-The SMOS Mission-

N.REUL

French Research Institute for the Exploration of the Sea

Oceanography from Space Laboratory

Outline

- Why measuring salinity of the ocean?
- How ?

=> the ESA Soil Moisture and Ocean Salinity (SMOS) mission

Why?

Why about salinity ?

And

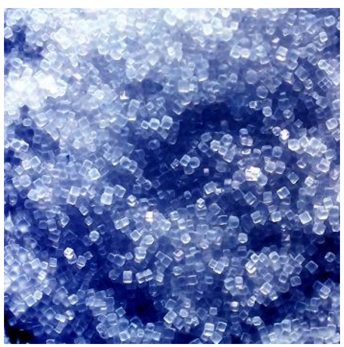
Why about SMOS ?

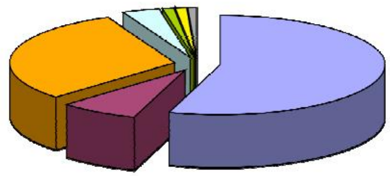
Salinity of the Ocean: What do we know about it ?

What is ocean salinity ?

Ocean salinity S≡ ionic salt concentration in sea water
At the sea surface it is referred to as "SSS" (Sea Surface Salinity)

Unity = PSU (Practical Salinity Unit)
1 PSU≈ 1 g/kg.





Chloride (Cl^-):	**19 g**
Sodium (Na^+):	**11 g**
Sulphate (SO_4^{--}):	**3 g**
Magnesium (Mg^{++}):	**1.5 g**
Calcium (Ca^{++}):	**0,35 g**
Potassium (K^+):	**0,35 g**
Others :	**0,00.. g**

Total ≈ 35 g/kg

(Mean chemical composition)

99% of oceanic waters have salinity between 33.1 and 37.2:
=>a global variation in salt concentration between 3.31% and 3.72% !

In Situ measurement of Salinity:
The Practical Salinity Scale-1978 / EOS-80

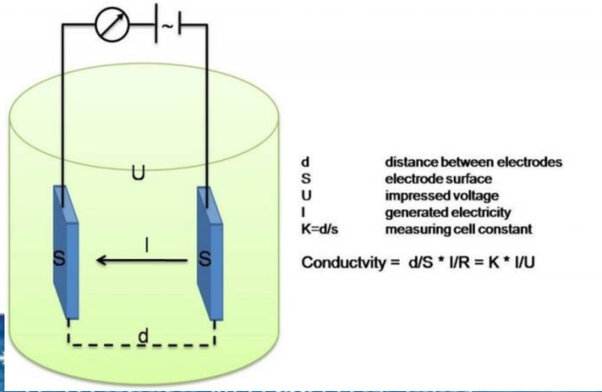
1) Relation between **salinity** and **conductivity** ratio:

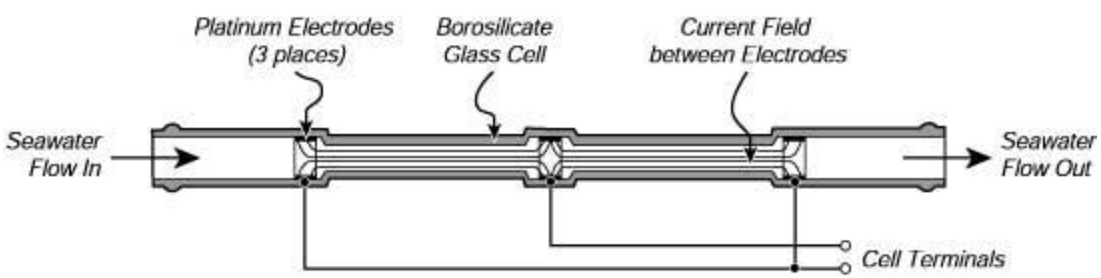
$$S = 0.0080 - 0.1692 R_T^{\frac{1}{2}} + 25.3853 R_T + 14.0941 R_T^{\frac{3}{2}} - 7.0261 R_T^{2} + 2.7081 R_T^{\frac{5}{2}} + \Delta S$$

where $R_T = \dfrac{C(S,T,0)}{C(KCl,T,0)}$ and $\Delta S = f(T, R_T)$

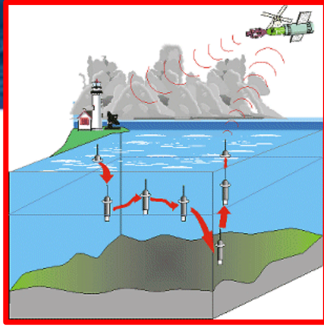
where *C (S, T, 0)* is the conductivity of the sea-water sample at temperature *T* and standard atmospheric pressure, and *C (KCl, T, 0)* is the conductivity of the standard potassium chloride (KCl) solution at temperature *T* and standard atmospheric pressure

2) **Salinity is a ratio and not a physical parameter**: what is measured is conductivity:

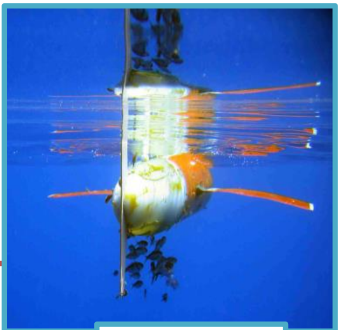




In Situ measurements of S



Profilers from the Argo network



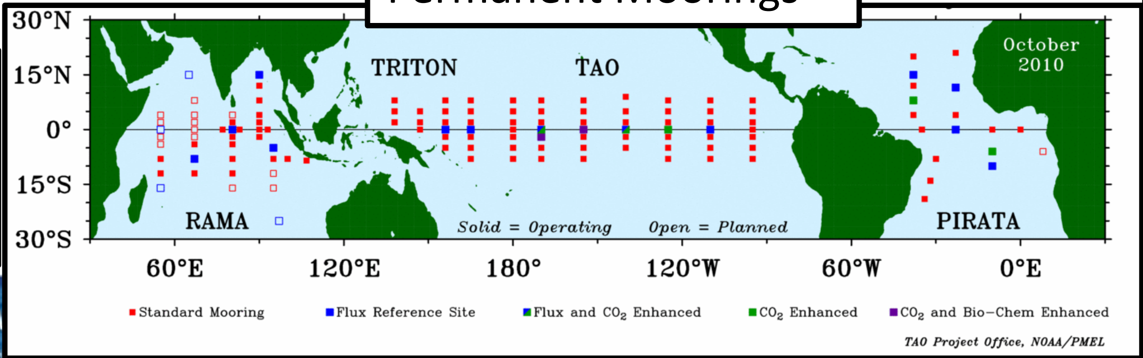
Gliders

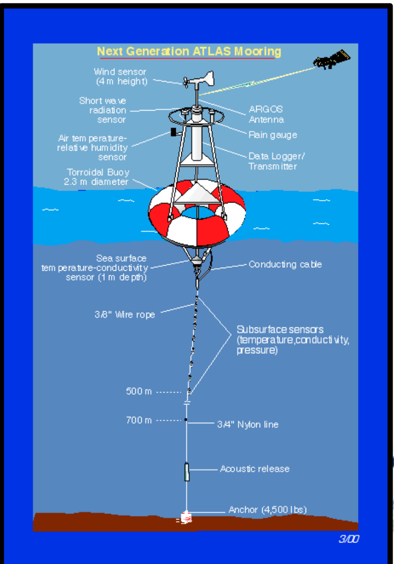
Surface ‘Drifters’

Equipped Mammals

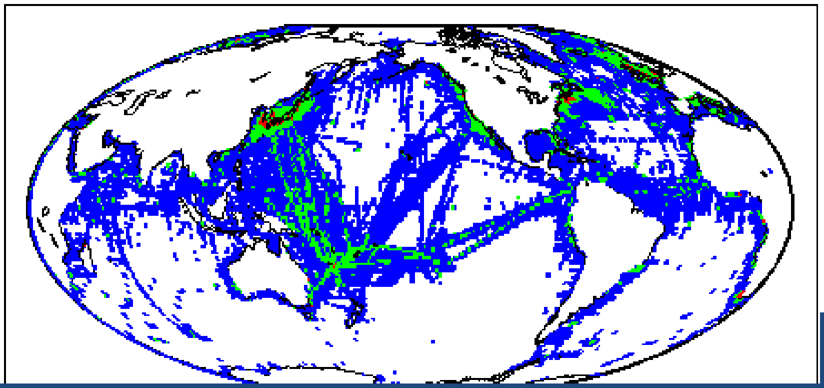
Thermo-salinographs
Installed onboard reasearch
Vessels and ships of opportunity

Permanent Moorings





Historical Density of surface observations 1874-2002



White - N < 10
Blue - 10 < N < 100
Green- 100 < N < 1000
Red - 1000 < N

F. Bingham et al, 2002

1.3 million SSS observations distributed over the global ocean since 125 years:

✓ No data in 27% elementary oceanic 1° x1° area, not accounting for arctic zones.

✓70% of these surfaces present at most 10 historical observations

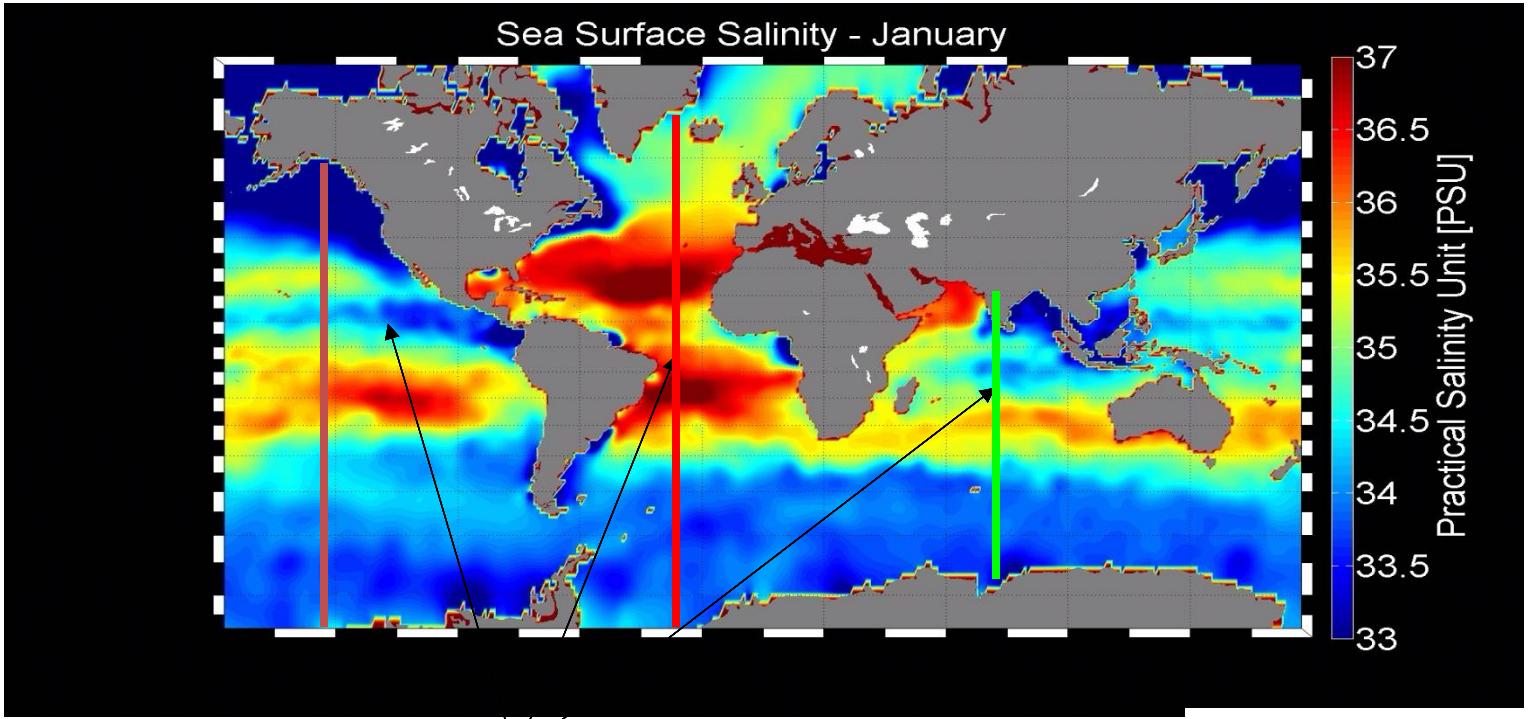
✓28% of all observations were sampled in the coastal domain

✓ Up to 1960, there was no more than 10,000 observations/year ⇔ 1 observation per 4°X4° cell

