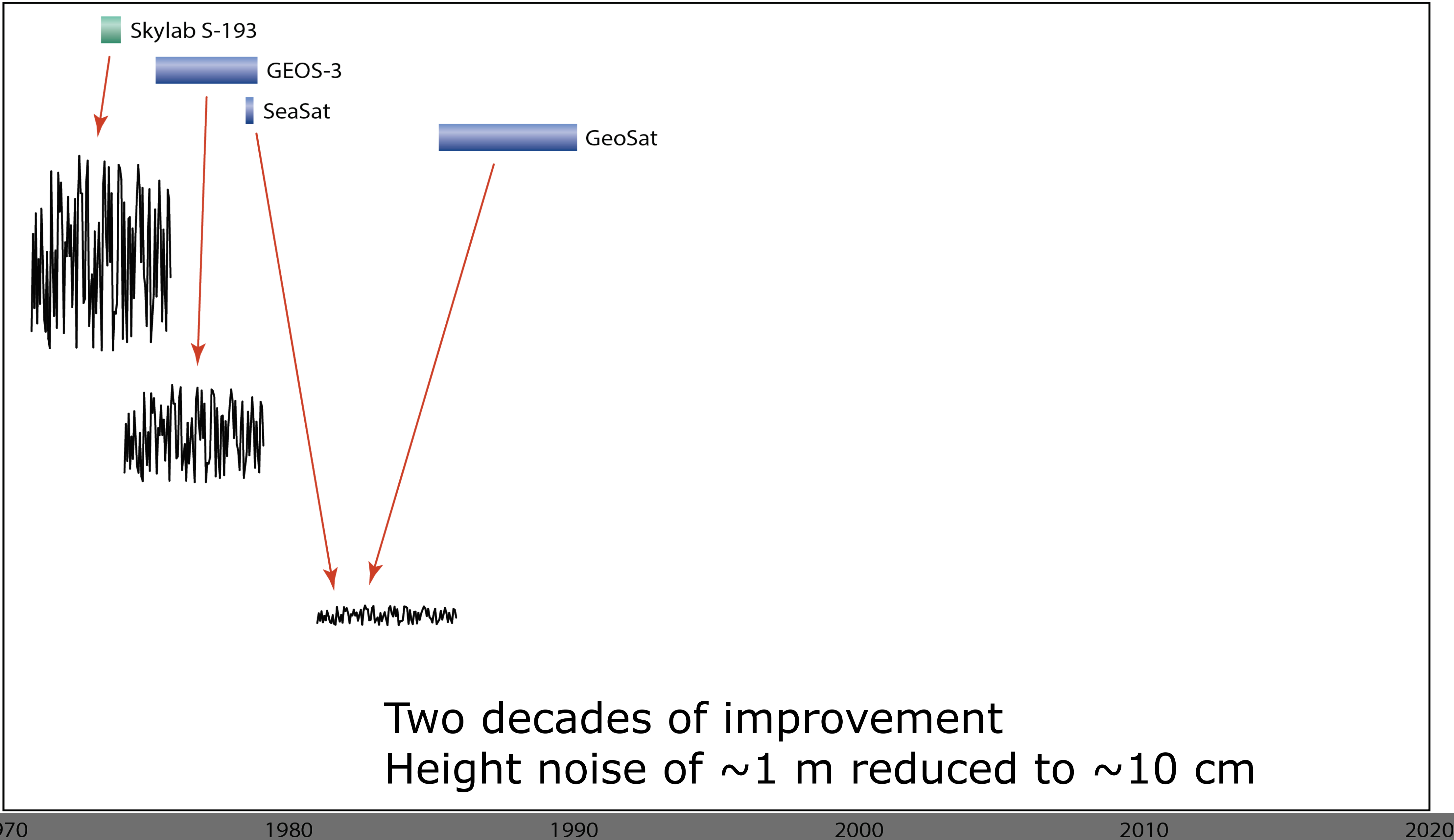


$$T_1 > n \cdot \mathrm{PRI} + \tau_u + \Delta$$

$$(n+1) \cdot \mathrm{PRI} > T_2 + \tau_u + \Delta$$

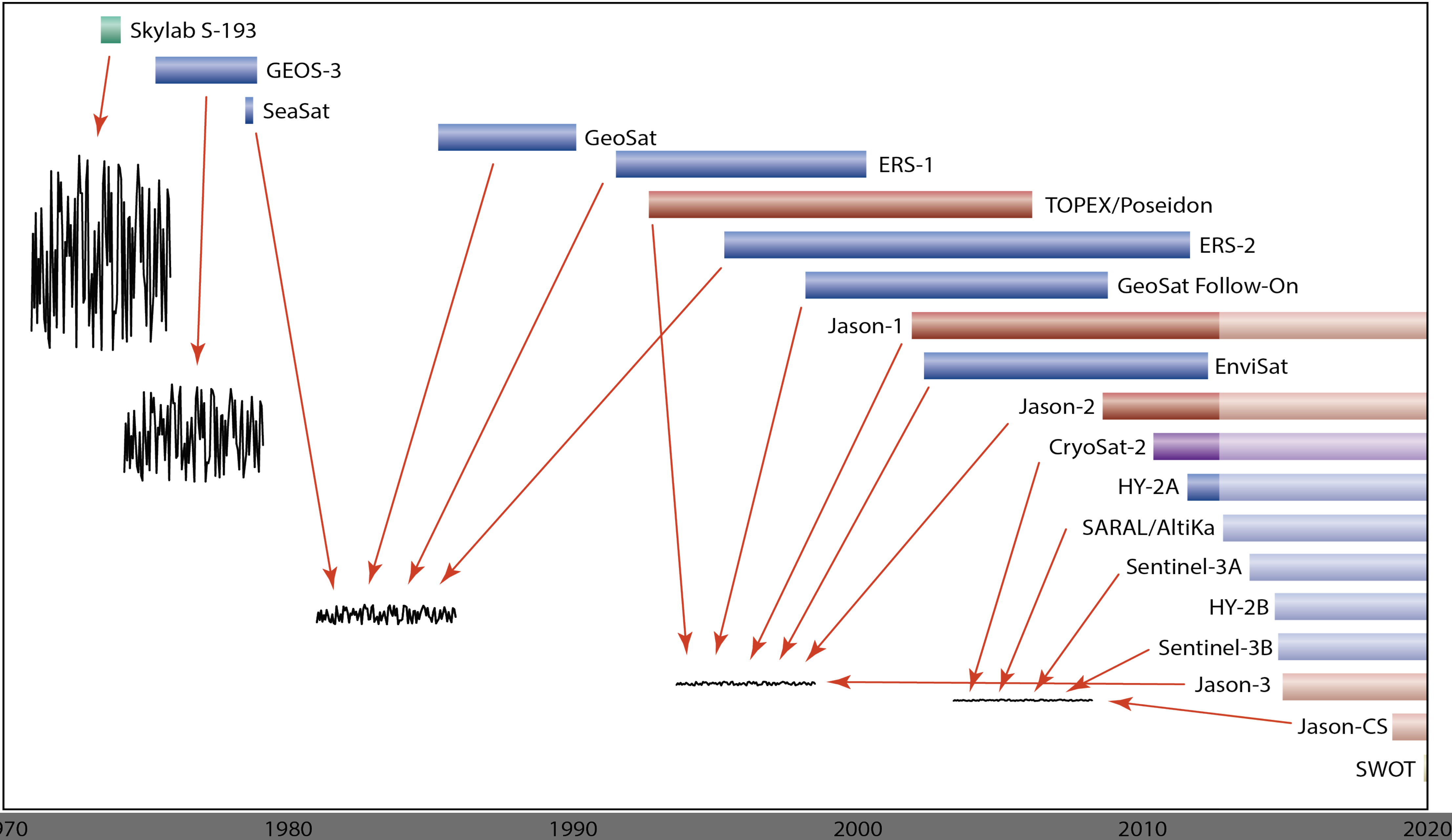
$$\therefore \mathrm{PRI} > T_2 - T_1 + 2(\tau_u + \Delta)$$

Height noise in altimetry missions



Two decades of improvement
Height noise of ~1 m reduced to ~10 cm

Height noise in altimetry missions



Technology

- Skylab S-193 was a conventional pulse radar
  - 100 ns uncompressed pulse (normally)
  - 435 km altitude
  - 250 Hz PRF
- GEOS-3 introduced pulse compression
  - 12.5 ns compressed pulse (compression ratio: 80)
  - 840 km altitude
  - 100 Hz PRF

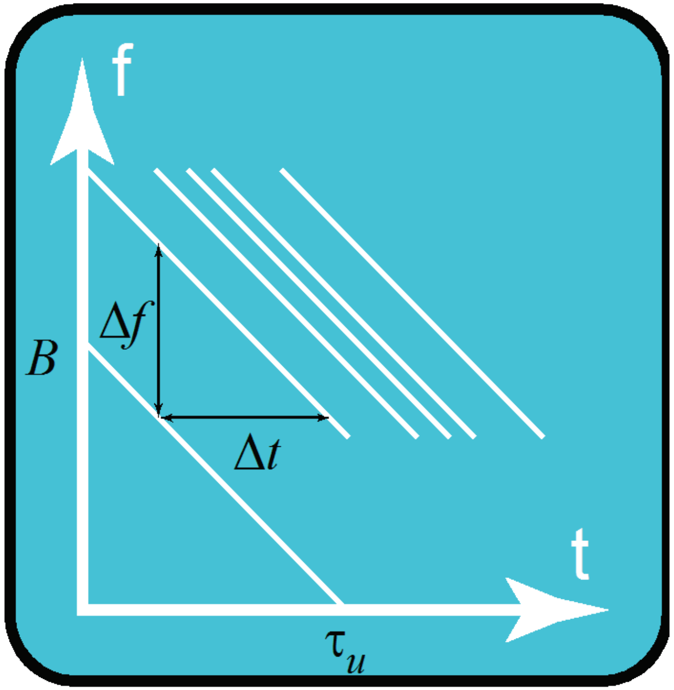
isardSAT®

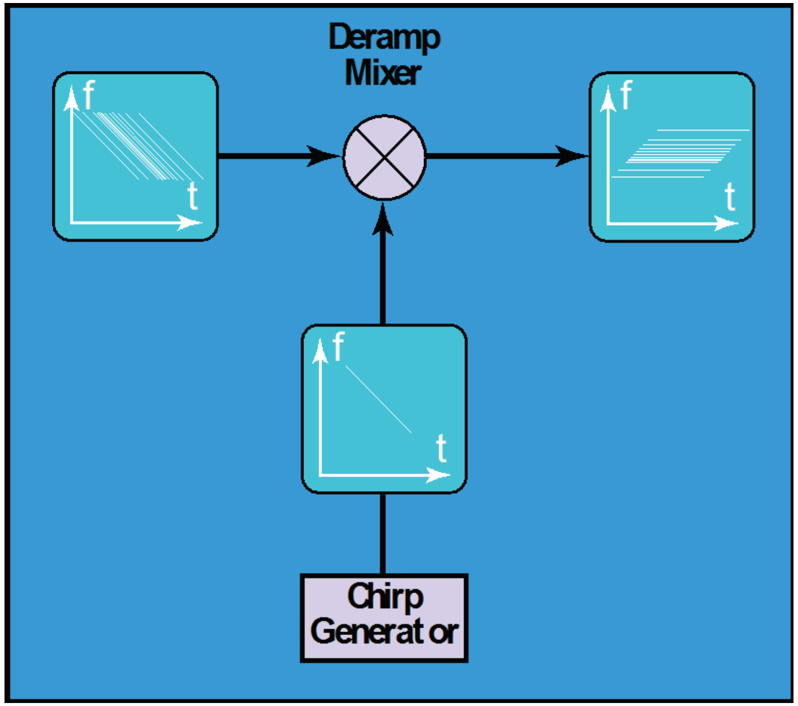
Technology

- Conventional pulse compression radar:
  - Range resolution driven by the bandwidth (B):
  - SNR driven by transmitted energy (P*τ) and noise bandwidth (B)
  - Solution: decouple the two problems by using a signal where B is not a function of τ → chirp
- Required altimeter performance:
  - range resolution ~ 50 cm
  - implies τ_c ~ 3 ns and δf ~ 300 MHz
  - link budget implies compression ration ~ 5000
- Implementation problems:
  - compression filter (expansion filter made by frequency multiplication)
  - video signal processing with 3 ns resolution (ADC etc. at 300 MHz)
- Solution: **Full Deramp Technique** maps relative time delay into frequency offsets.

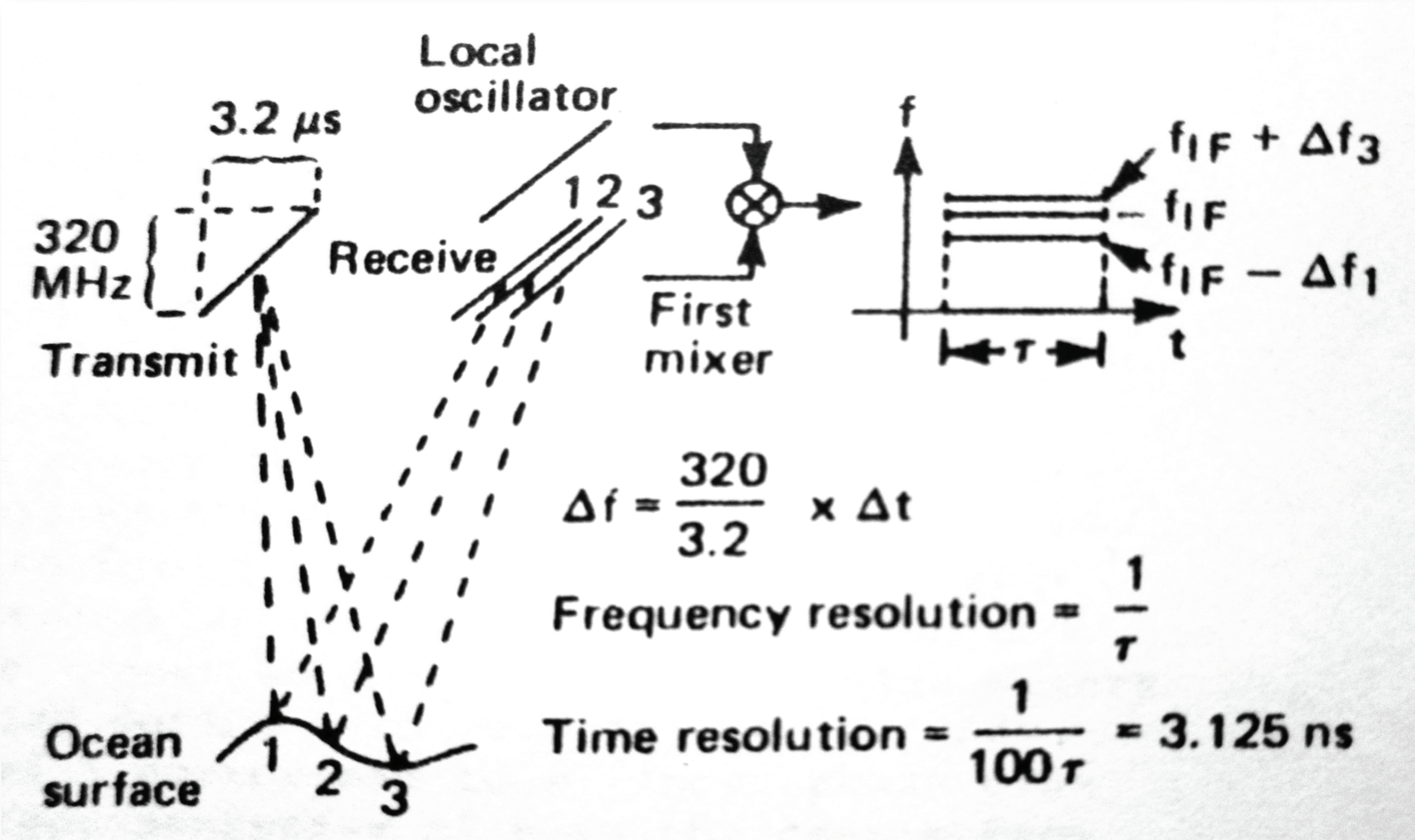
- SeaSat introduced "full deramp"
  - recommended by Brooks and Dooley, NASA CR 1975
  - 800 km altitude
  - compressed TX pulse

$$\Delta f = f_2 - f_1 = B\frac{\Delta t}{\tau_u} = B\cdot\frac{2\Delta h}{\tau_u \cdot c}$$





Full Deramp



J. MacArthur, OCEANS '76

Full Deramp

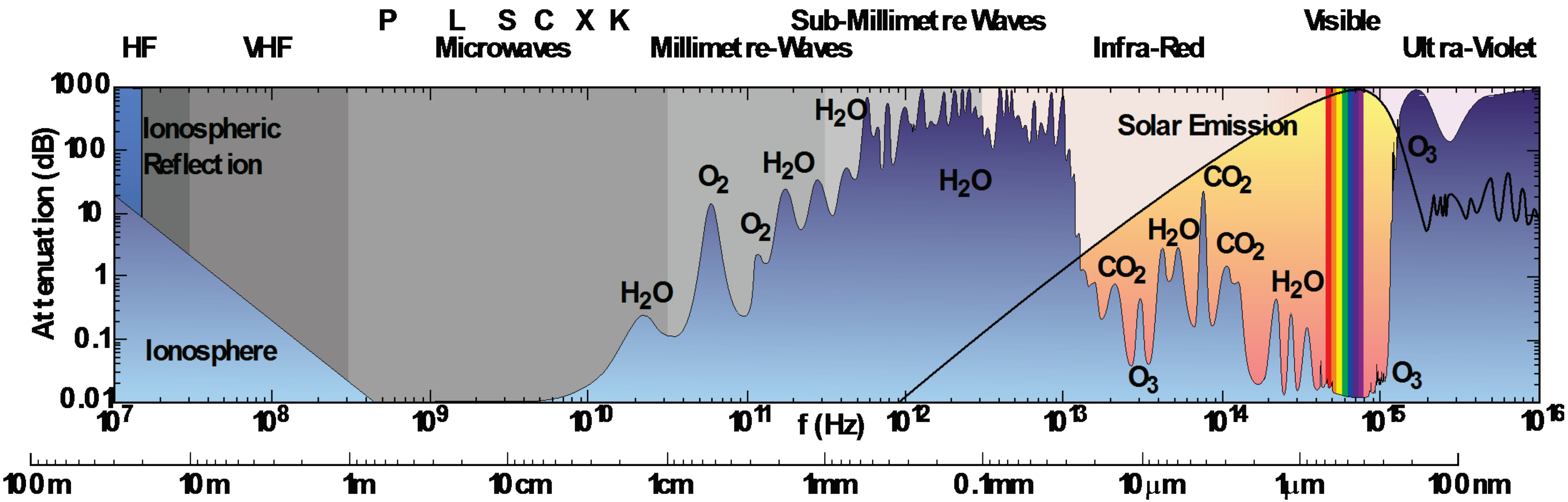
- Same chirp-generator used for TX and RX, reducing effect of phase/amplitude errors
- Transformation from time-domain to frequency-domain replaces high-frequency timing by spectrum analysis
- After deramp, timing variations have no effect

- Technology has radically evolved lately with Sentinel-6, and thanks to a digital architecture, a match filter has been incorporated.

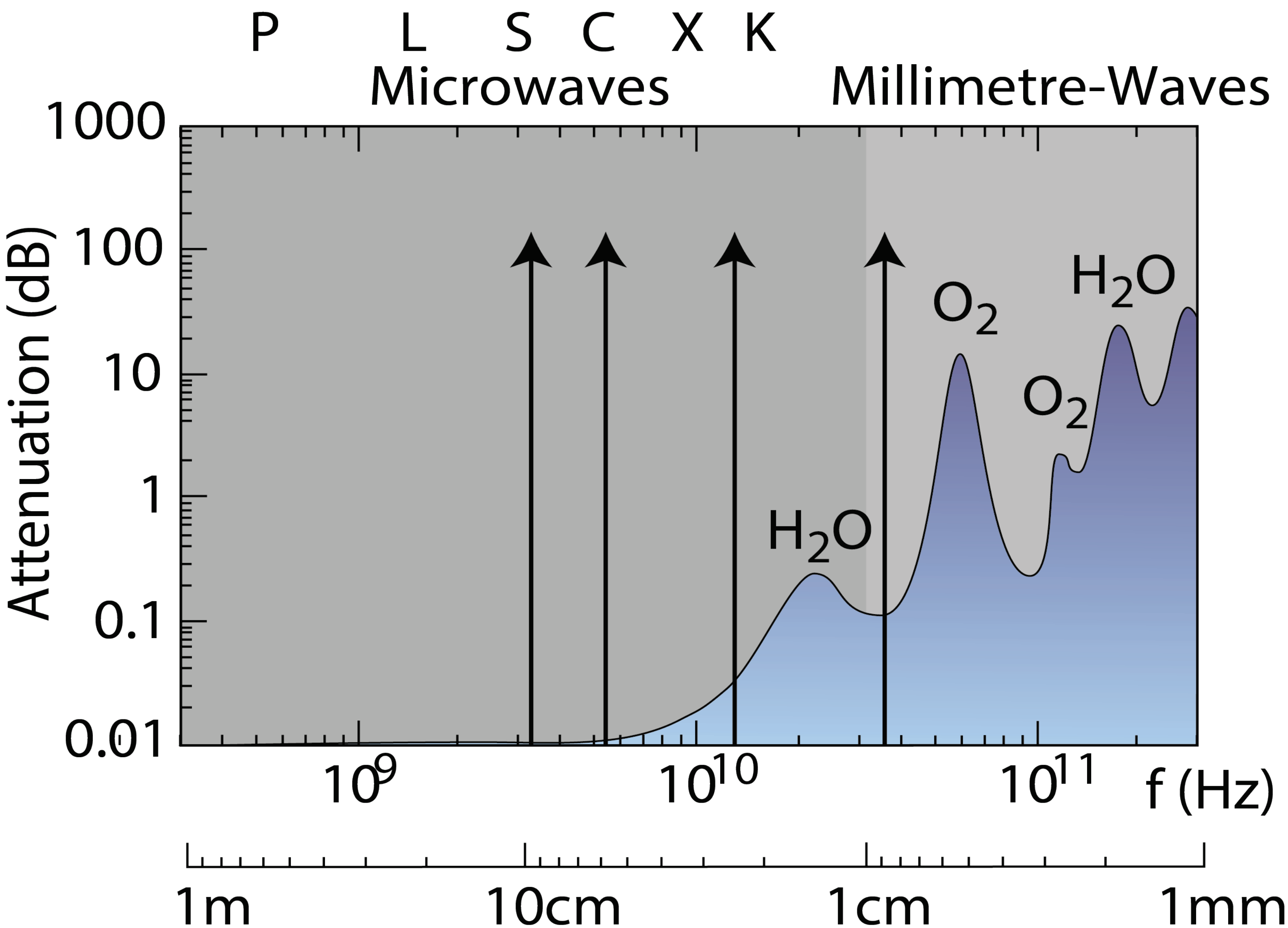
Frequencies

Electromagnetic Transmission

- Electromagnetic radiation only penetrates the atmosphere in a few “windows” where surface measurements can be made.
- Microwave: mature technology; not blocked by clouds.
- Optical: high spatial resolution.

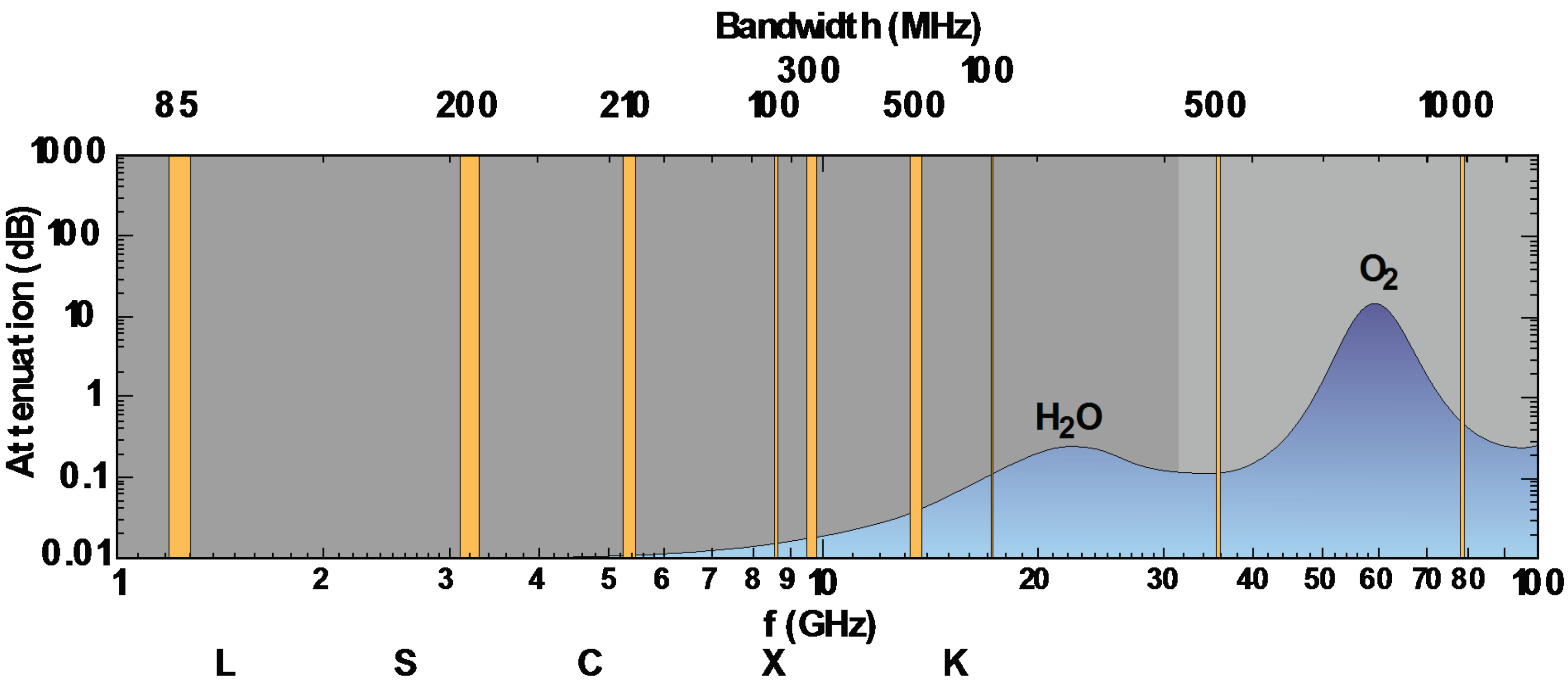


Altimeter Frequencies



System Design: Frequency Choice (3)

International Telecommunications Union permitted Frequency bands and bandwidths



System Design: Frequency Choice (2)

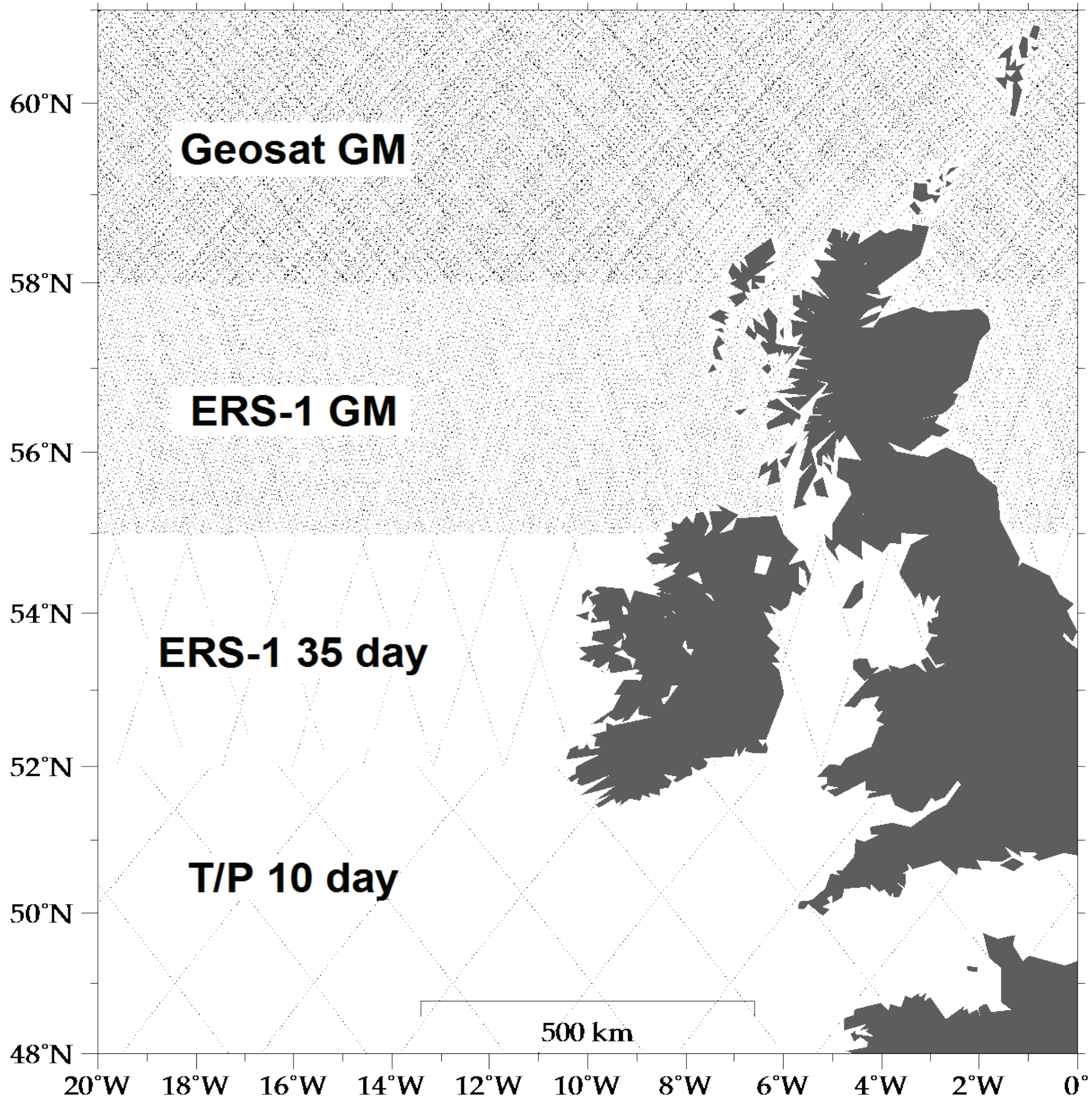
- Factors to be considered in selecting microwave frequency:
  - Reflectivity of the surface
  - Gain of antenna and its dimensions
  - Propagation loss in rain and clouds (lower frequencies are better)
  - Effect of the refractive index of ionosphere ($\propto 1/f^2$)
  - Available transmitter technology (less mature at millimetre waves)
  - Available frequencies and bandwidths (ITU regulations permit 9 frequency bands between 1 and 100 GHz, bandwidths 85 – 1000 MHz)
  - Decorrelation between subsequent measurements (higher frequencies decorrelate faster i.e. in a shorter time)
- Existing instruments have all used Ku-band; secondary frequencies at either C-band or S-band