✓Since 2002, very net increase in the density of measurements (ARGO network)

Global distribution of the SSS

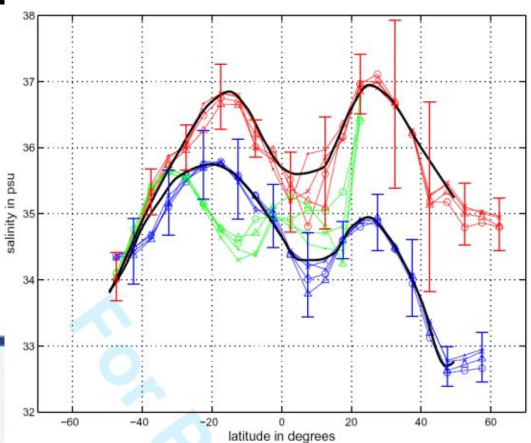
Monthly climatology of the sea surface salinity:



Atlantic Ocean saltier than Pacific and Indian oceans

✓ Low variability particularly in the Southern seas and North Pacific

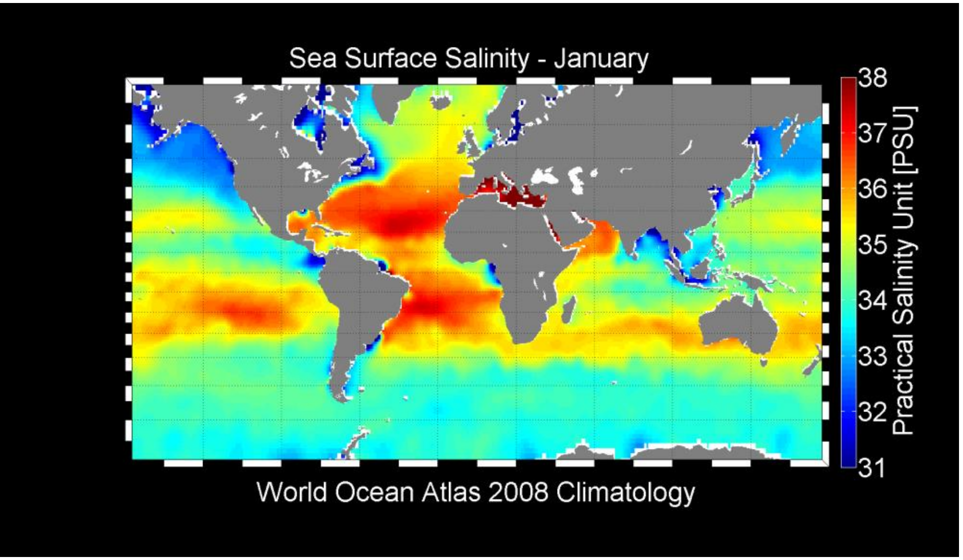
✓But higher variability around large river run off (Amazon Congo, Yang Tse, Ganga..), largest currents (Gulf Stream, kuroshio, Agullas, …) & in the Tropical bands

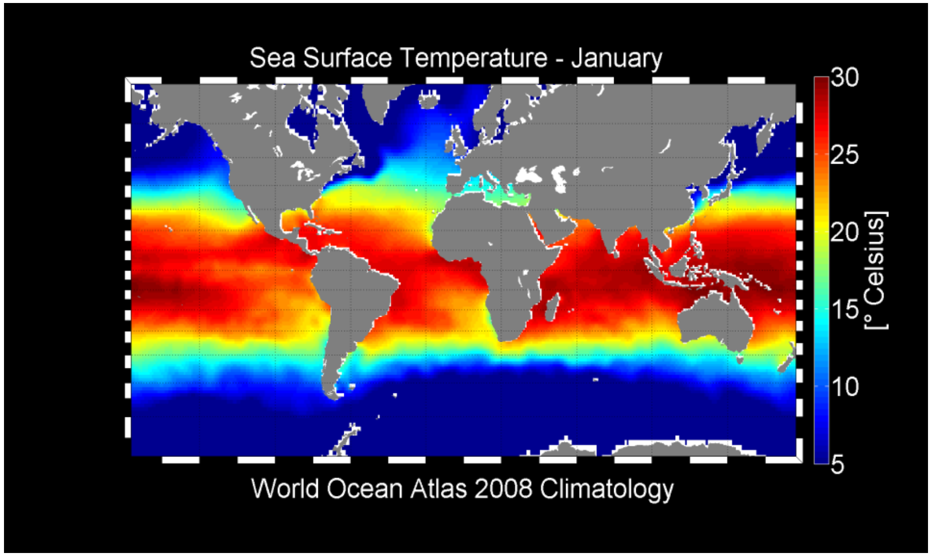


Salt versus temperature at the Ocean Surface

Salinity

Temperature





Global and seasonnal distributions of surface salinity strongly differ from the surface temperature one.
It is because the processes involved and sources responsible for their own variability are different:

➢Ocean are heated in the Tropics and lose heat at higher latitutes

➢Salinity is modified by dilution-concentration processes associated with the fresh water fluxes.
The latter result from the balance between precipitation, evaporation, ice melting/pounding and river run off.

Why Measuring Ocean Salinity From Space ?

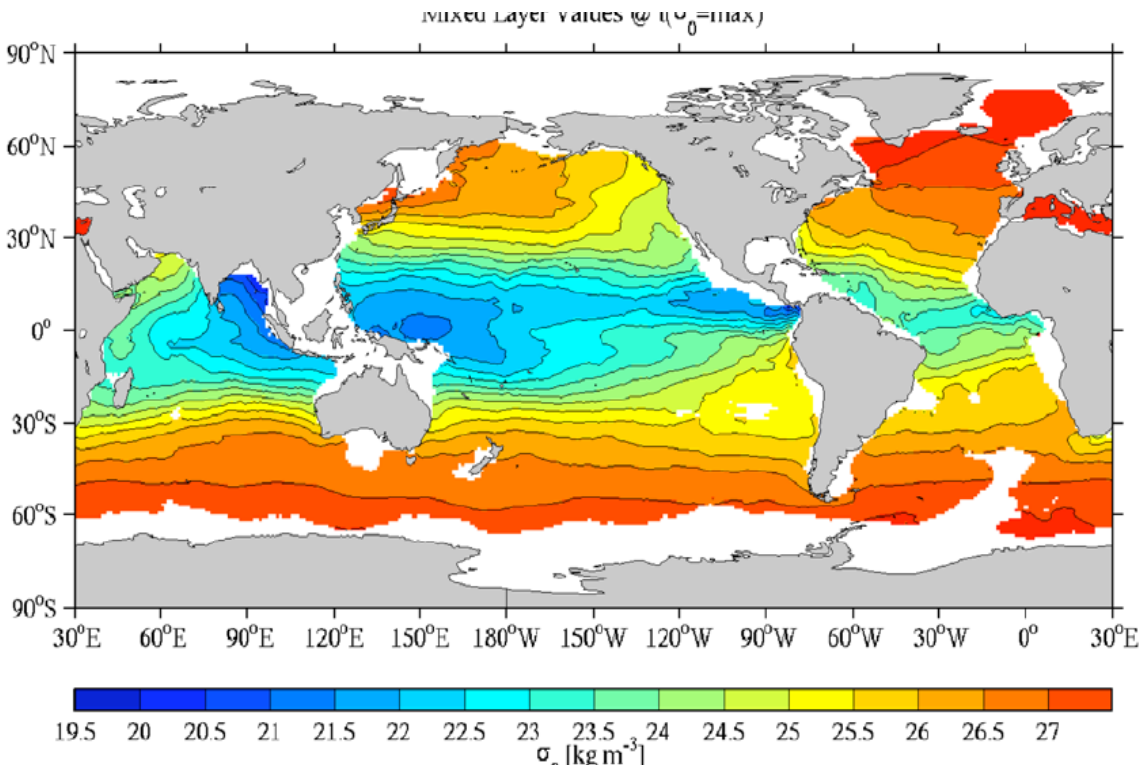
Salinity & Temperature: indicators of water masses thermo-dynamical state

Salinity S & Temperature T are indicators of the water masses density ρ:

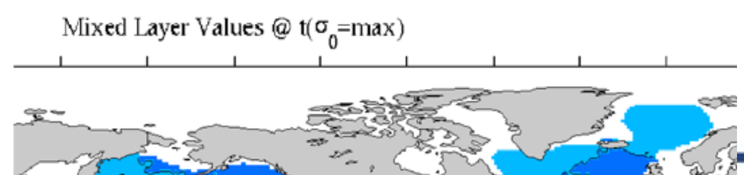
$$\rho_{sw}(S,T) = \rho_{fw}(T) + b(T)S + c(T)S^{3/2} + dS^2$$

« State equation »

Similar to temperature and humidity for the atmosphere

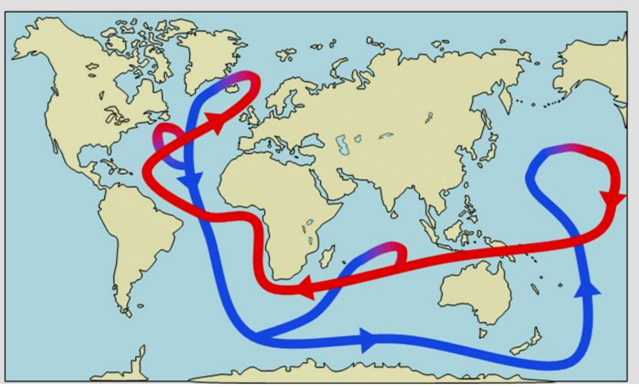


- Denser Poleward
- Equatorial Cold Tongue
- Salty (&Dense) N. Atlantic
- Warm Pool & ITCZ
- Eastern Subtropics
  - Compensating T & S
- Indian Ocean Contrast



The Thermo-Haline Circulation

Idealized global thermohaline circulation (~1000 years)



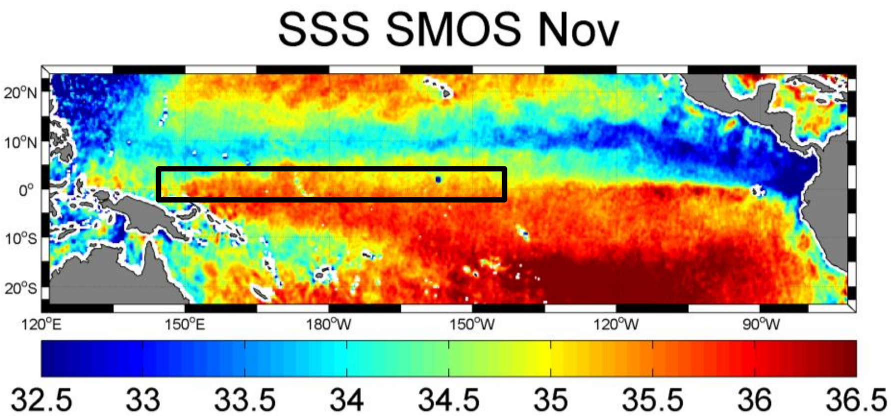
➡ Warm surface currents

➡ Deep cold currents

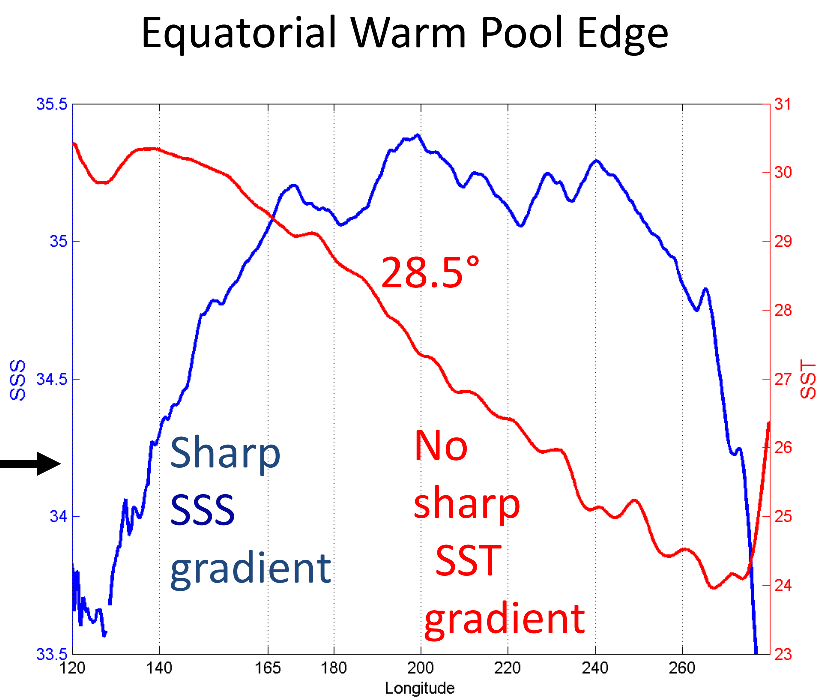
The higher salinity in the Atlantic sustains the oceanic deep overturning circulation