Orbits

Orbit classes

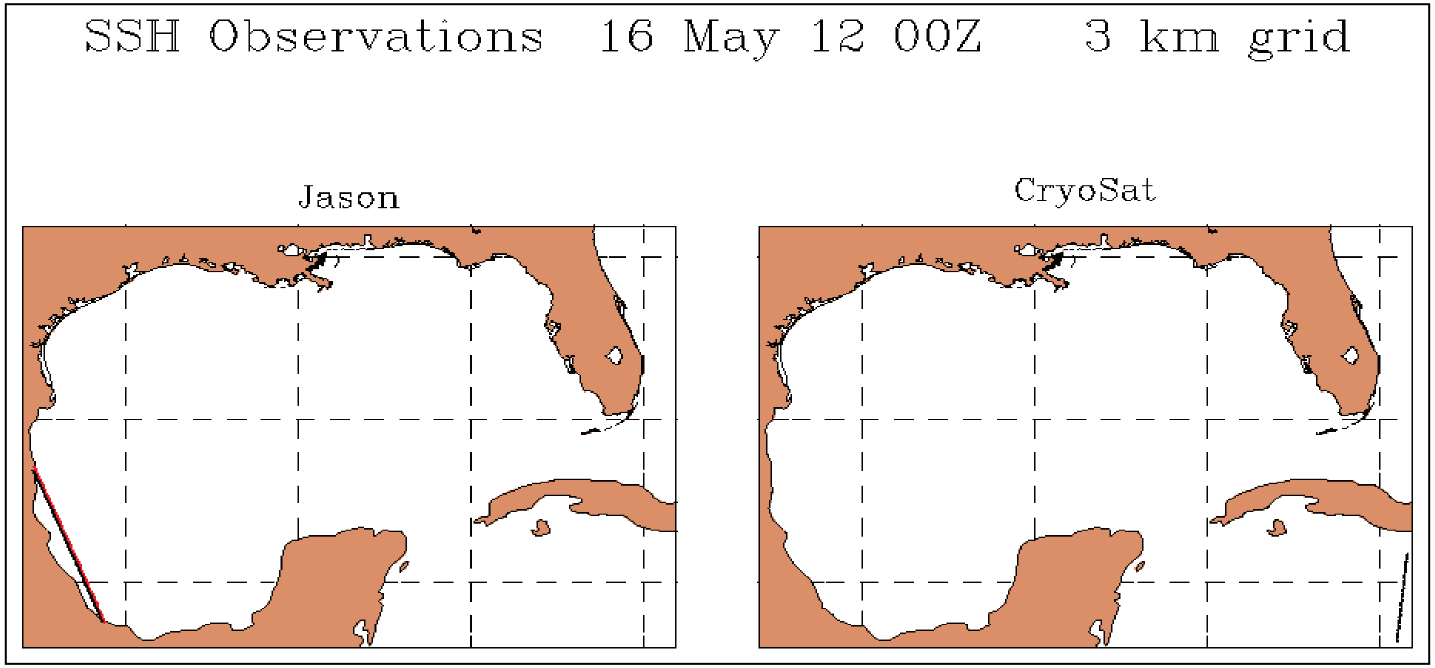
- Altimeters now fly in 3 broad classes of orbit:
  - Oceanography “reference” orbit:
    - 1336 km altitude
    - 66° inclination
    - 10-day repeat cycle
  - “complementary” orbit:
    - ~800 km altitude
    - ~98° inclination (sun-synchronous)
    - repeat cycle 29 or 35 days
  - “geodetic” orbits (several)
    - long repeat period