- Conveyor belt . Return period ~1000 years.
- Density differences
- Global scale circulation

Oceanic Fronts Monitoring

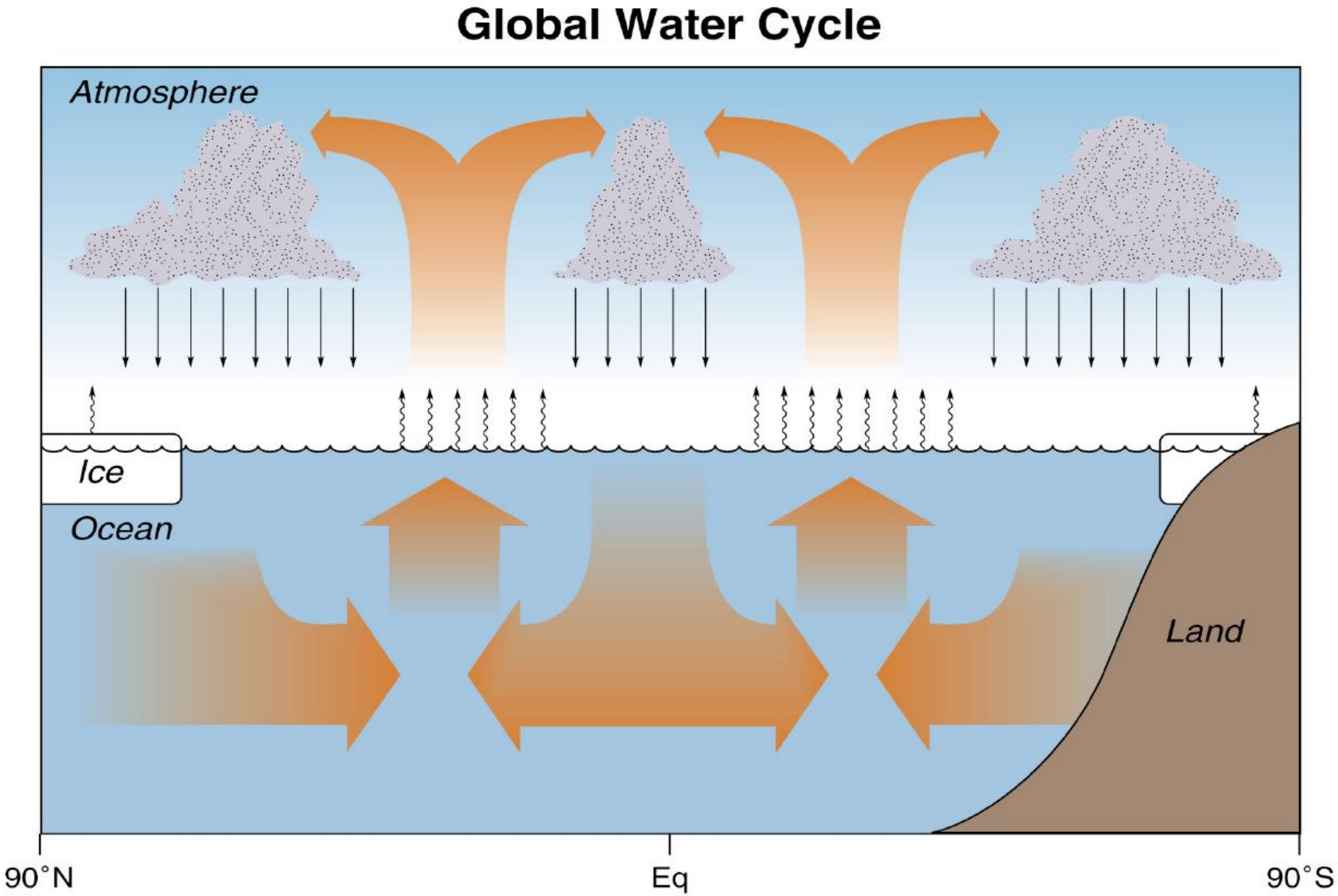


- Oceanic fronts at ocean surface often clearer on SSS than on SST (SST strongly affected by air-sea heat exchanges)



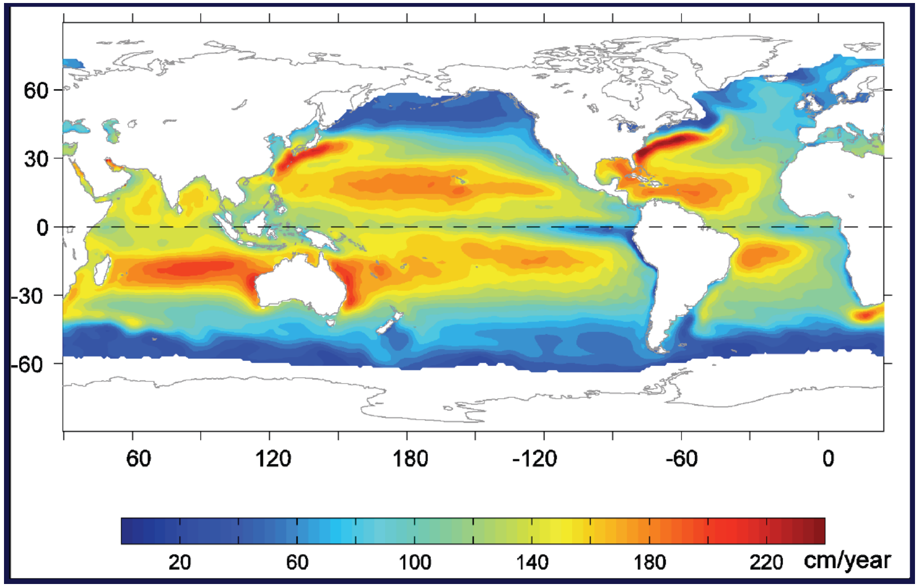
Rodier et al. (JPO, 2000)

The Oceanographer's Water Cycle

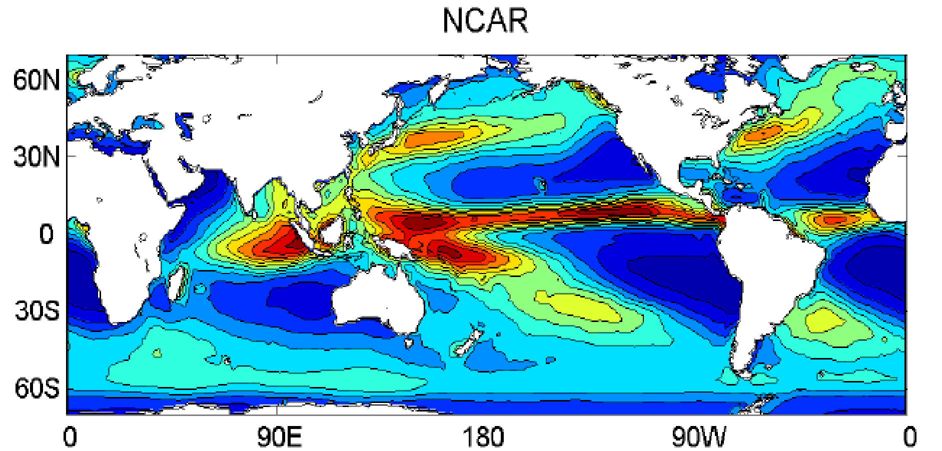


Sea Surface Salinity : an air/sea/land/ice interface proxy of The Global Freshwater Exchanges

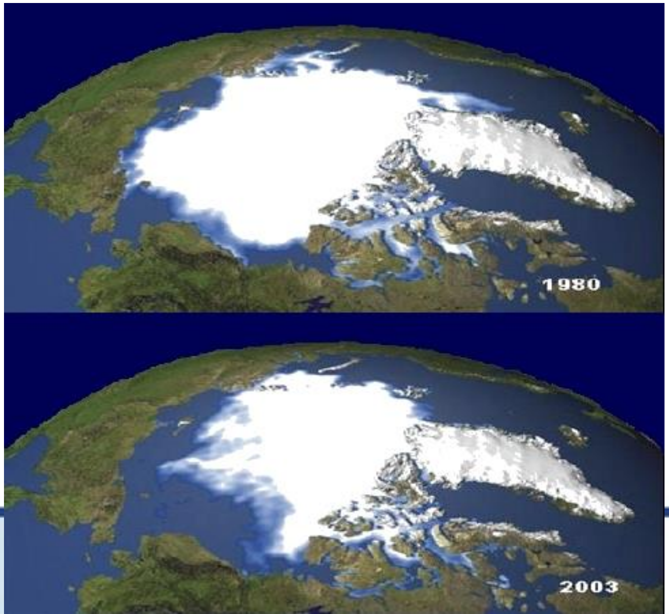
Evaporation



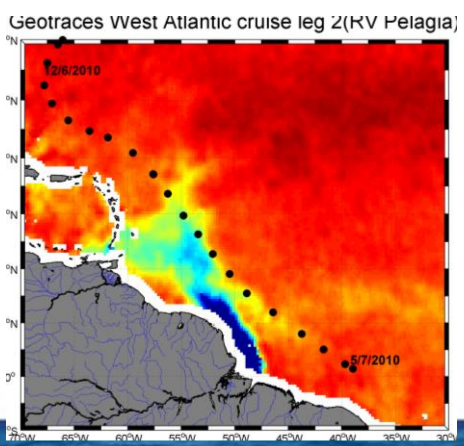
Precipitation



Sea ice Melting/Pounding

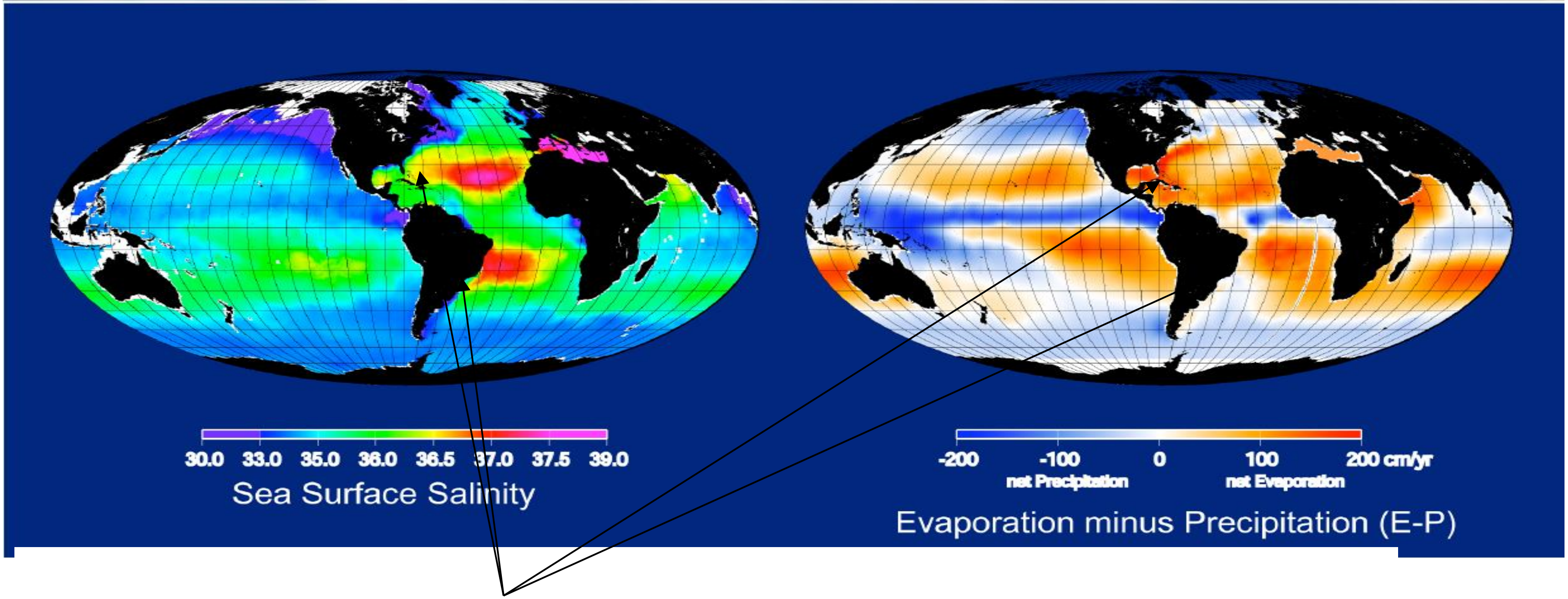


Large River run offs



- 86% of evaporation over the ocean
- 78% of precipitations over the ocean
- => Ocean is a main component of the earth water cycle
- **Sea surface salinity is a tracer of the fresh water flux:**
-