Ground tracks



Courtesy of R. Cullen

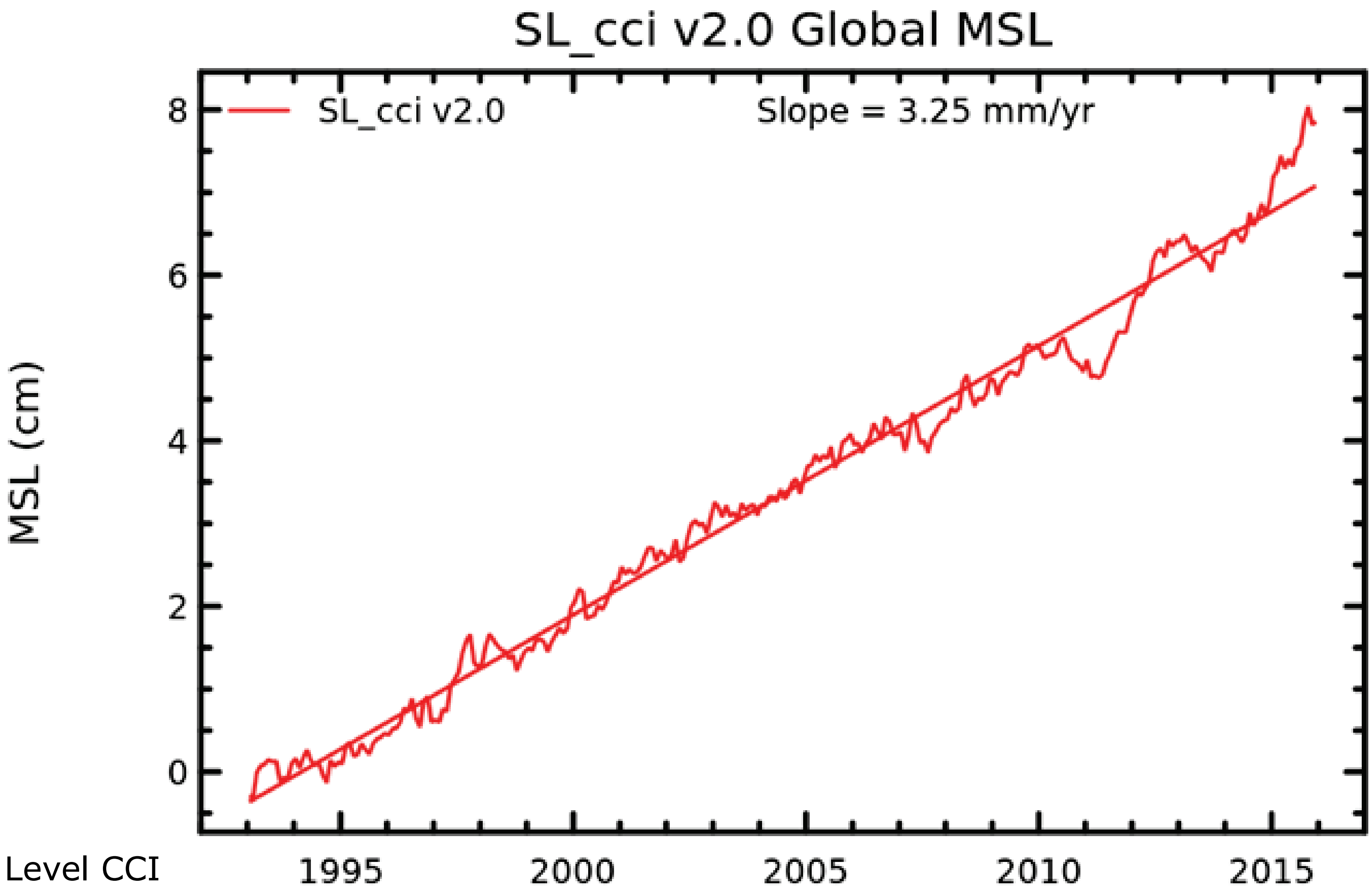
Orbit Pattern Build-up



G. Jacobs, US Navy

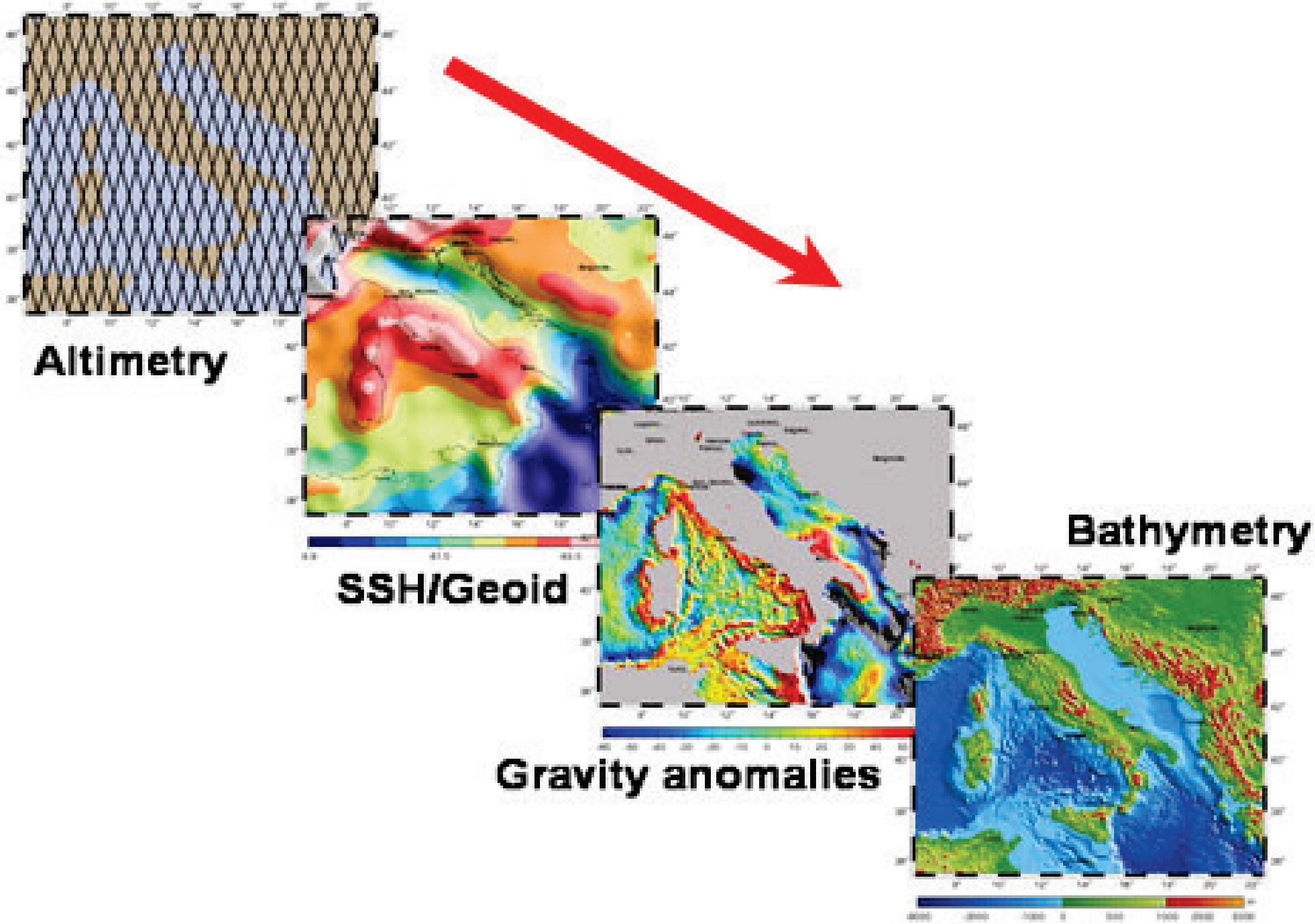
Applications

Mean Sea Level Rise



Sea Level CCI

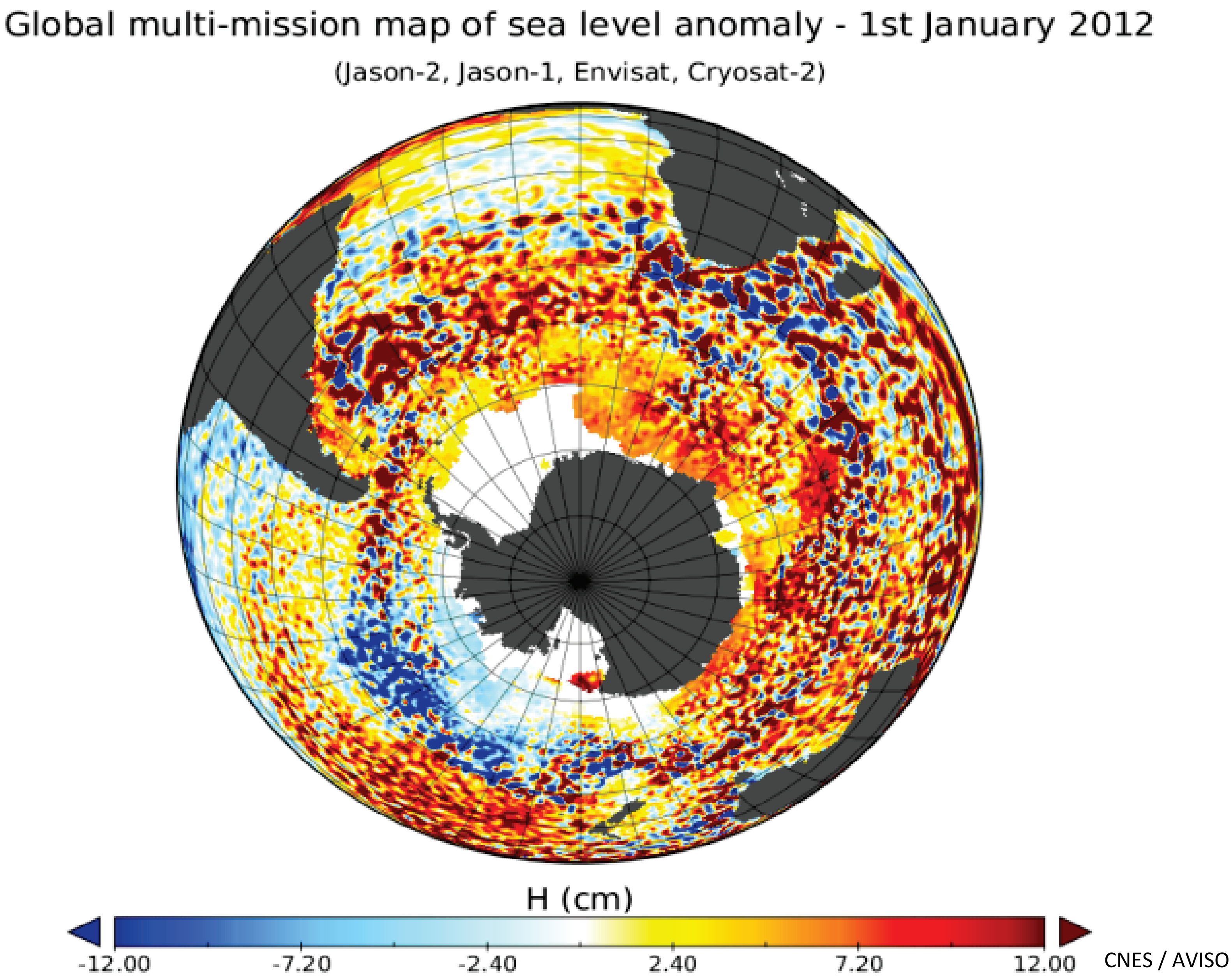
Geodesy and Bathymetry



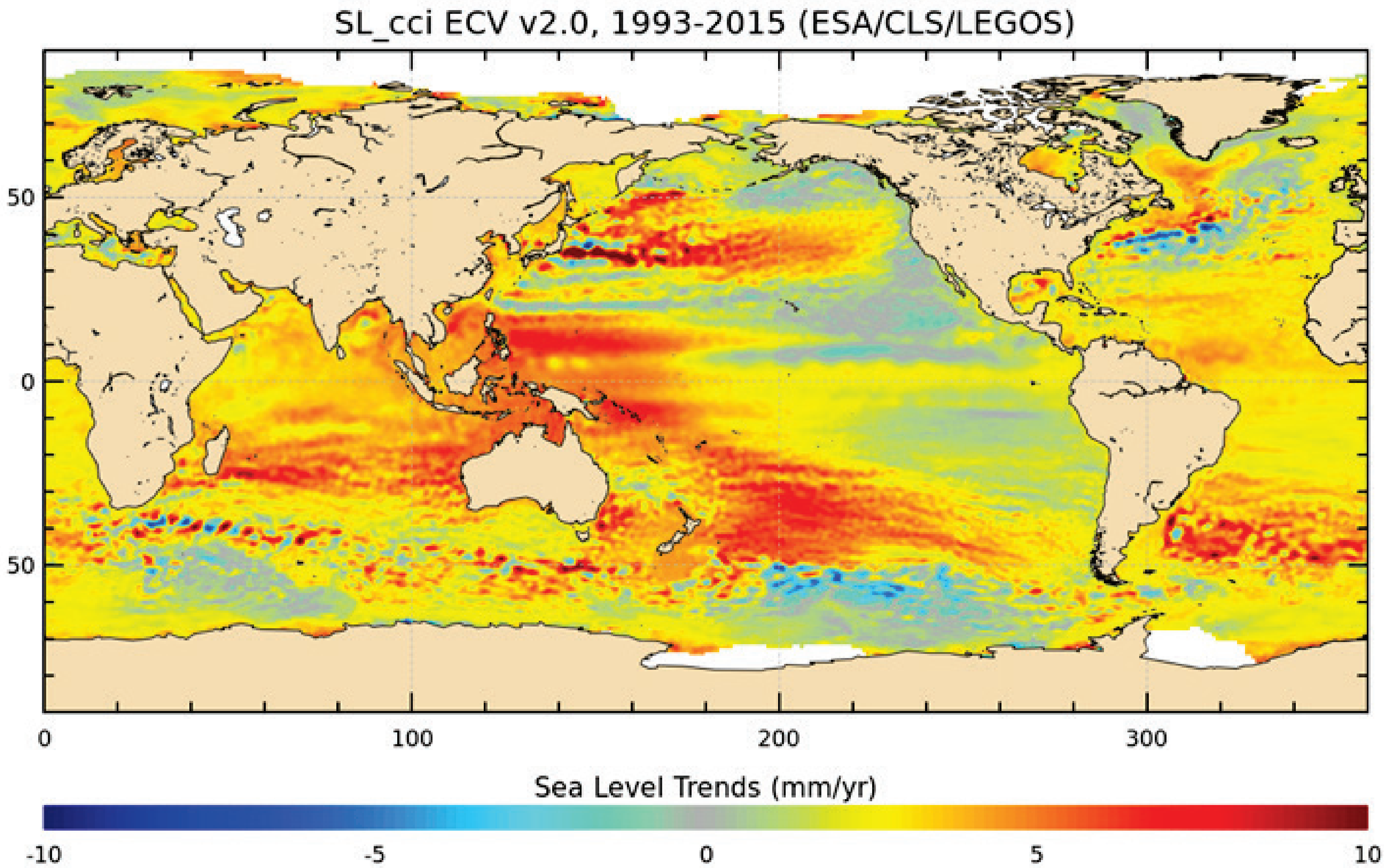
University of Calgary

Sea Level Anomaly: 1 Jan 2012

Sea Level Anomaly is the deviation of ocean height from the mean due to variability in the ocean circulation patterns

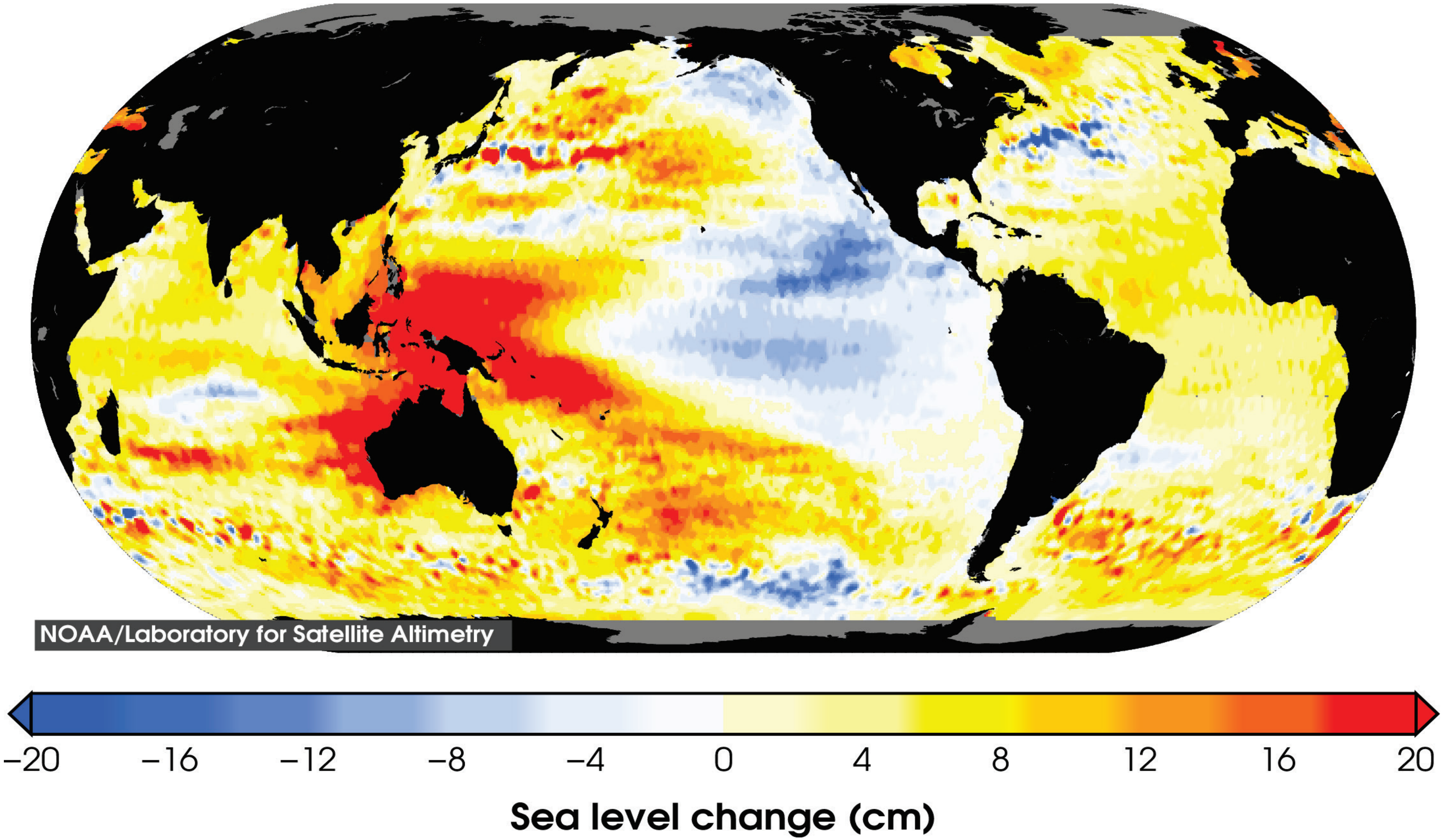


Mean Sea Level Trends



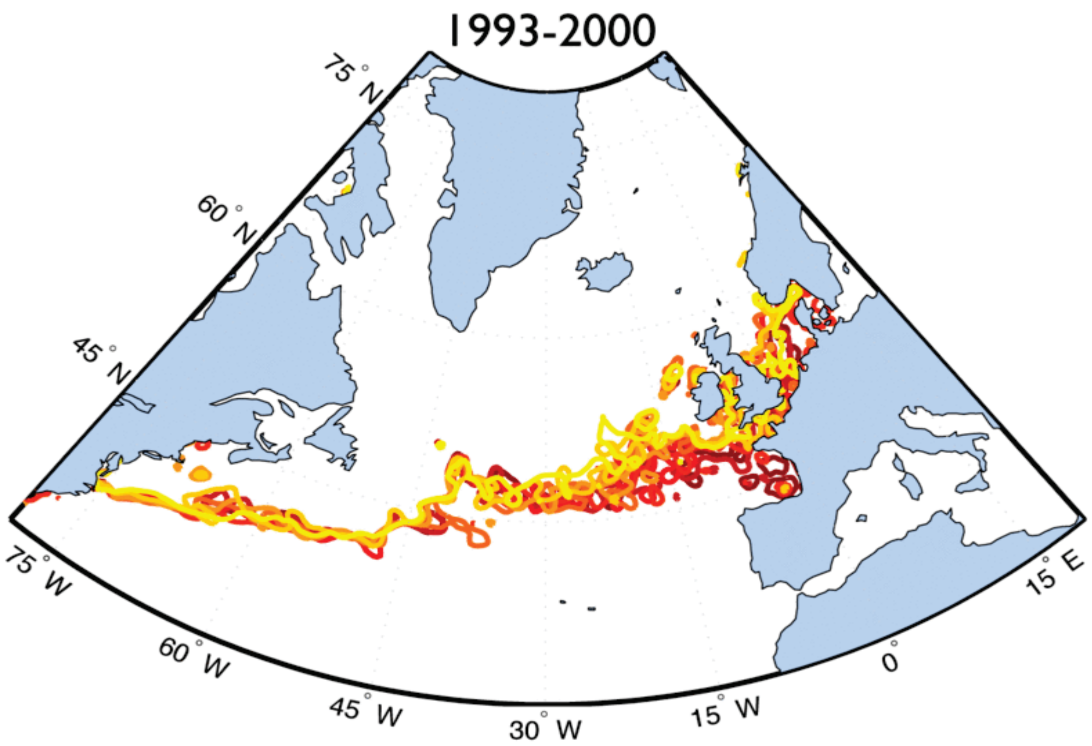
Sea Level CCI

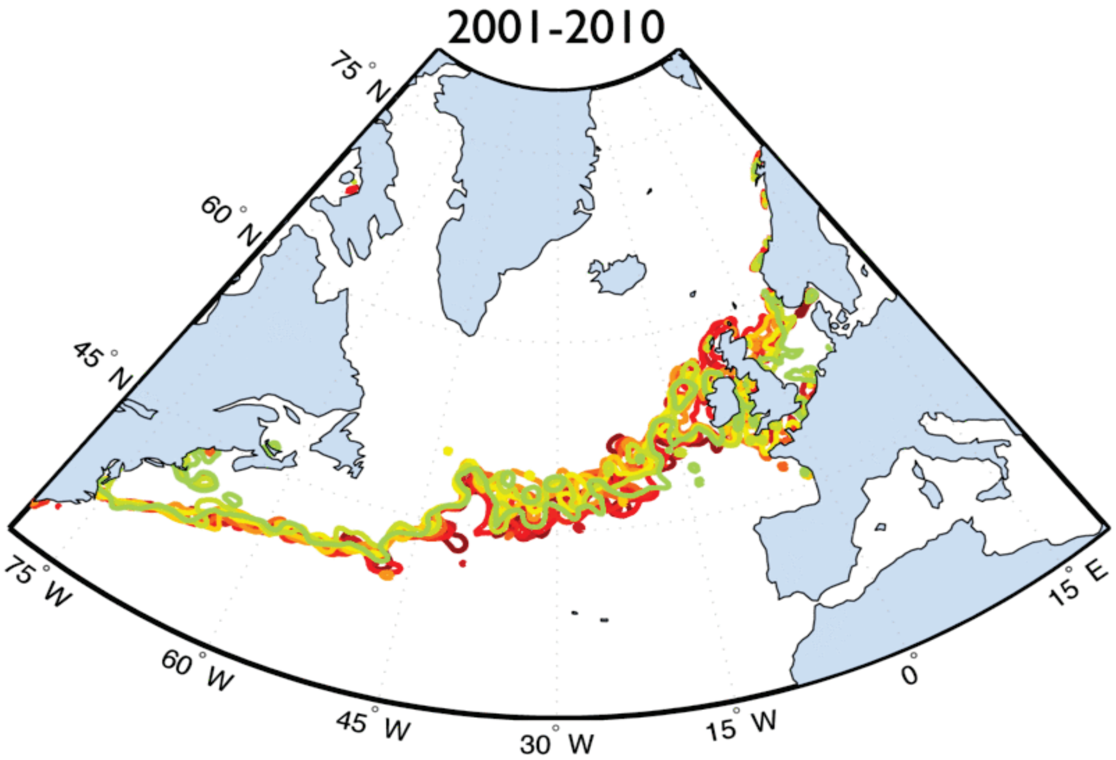
Regional Sea Level Rise Since 1993



Variations due to changing heat content and winds

Ocean Currents

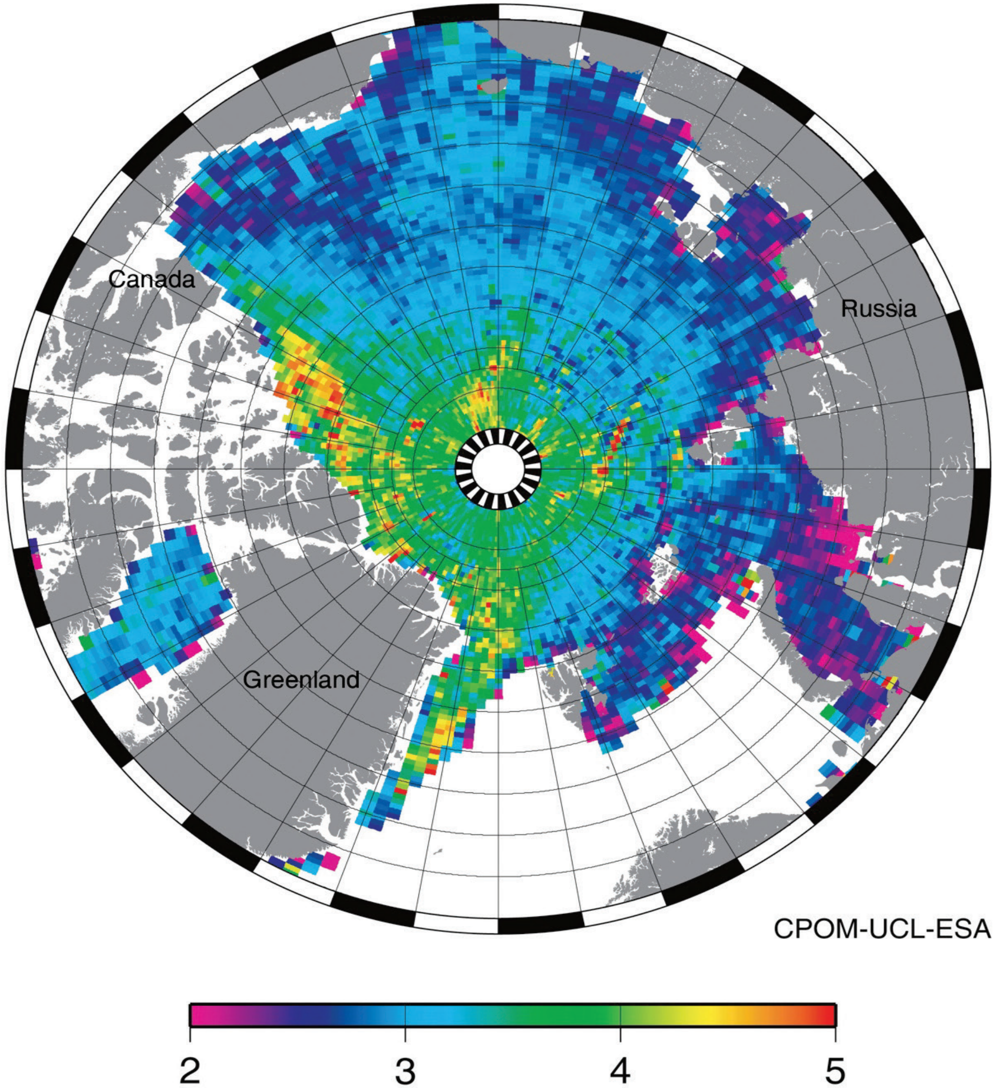




L. Chafik, Stockholm University

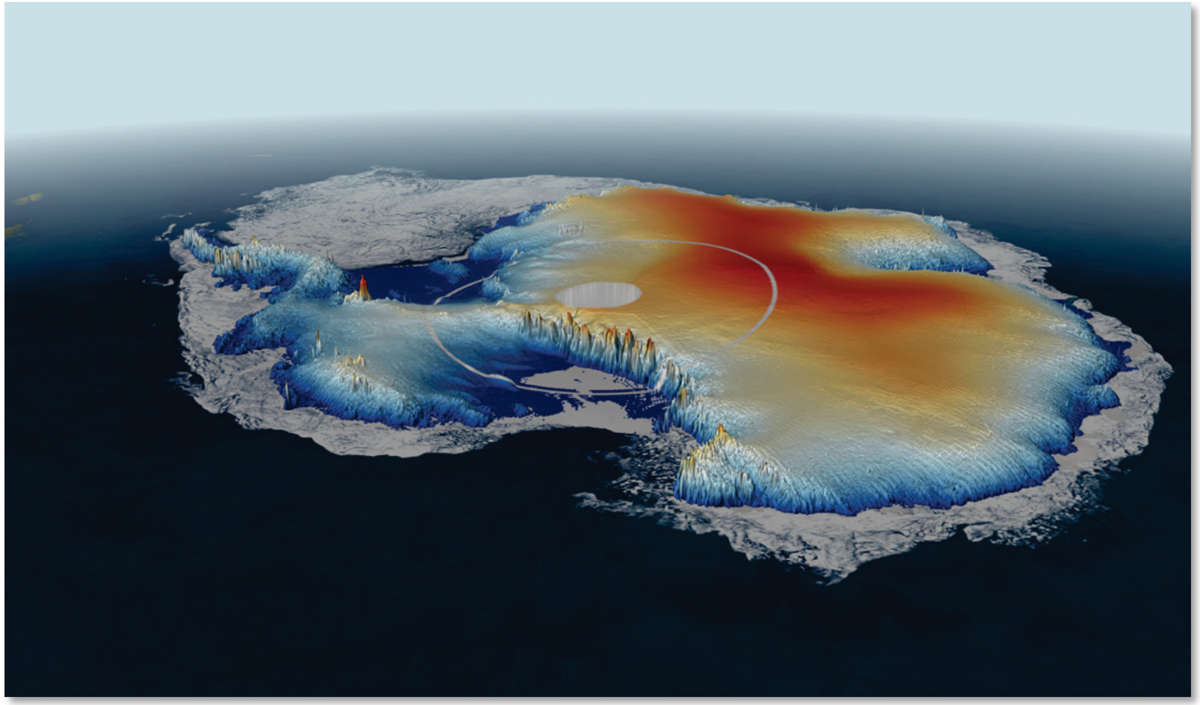
Sea ice thickness in the Arctic ocean

(January/February 2011)



CPOM-UCL-ESA

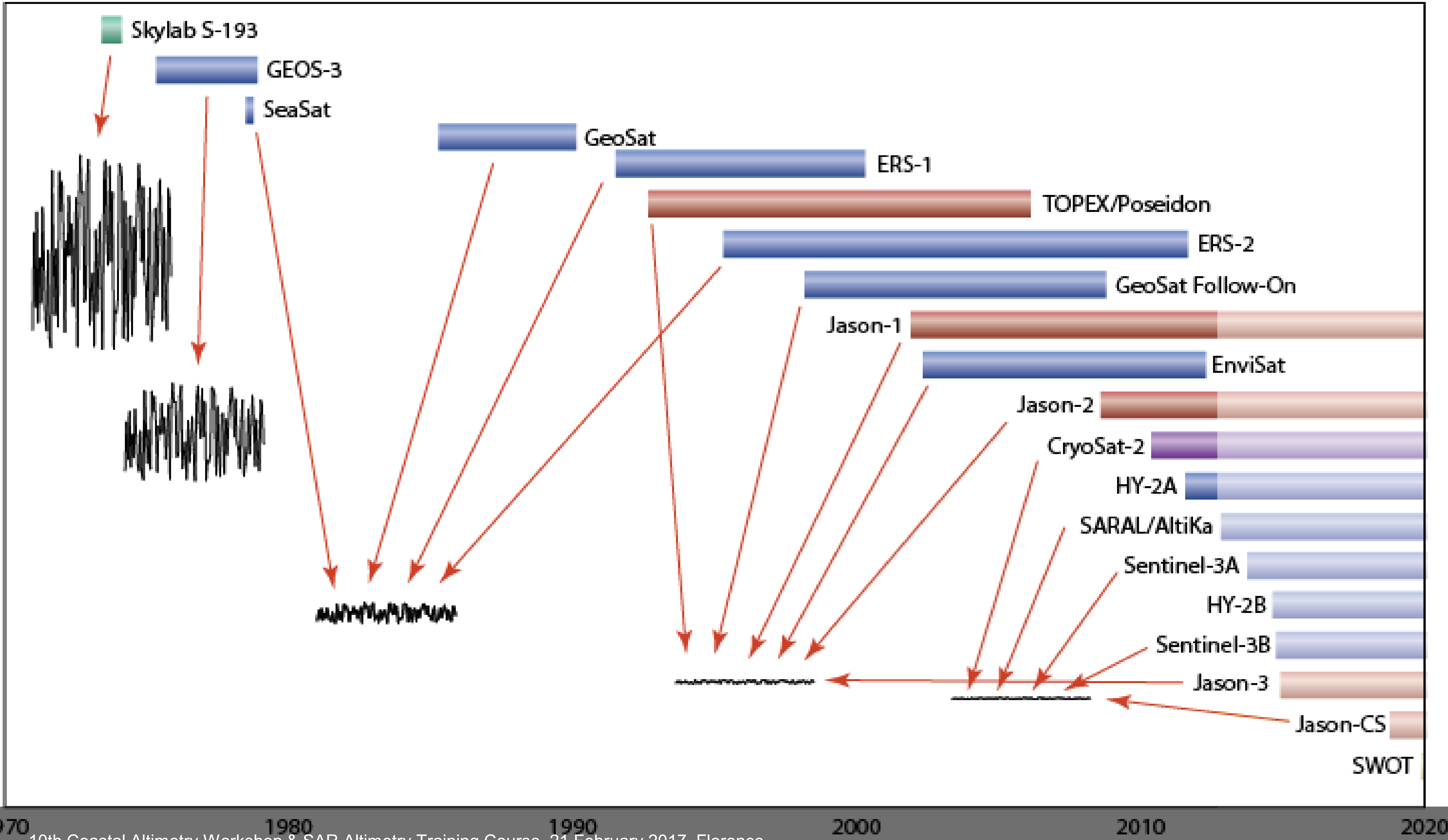
Antarctic Topography



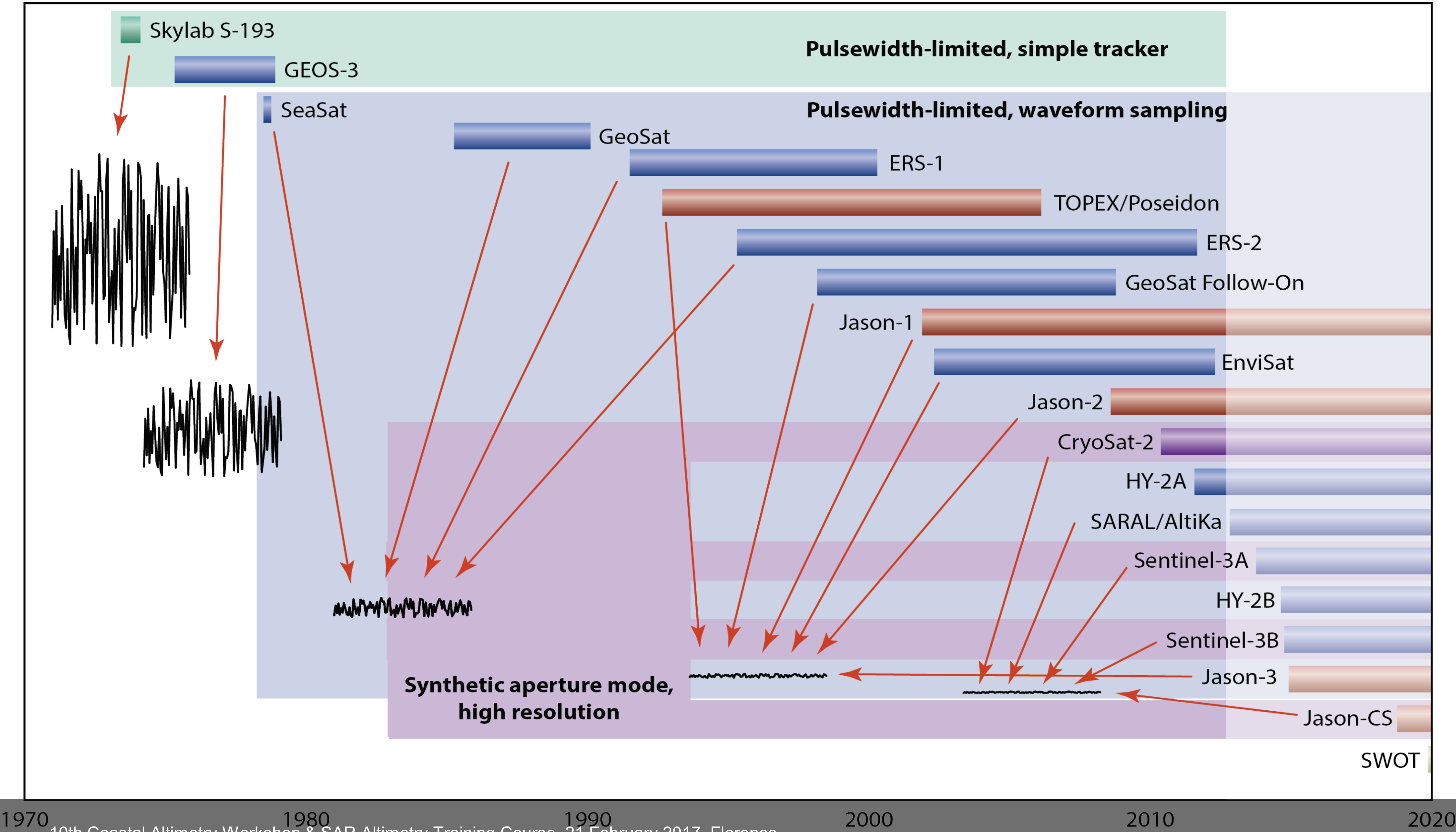
CPOM/UCL/ESA/Planetary Visions

Current missions:
High resolution modes

Altimetry missions



Techniques



Skylab S-193
GEOS-3
Pulsewidth-limited, simple tracker
SeaSat
Pulsewidth-limited, waveform sampling
GeoSat
ERS-1
TOPEX/Poseidon
ERS-2
GeoSat Follow-On
Jason-1
EnviSat
Jason-2
CryoSat-2
HY-2A
SARAL/AltiKa
Sentinel-3A
HY-2B
Sentinel-3B
Jason-3
Jason-CS
SWOT
Synthetic aperture mode, high resolution
1970
1980
1990
2000
2010
2020