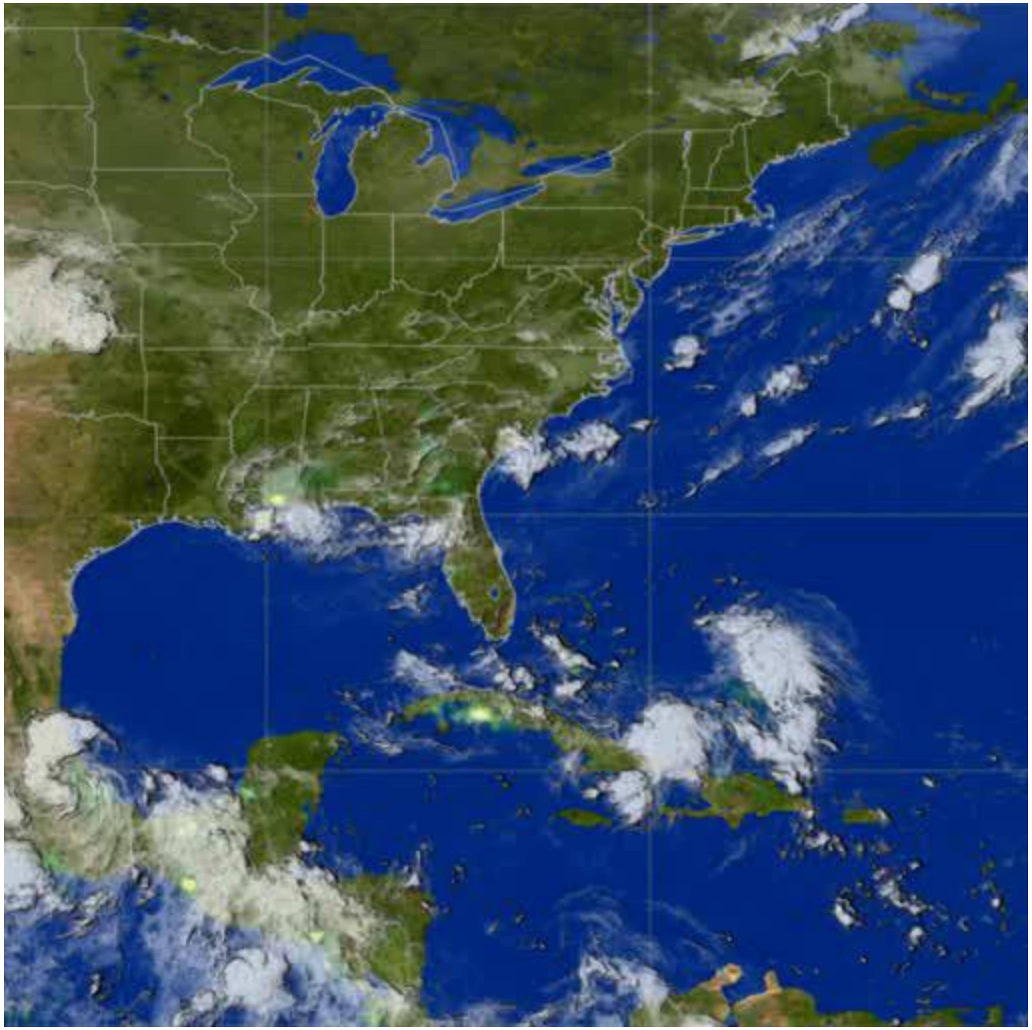
Surface salinity distributions are closely tied to E-P patterns



Evaporation increases in the Sub-tropical areas and so does the surface salinity

Where precipitation dominates, surface salinity decreases. (Equatorial convection zone & mid-latitudes

Salinity wake behind hurricanes



Heavy rainfall

=>
Fresh water lenses ?

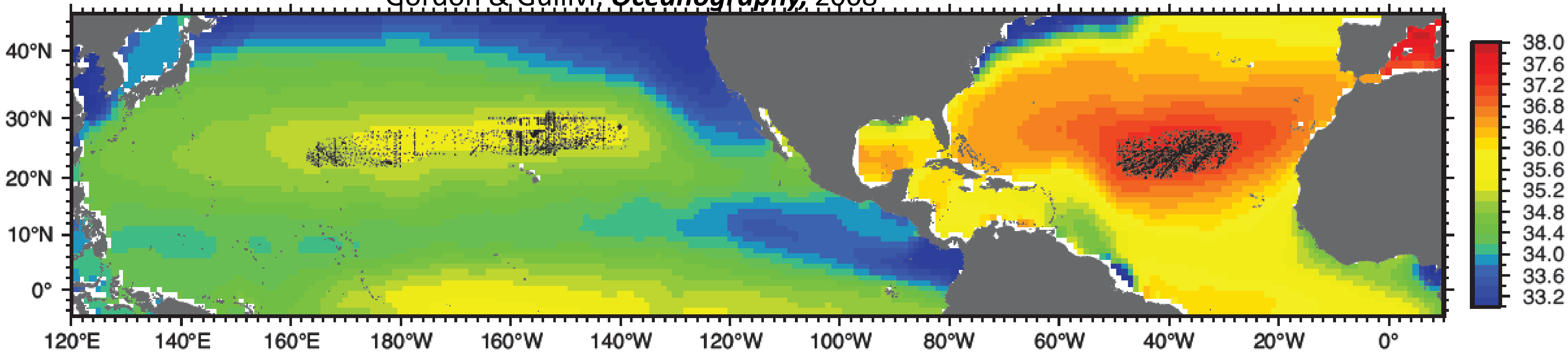
Very large winds=>mixing
And upwellings

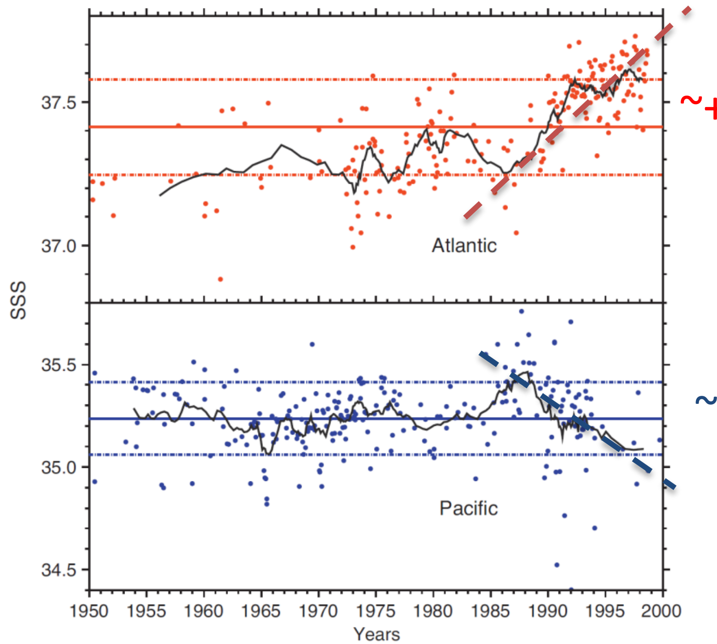
Salty or Fresh water response
Of the upper ocean in the
wakes of Tropical Cyclones?

Sea Surface salinity: a climat change indicator

Trends in Sea Surface Salinity in Pacific and Atlantic Oceans

Gordon & Guilivi, ***Oceanography,*** 2008

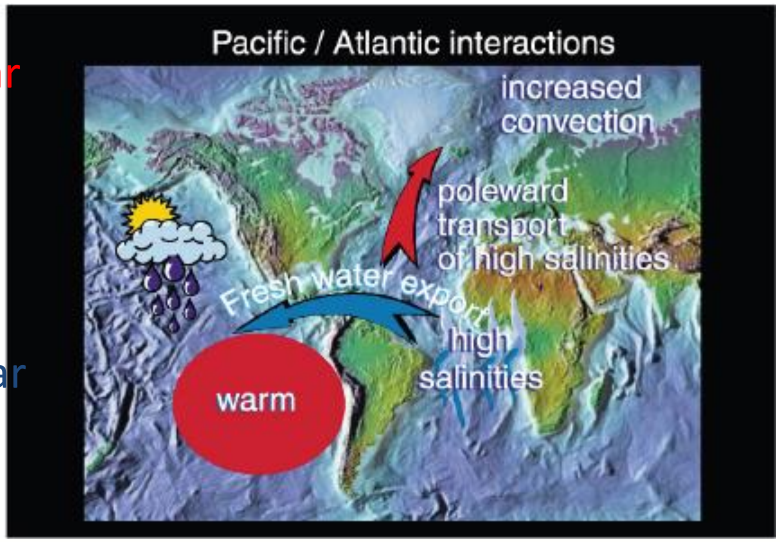




~+0.03 psu/year

~-0.03 psu/year

1950 1987 2000

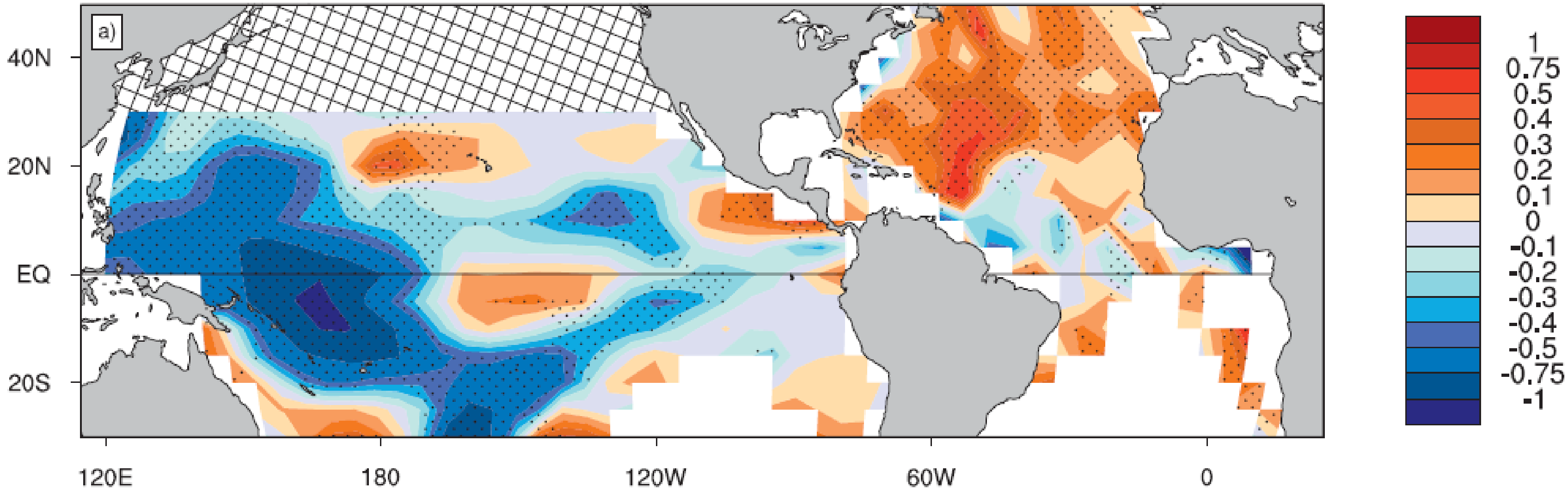


NMCI

Beaufort Research

Near-Surface Salinity as Nature's Rain Gauge to Detect influence of Climate Changes on the Tropical Water Cycle

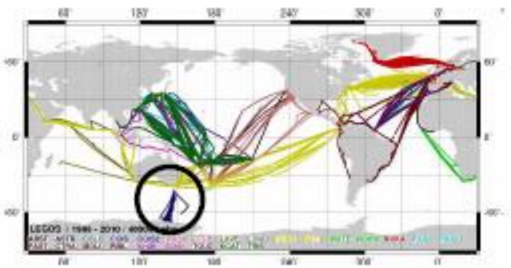
Trends in the observed SSS from *in situ* data over 1970-2002 (PSU/century)



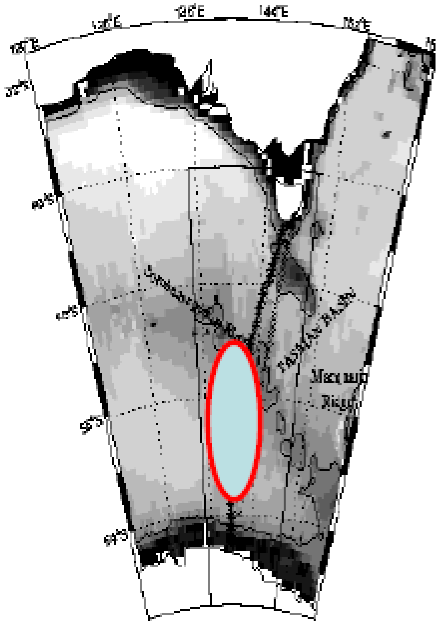
SSS changes over the past decades exhibit a strong Pacific freshening and Atlantic salinity increase leading to a strengthening of the mean SSS interbasin contrast, which reflects to a large extent the mean pattern of freshwater fluxes.

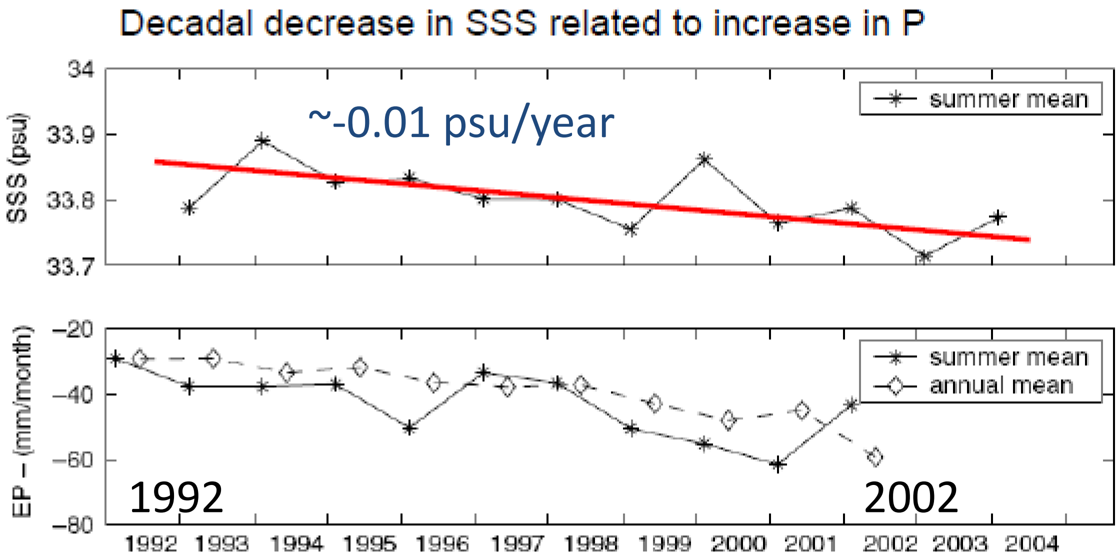
=>We observe a recent increase in the marine tropical hydrological cycle strength (*Terray et al, 2012*).

Trends in SSS in the Antarctic Ocean



10 sections /year since 1993

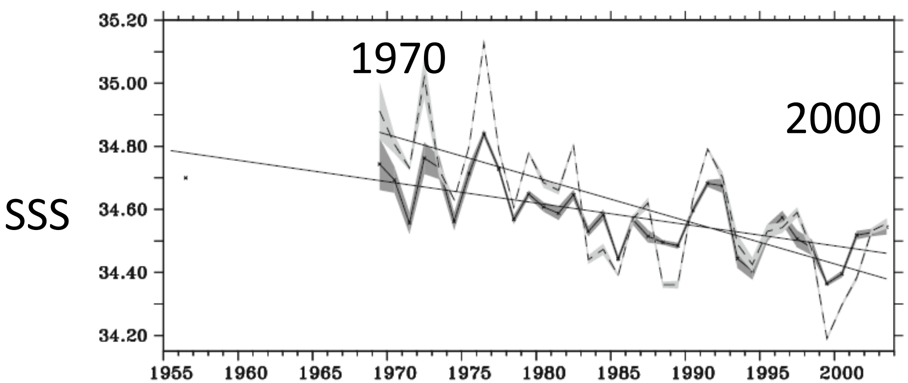




(Morrow et al., 2008)

Trends in Sea Surface Salinity in the Western Tropical Pacific Warm Pool

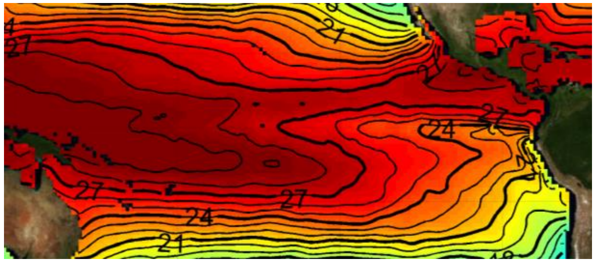
The surface extension of the Warm Pool (equivalent to Europe Area with temperatures>28°C) is associated with a surface salinity freshening



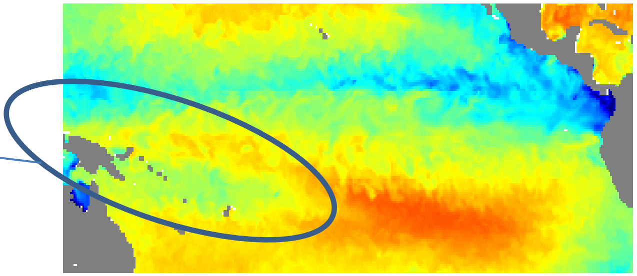
~-0.013 psu/year

Cravatte et al., 2009

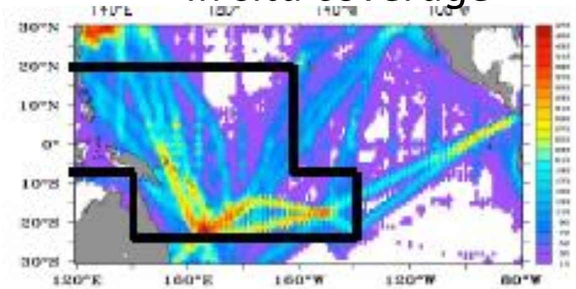
Temperature



Salinity

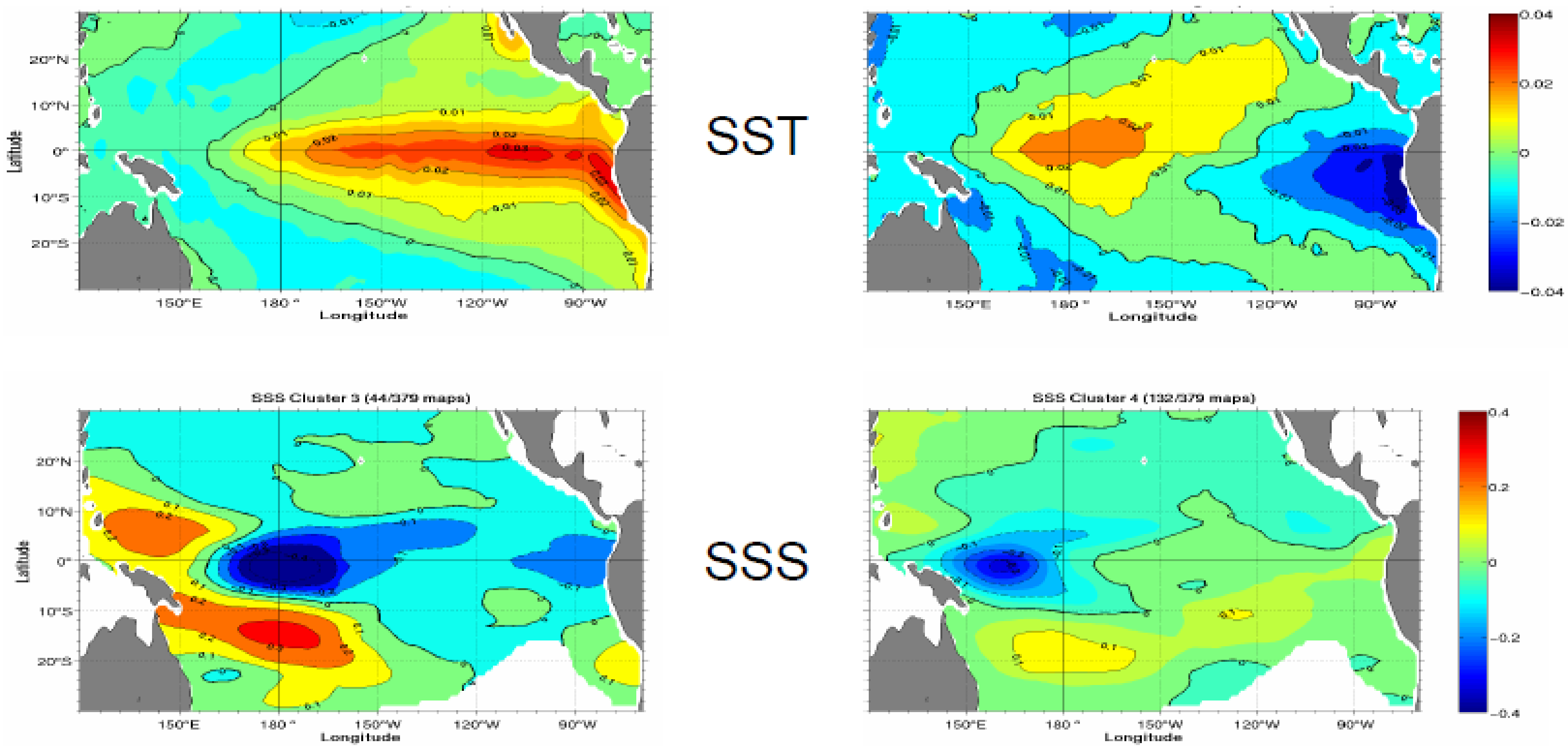


In situ coverage



The spicy waters that change El Niño

Eastern Pacific El Niño | Central Pacific El Niño



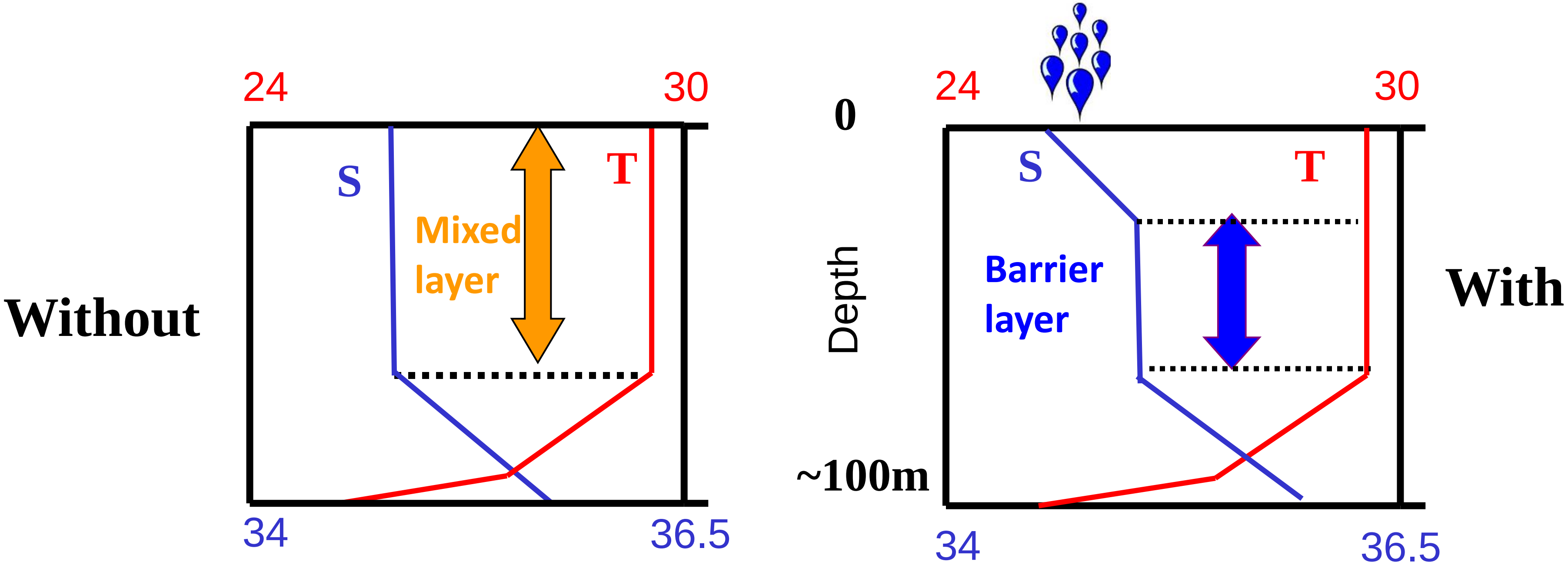
Christophe Maes, 2002
Singh et al., 2010

Salinity of the upper ocean play an important role (barrier-layer effects) in the on-set of the phenomenon. Monitoring this variable will help in better predicting El Niño.