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

isardSAT®

Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

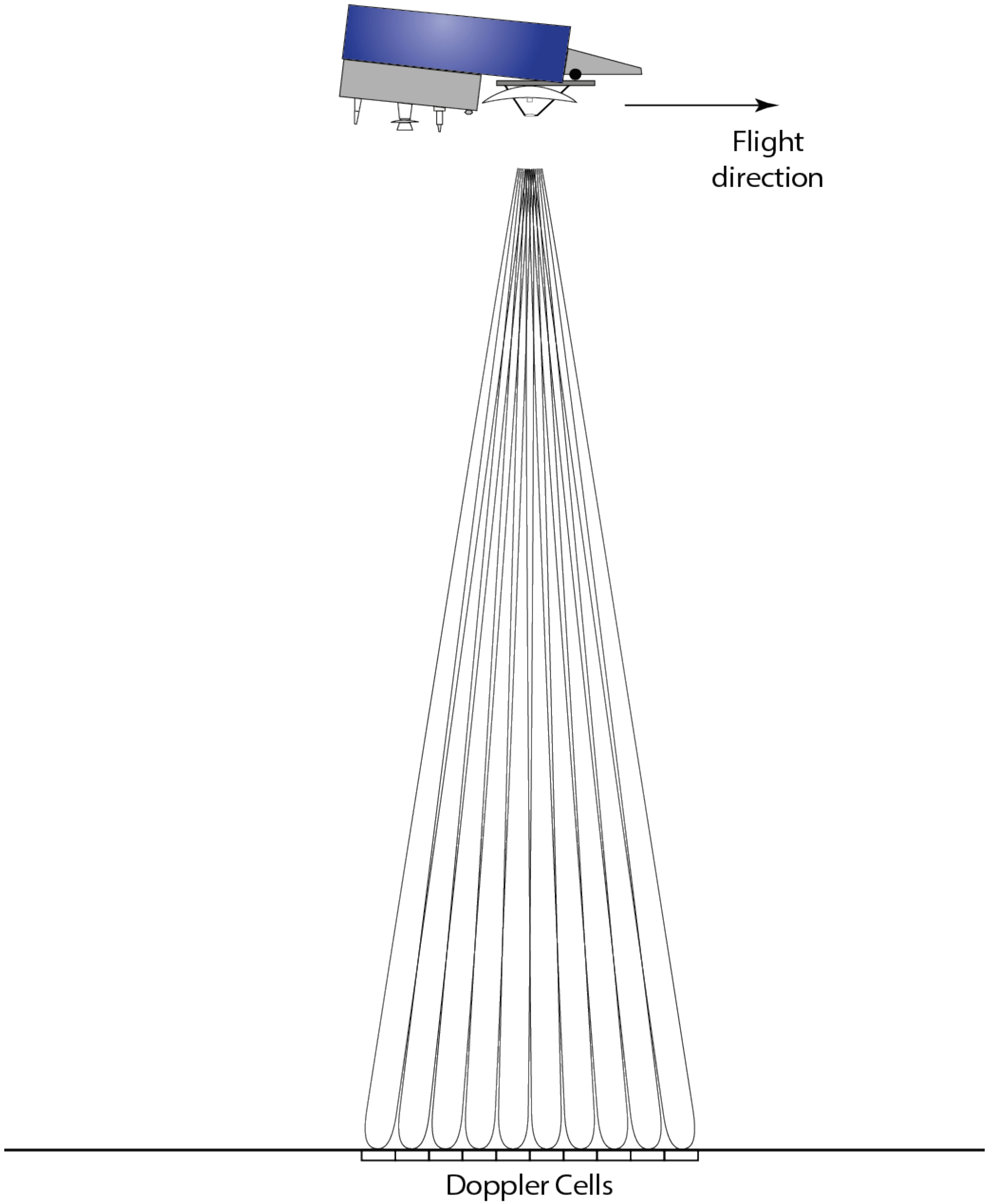
Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

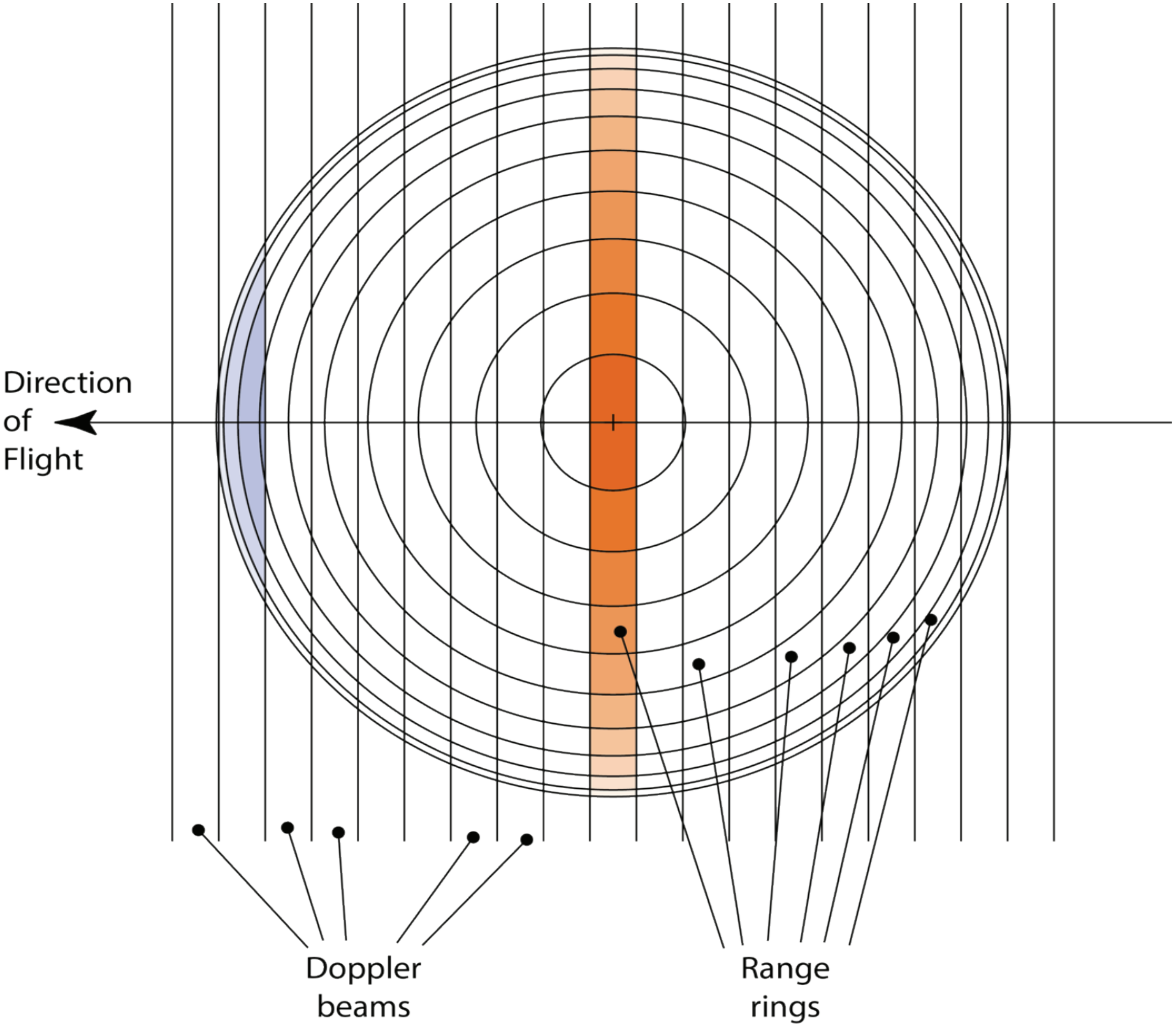
Current Techniques

- CryoSat: SIRAL
  - high resolution Synthetic Aperture mode
  - interferometer
- Sentinel-3: SRAL
  - high resolution Synthetic Aperture mode
- AltiKa: SARAL
  - High-frequency pulse-width limited
  - Ka-band
  - integrated microwave radiometer
  - increased bandwidth: increased resolution
- Sentinel-6/Jason-CS: Poseidon-4
  - conventional Ku-band and C-band
  - multiple new technologies
- SWOT
  - wide-swath, Ka-band system

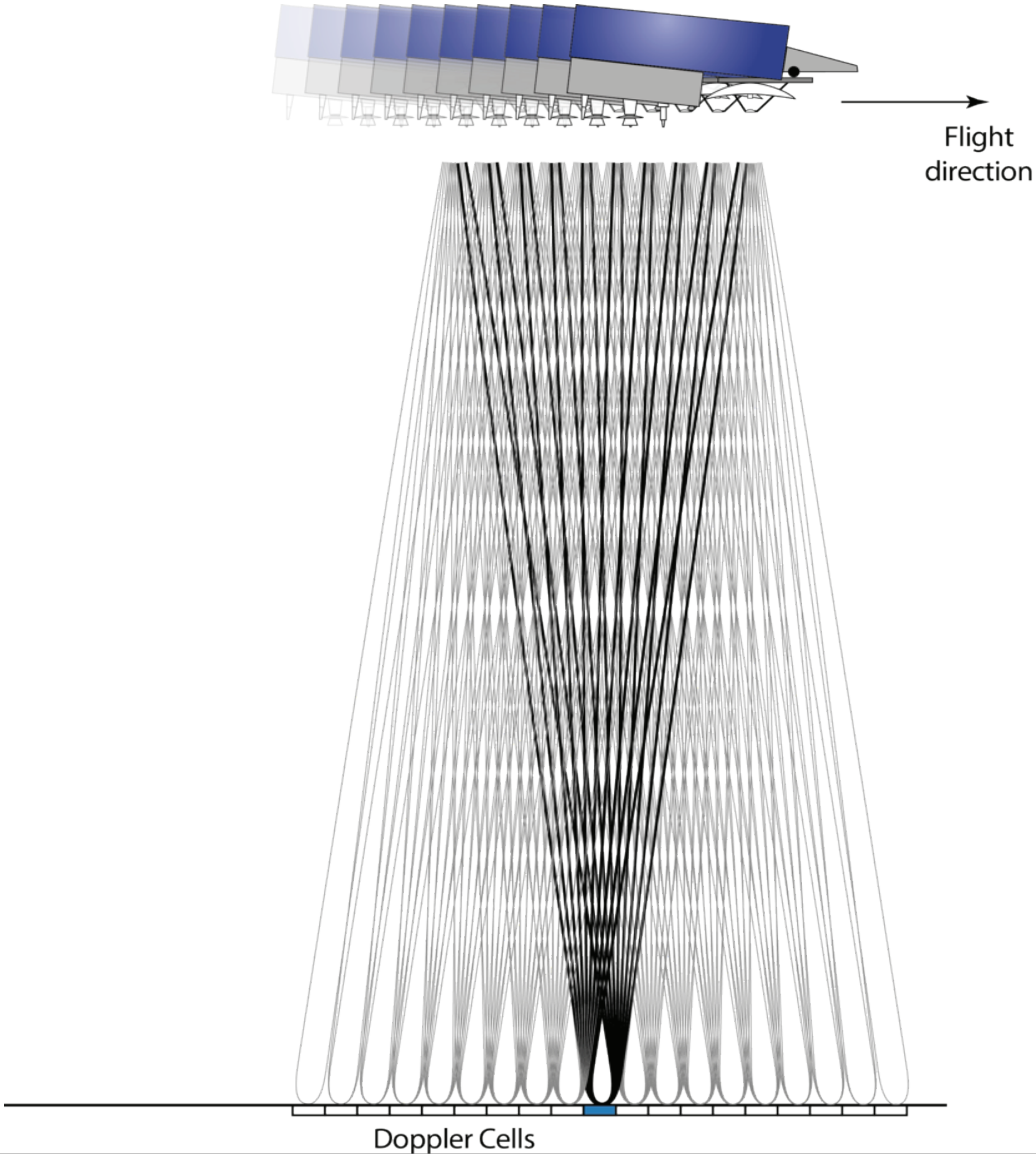
SAR Altimetry (1)

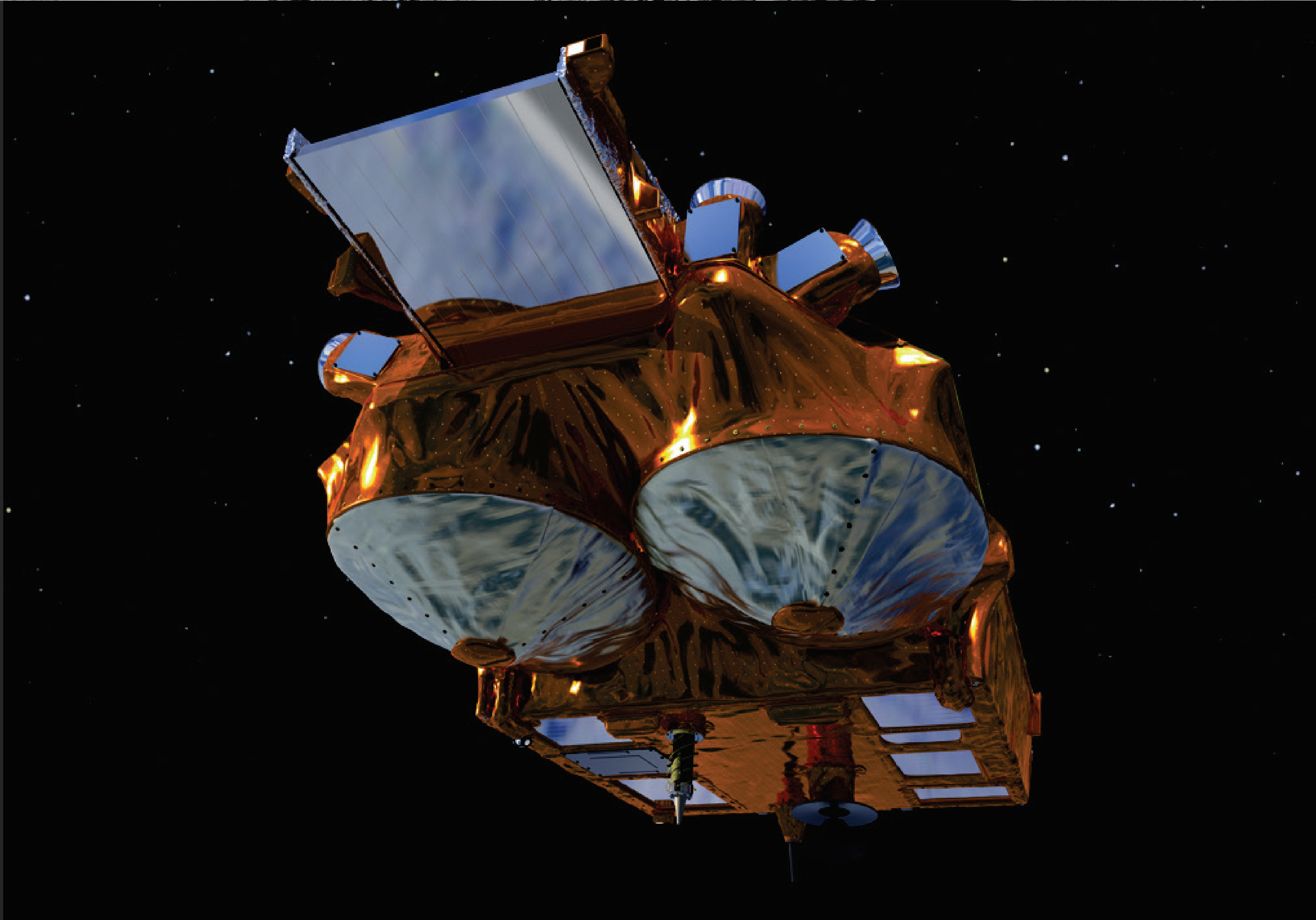


SAR Altimetry (2)