Barrier Layers

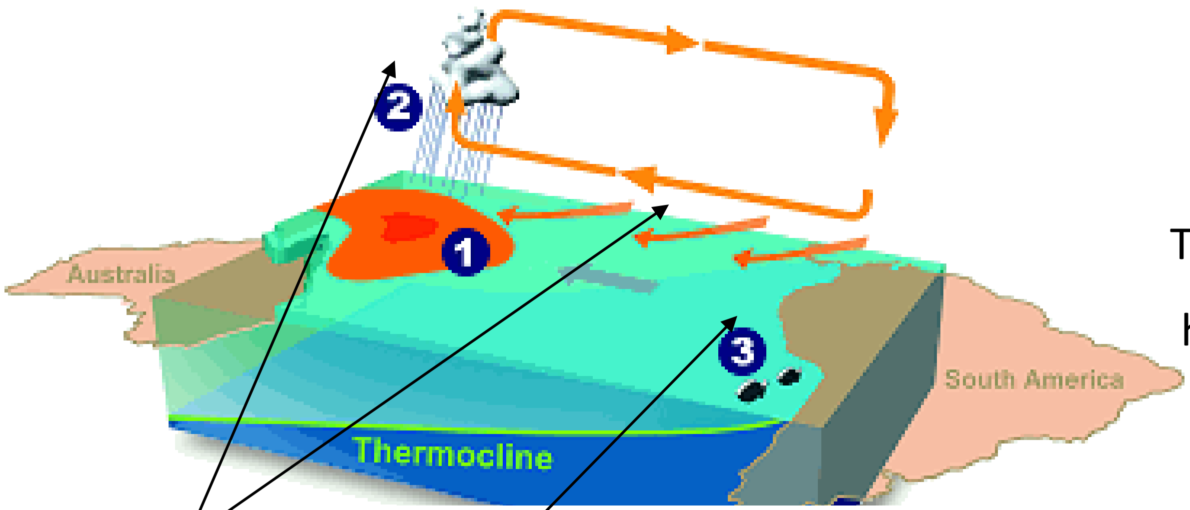
T & S profiles; wo/w barrier layer

Température (T), Salinity (S), Barrier layer, Mixed layer



Barrier Layer acts to isolate surface waters from below and is strongly affecting by air-sea exchanges

Monitoring El Niňo via Salinity»



Thermocline and sea level

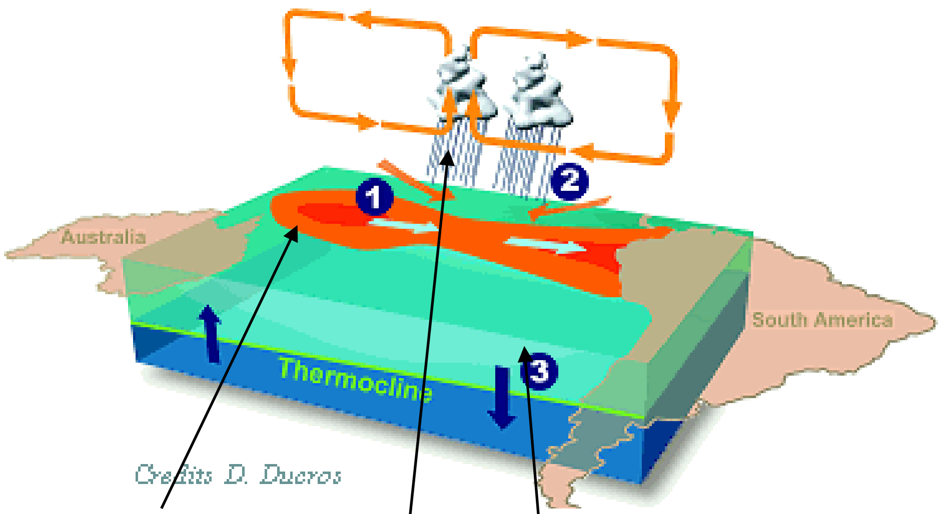
have opposite slopes

1.Trade winds create a warm pool to the west where both temperature and sea level are higher than to the East

2. Crossing the Pacific, warm air is loaded with wetness which lead to heavy rain over the warm pool.

3. On the east side (Chiki and Perou) upwelling (anchovie fishing) A anchois.

When El Niño occurs



1. West winds push the warm poll to the East. Trade winds decrease.

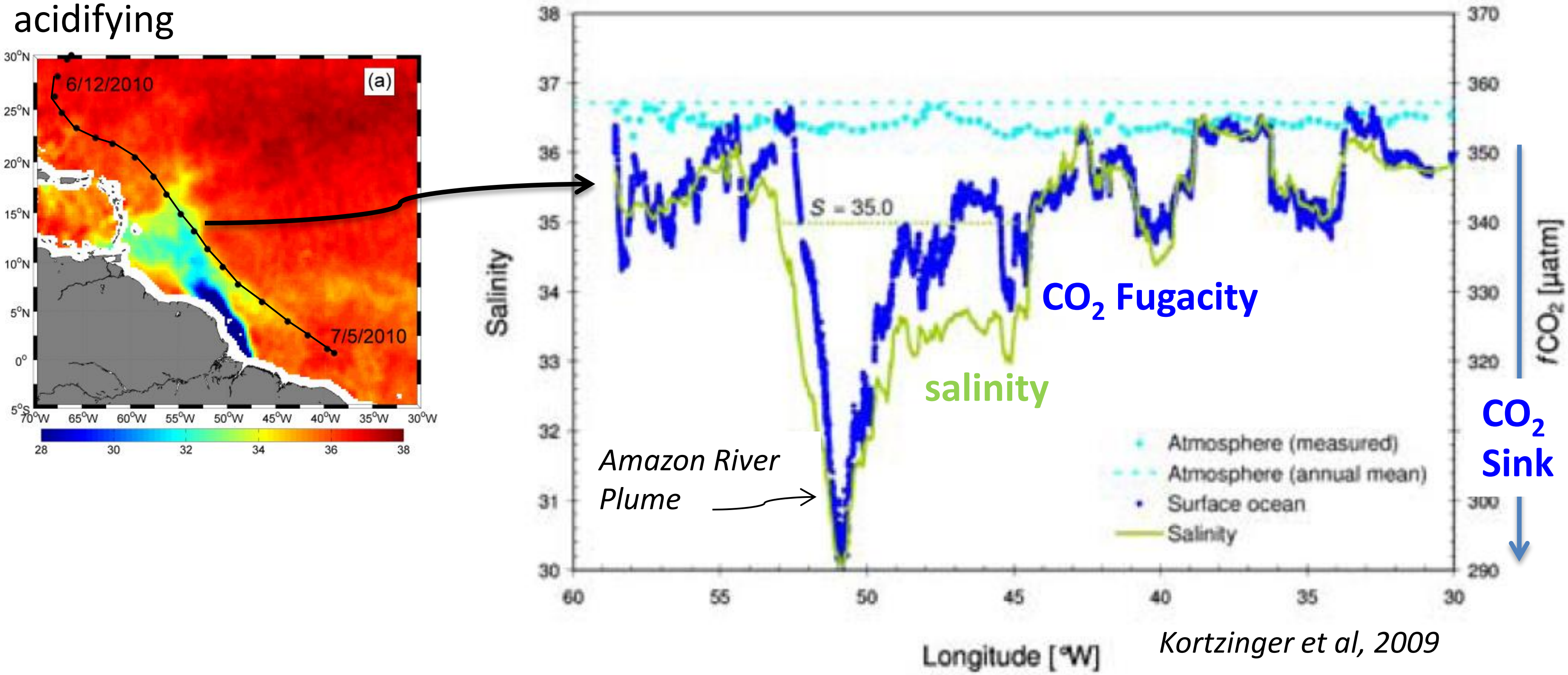
2. Rain cells and cyclones drift to the East (Salinity signature at the surface)

3. The thermocline levels and the Upwelling is blooked. (lack of nutrients for fishes)

Surface Salinity & Marine Bio-chemistry

Ocean is a major sink for atmospheric CO2

It absorbs ~25% of human emission in the atmosphere, however it is saturated and start acidifying



Kortzinger et al, 2009

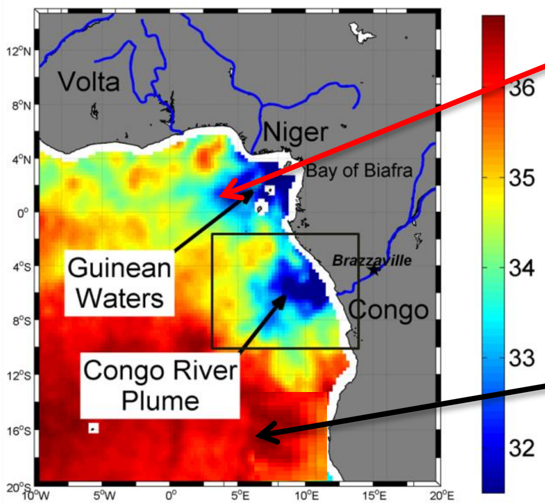
Through its links with carbonate chemistry and surface water masses monitoring, **Sea surface salinity data will improve estimates of air-sea CO_2 fluxes.**

SMOS will help in better quantifying ocean acidification (corals reefs, tropical ecosystem) & ocean-atmosphere CO_2 exchanges in some key areas

Surface Salinity and Marine Biology

Salinity is one of the key environmental factor for the living of fishes and marine biology

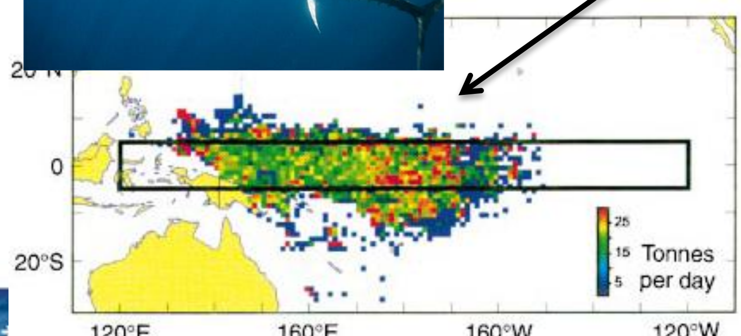
SSS SMOS



S. Maderensis is stenohaline: it lives in warm freshwaters of the Guinean Gulf (rain effects, river influence from Volga, Niger, Congo,..)

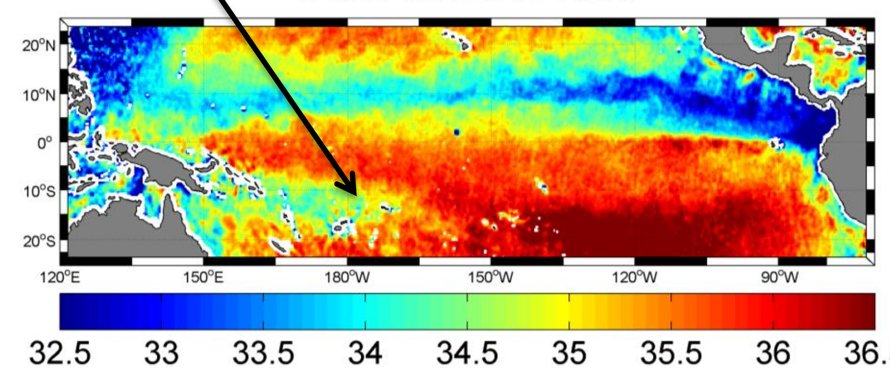
S. Aurita is stenohaline: it lives in the cold and salty waters of the benguela upwelling

Tuna takes & Haline Fronts in the western Tropical Pacific



Lehodey, 1997

SSS SMOS Nov



Why measuring SSS from Space?