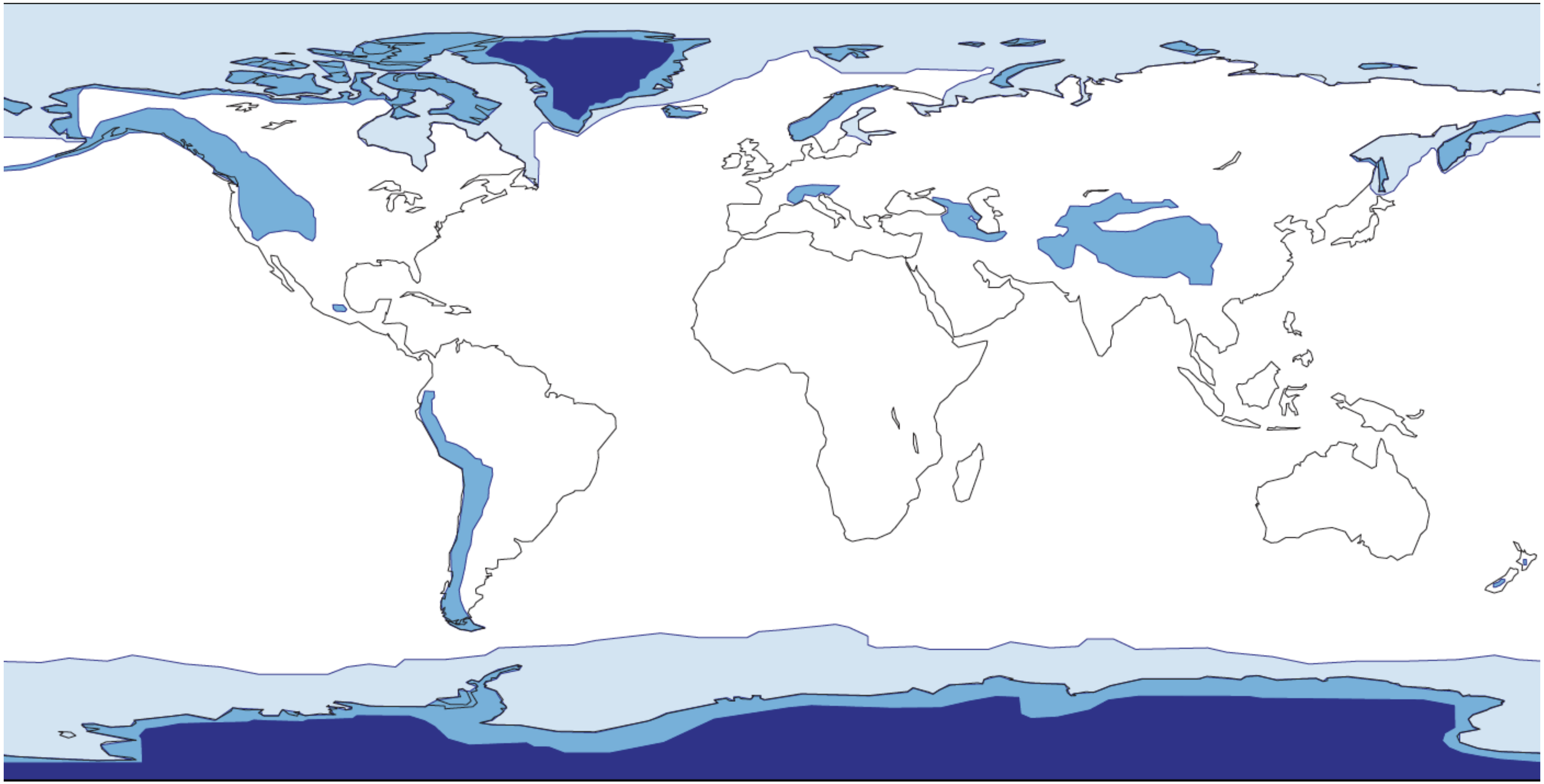


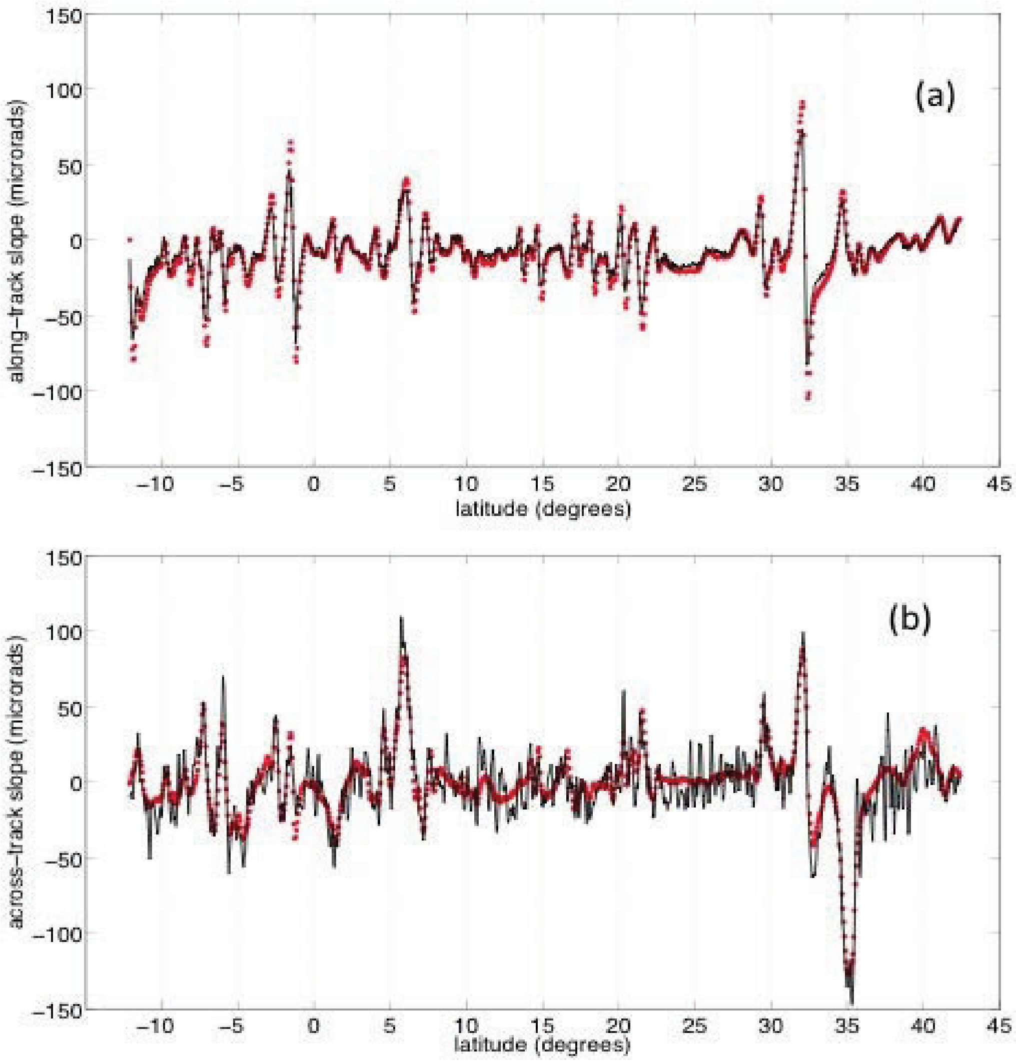
SAR Altimetry (3)





The medium shaded areas are regions of high surface slope – these are being measured using the SARIn mode.





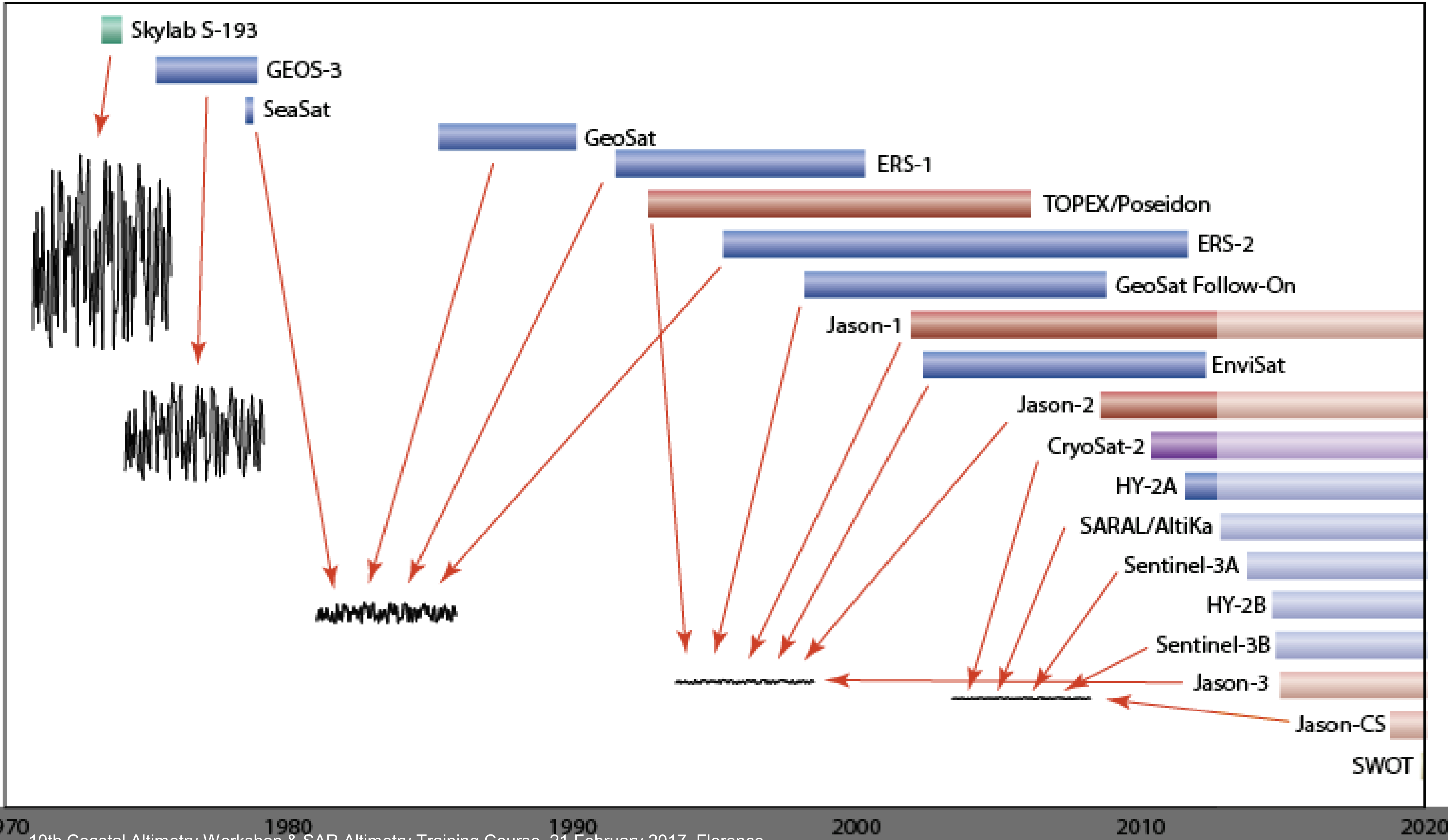
Black: SIRAL
Red: EGM08

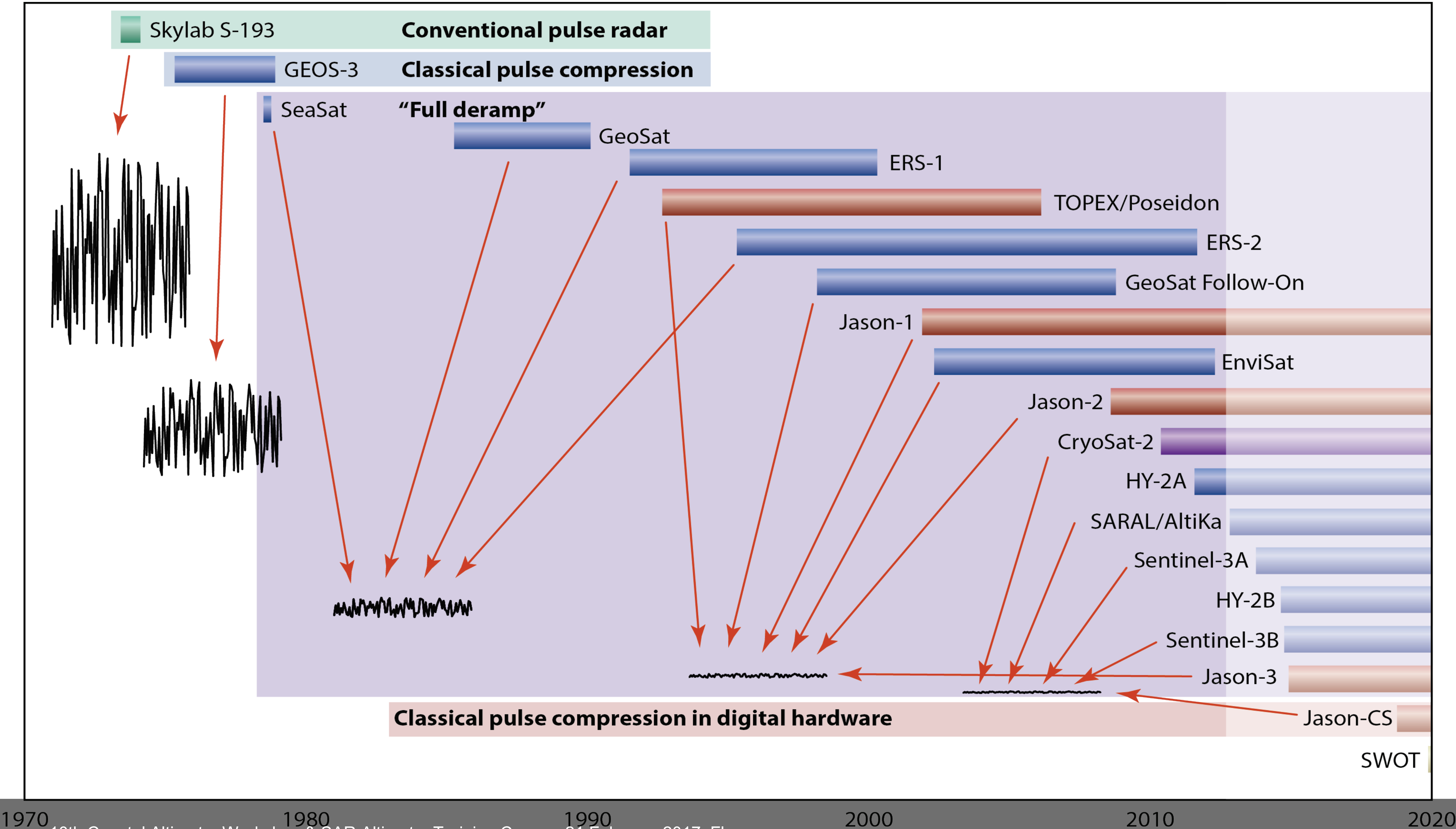
UCL/ESA/NOAA

2-D Ocean Surface Gradient from Interferometry

Newest developments

Noise in altimetry missions

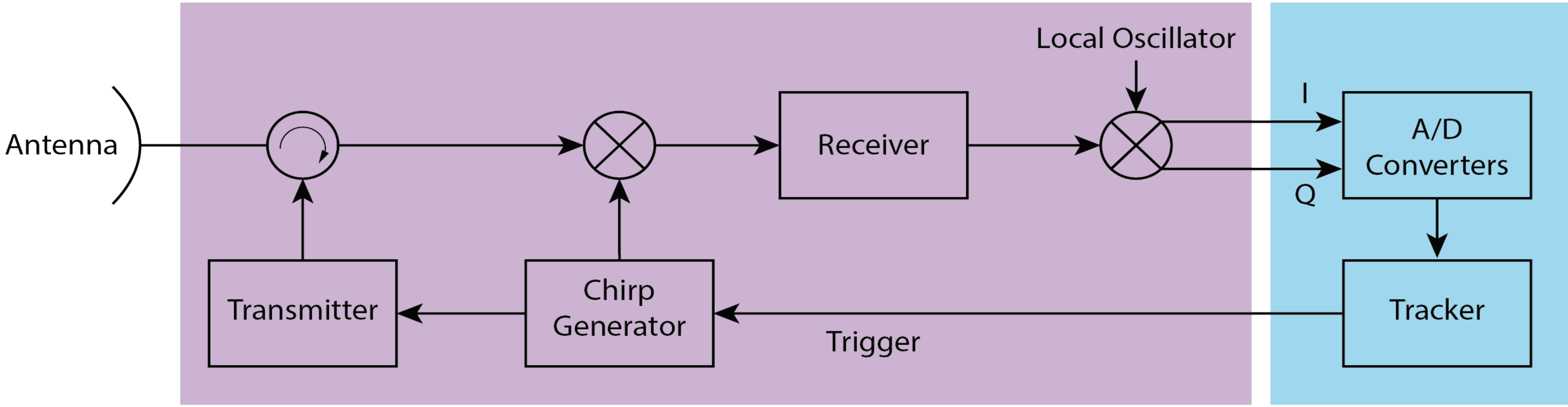



Skylab S-193
Conventional pulse radar
GEOS-3
Classical pulse compression
SeaSat
"Full deramp"
GeoSat
ERS-1
TOPEX/Poseidon
ERS-2
GeoSat Follow-On
Jason-1
EnviSat
Jason-2
CryoSat-2
HY-2A
SARAL/AltiKa
Sentinel-3A
HY-2B
Sentinel-3B
Jason-3
Classical pulse compression in digital hardware
Jason-CS
SWOT
1970
1980
1990
2000
2010
2020

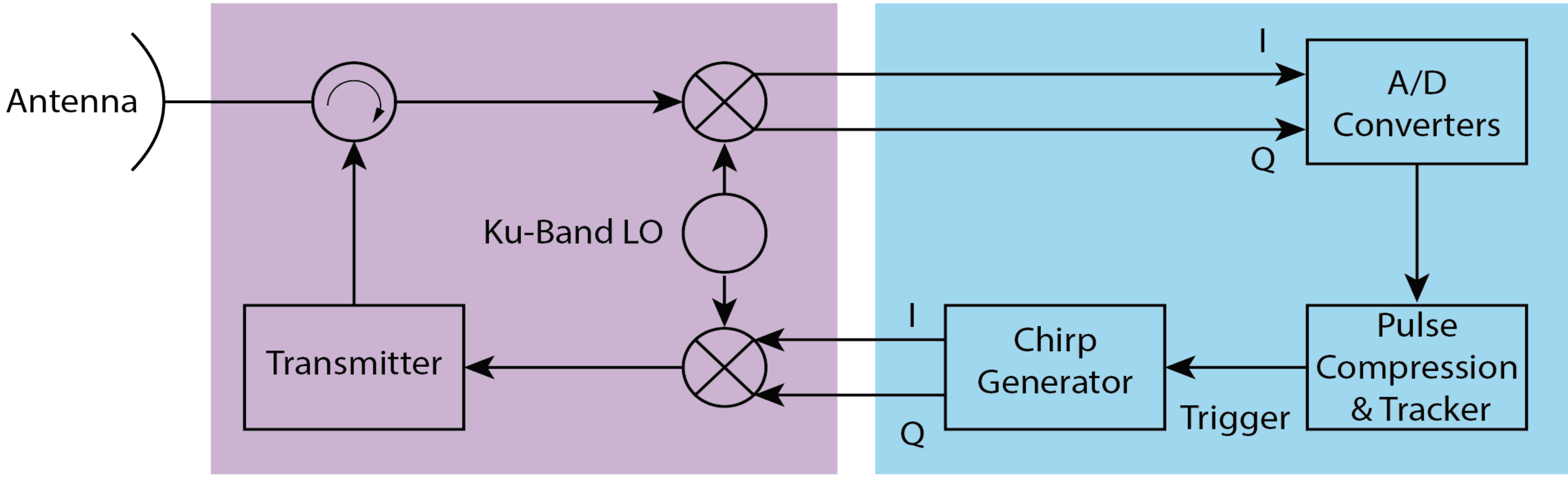
Digital Architecture (1)

- Original SeaSat (1978) concept of full deramp used by all subsequent altimeters
- Boundary between digital and RF hardware continually evolved
- Chirp generator required frequency multiplication (analog or digital)

Digital Architecture (2)

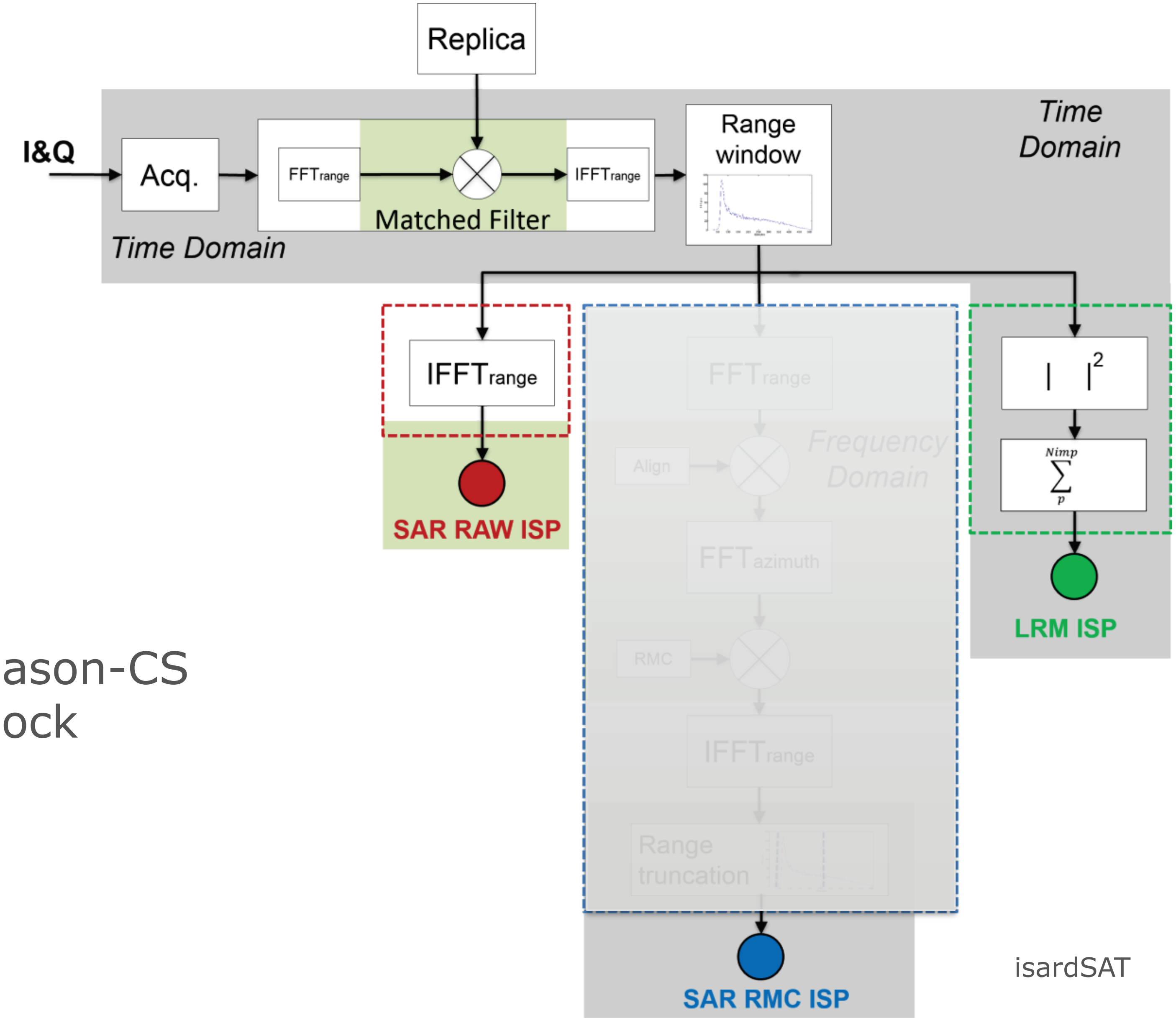


SeaSat



Sentinel-6/Jason-CS

Matched filter



Sentinel-6/Jason-CS high level block diagram

isardSAT

Chronograms

Classical ("Low Resolution") Mode

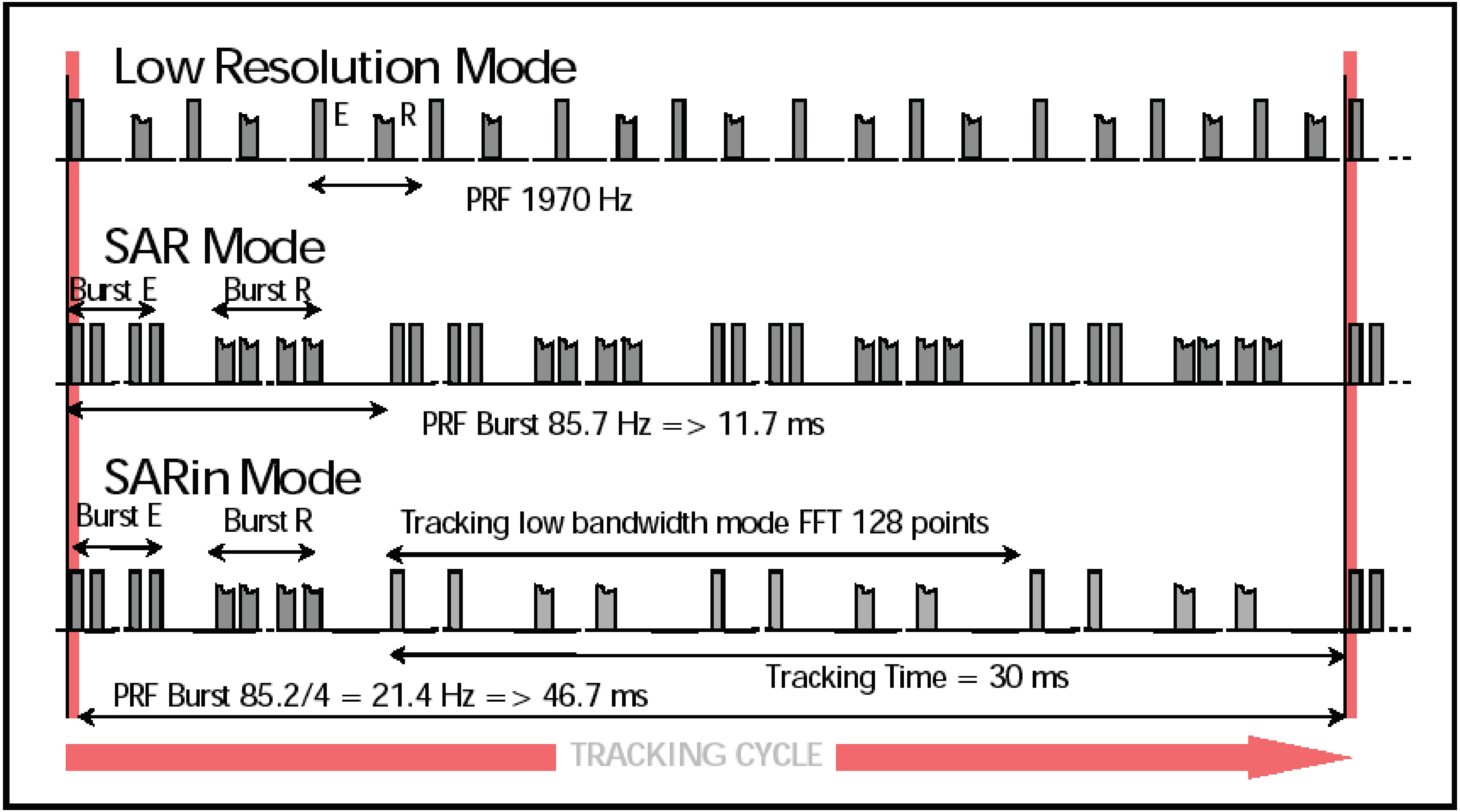
Thales Alenia Space

SAR (“High Resolution”) Mode

Thales Alenia Space

isardSAT®

SAR/SARin ("High Resolution") Mode



“Interleaved” Mode

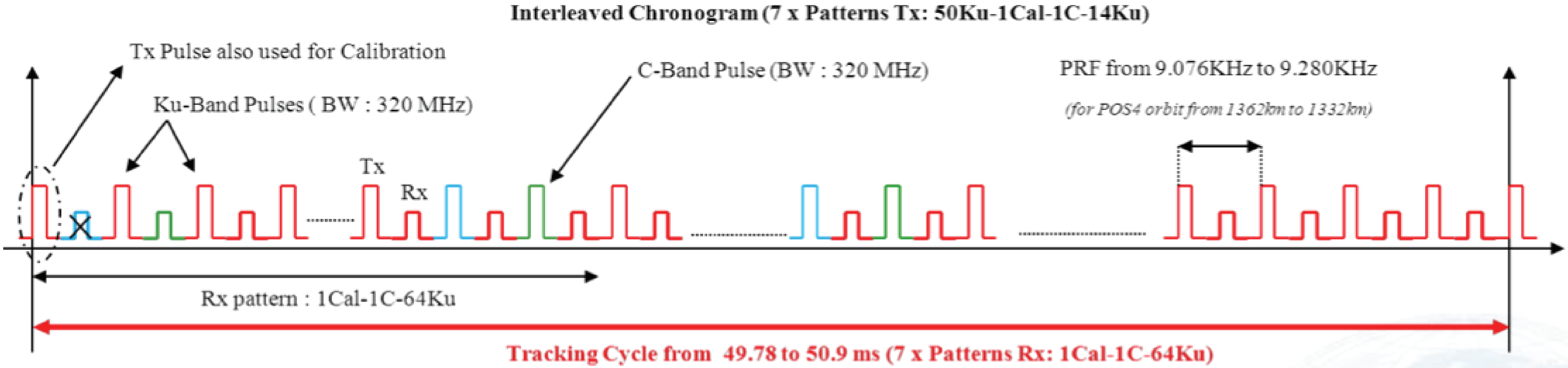
- A further mode is under development o Thales Alenia Space for Sentinel-6/Jason-CS:
  - continuous transmission of pulses at ~9 kHz
  - receive window between each transmitted pulse
  - requires adaptive PRF to accommodate altitude changes
  - 1 out of *n* pulses is a C-band pulse

- Enables simultaneous SAR and LRM operation

Sentinel-6/J-CS Interleaved

– PRF ~ 9 KHz   Careful with Doppler ambiguities !

PRF (or PRI) changes around the orbit.
PRF constant in reception.



Thales Alenia Space

Conclusions

Conclusions

- Altimetry from space has been used for almost 40 years and continuously since 1991
- Its original promise has been realised and exceeded
- Today it is a vital tool in operational oceanography
- New techniques, under development now, will enable improved performance in the future.

Thank you !