•Salinity is a key parameter of ocean dynamics and Climate:

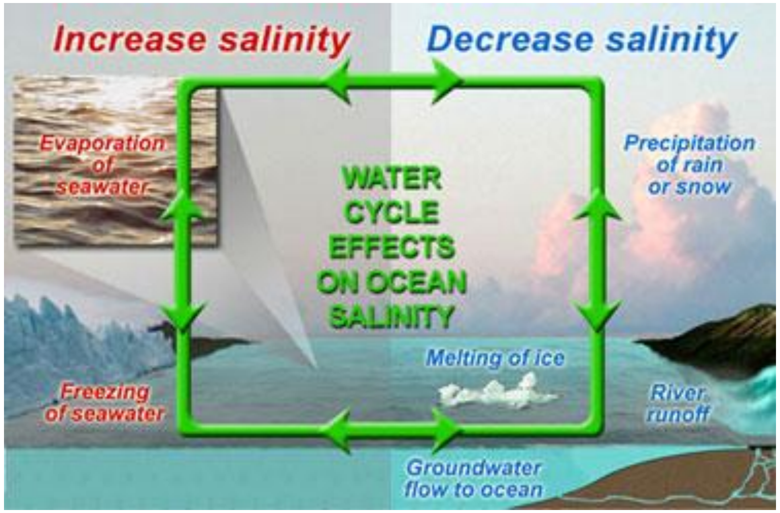
✓Thermo-haline Circulation

✓Global Water Cycle

(Fresh water flux , E-P-R)

✓Oocean-atmosphere Coupling

(e.g., ENSO, en rate of CO_2 absorbtion)



•Salinity is a key parameter for ocean Bio-chemistry and Biology

•Lack of SSS measurements

Implications on climatology

GOOS (Global Ocean Observing System) scientific plan :

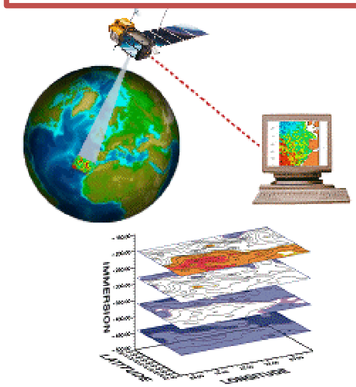
Accuracy ~0.1 psu/monthly

Spatial scale: 100-200 km^2

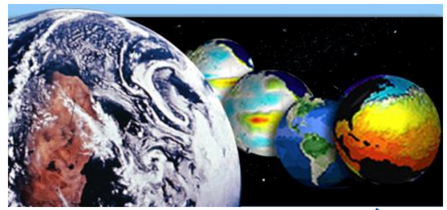
What are the main oceanic applications ?

esa

Ocean circulation Modeling

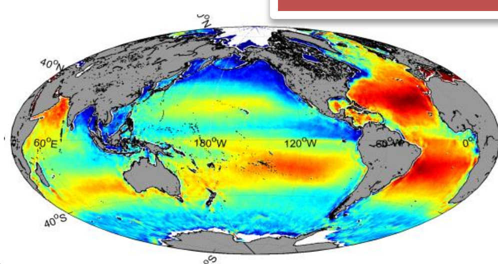


Climate change Studies

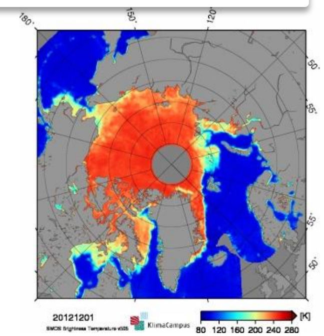


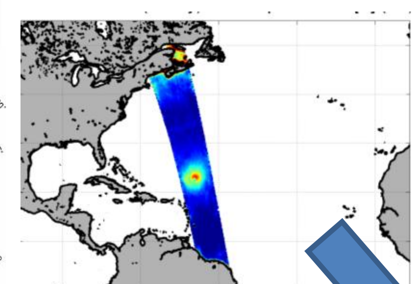
Marine Biology & Biochemistry


SMOS data



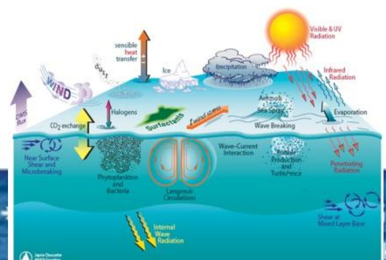
Salinity



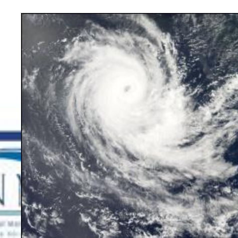


brightnesses

Ocean-atmosphere interactions



Weather Predictions

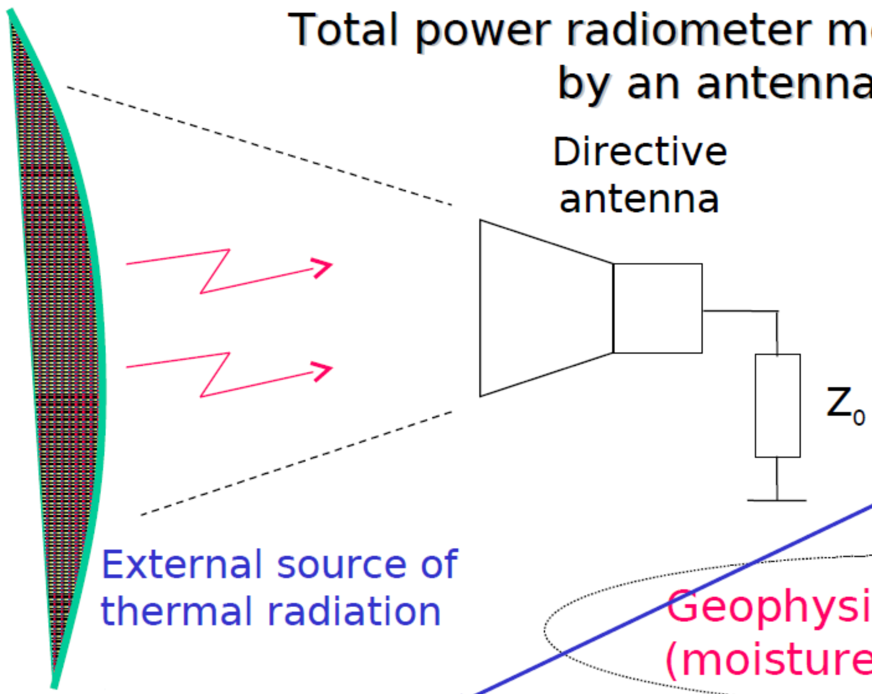


How can we measure sea surface salinity From Space?

Physics principle
Of SSS measurements
From Low Microwave frequency radiometry

Radiometry

Total power radiometer measures the signal power captured by an antenna (Rayleigh-Jeans Law)



Black body: $P = k\,T\,B$

T: physical temperature

Grey body: $P = k\,T_B\,B$

T_B: brightness temperature

Geophysics parameters (moisture, salinity, etc.)

Wind speed over the sea

T_B depends on:

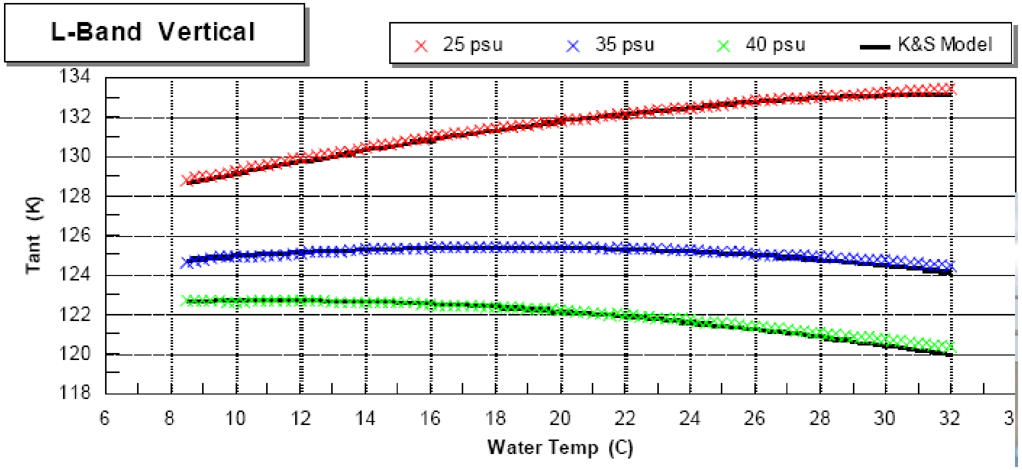
- Physical temperature
- Electrical and geometrical parameters
- Antenna orientation and polarization
- Frecuency

Basics of SSS measurements from Space

- At electromagnetic frequency f < 20 GHz, sea water dielectric constant ε is a function of SSS and sea surface temperature SST. $\varepsilon = \varepsilon(SSS, SST)$.

ε = f(S, T, Freq, Incidence) $T_b = \varepsilon T$

- The sea surface brightness temperature T_{ant} as measured by a radiometer is thus related to salinity

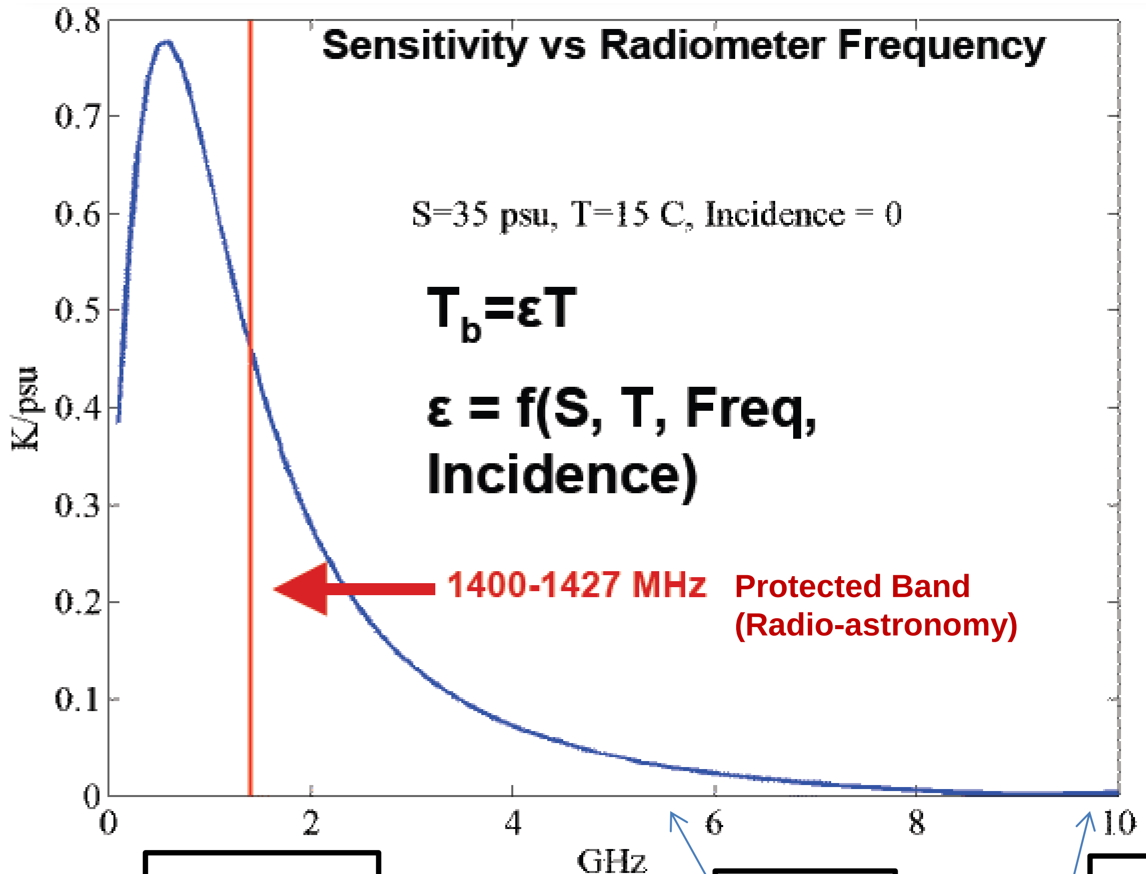


Given SST(T) & Tb data=> one can deduce SSS (S) in theory

Tb sensitivity to SSS as function of Electromagnetic Frequency

Brightness temperature Sensitivity to Salinity as function of **Electromagnetic Frequency**

$$\frac{\partial T_B}{\partial SSS}$$



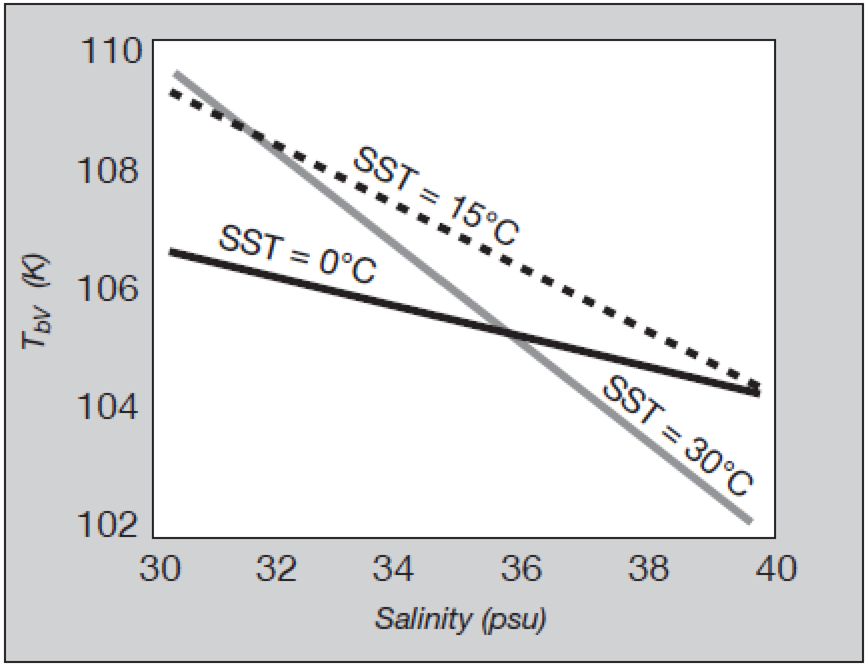
SMOS
Aquarius
(L-Band)

C-Band

X-Band

AMSR-E, WindSat, TMI

A weakly sensitive principle



The sensitivity of the brightness temperature at L-band to SSS remains small. It depends on the sea surface temperature (SST):

-0.3 K/psu in cold waters (~0°C)
à
-0.7 K/psu in warm seas (~30°C)

An istantaneous accuracy on SSS of 0.1 psu would require a radiometer TB measurement accurate to within:
~0.03 K for an SST=0°C !
~0.07 K for an SST=30°C !

The one from **AMSR-E & WindSat at 6 GHz: 0.5-0.6 K** => technological challenge !

First attempts during NASA Mission SkyLab in 1973

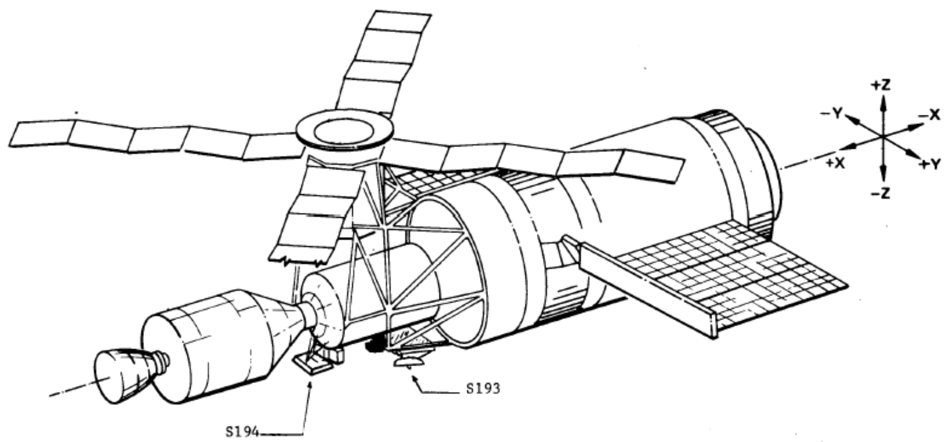


Fig. 1 — Location of radiometers on Skylab

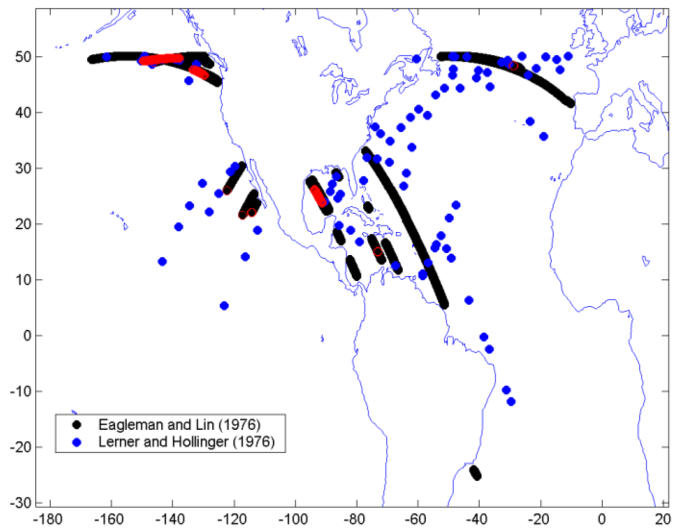
First trial 1973 SkyLab S-194:

L-band radiometer data

Low accuracy & Spatial resolution

Not enough data

Technical limitations due to the size of antennas at L band



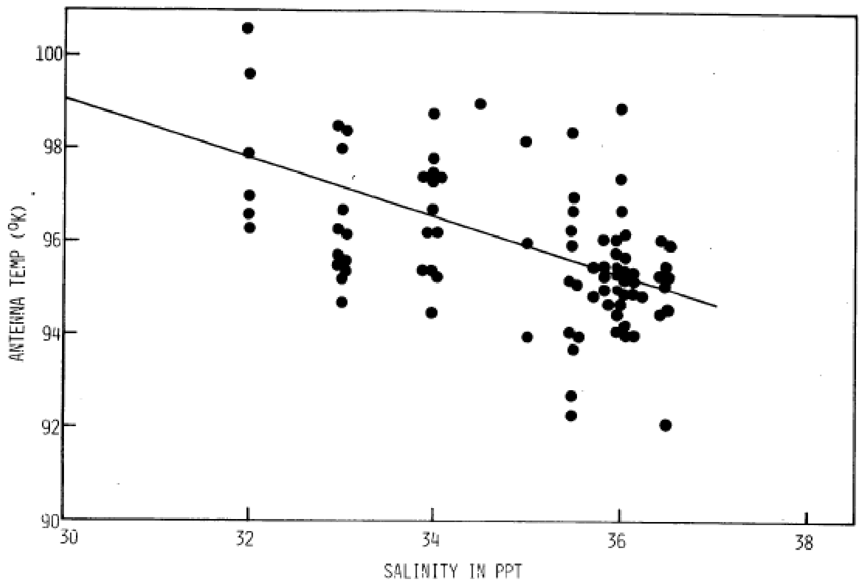
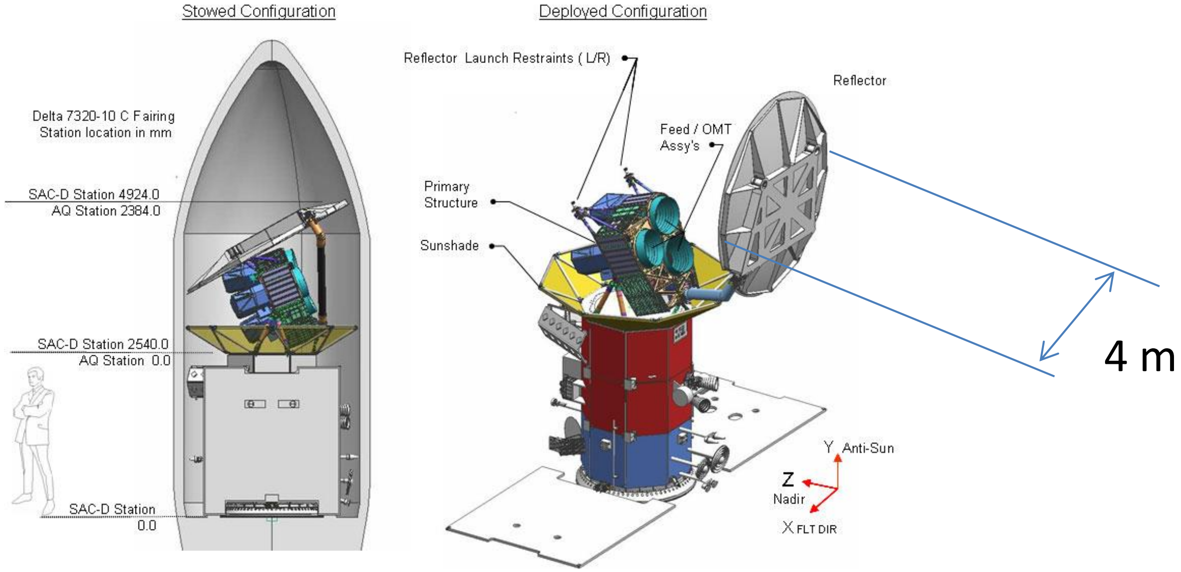


Fig. 17 — Antenna temperature dependence on salinity

Antenna size: the limiting technological factor for SSS remote sensing developement until the 1990s

To obtain a spatial resolution on ground of 50 km (at nadir), from an altitude of 750 km and for an electromagntic wavelength of 20 cm (f=1.4 GHz), a real aperture radiometer must have a characteristic antenna size of ~4 m



Technological Evolution associated with Antenna

- SMOS (Soil Moisture & Ocean Salinity)
  Launch date: November 2^{sd}, 2009

  L band radiometer required: No existing device

  How to by-pass the antenna size technical difficulty ?:
  Antenna deployed in space and Interferometry

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NASA CONAE

- AQUARIUS/SAC-D (NASA/CONAE): launch date: july 2010

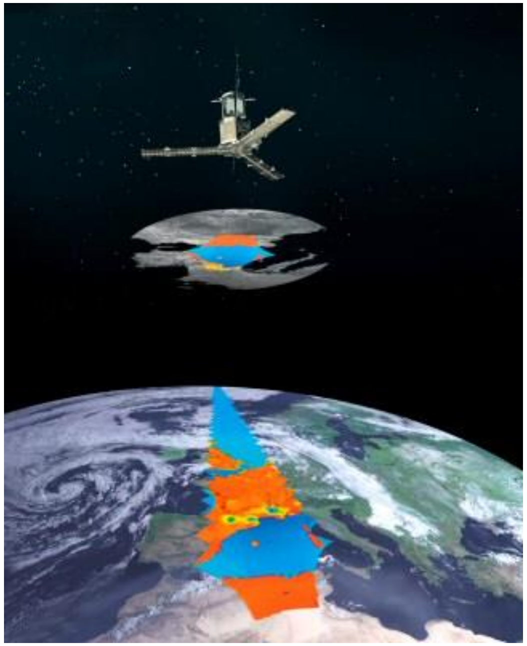
Goal of both missions:

- SSS measurments with an accuracy of 0.1-0.2 psu and a spatial resolution of 100x100 km every 10 days (GODAE requirements).

Soil Moisture and Ocean Salinity

The sensor: L band interferometric synthetic aperture Radiometer (1.4 GHz)

a) SMOS artist view

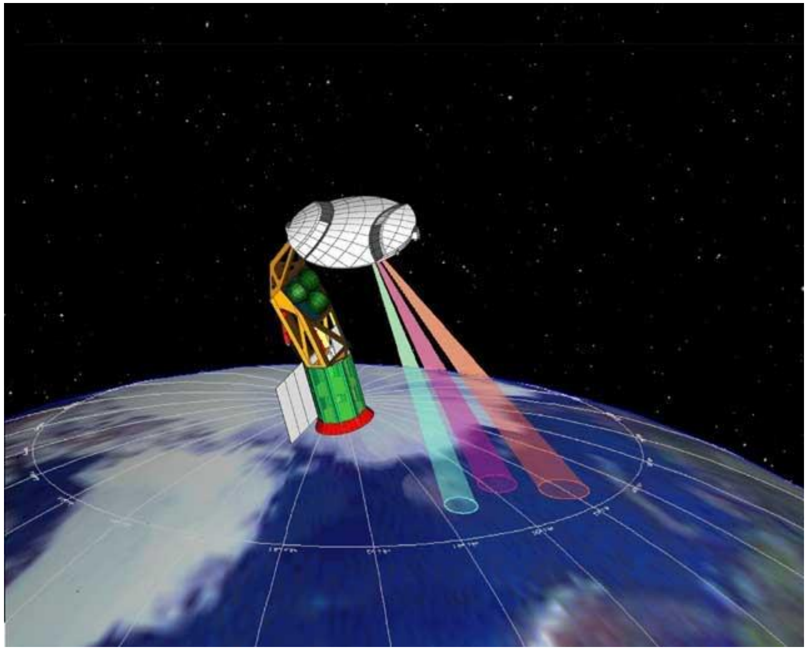


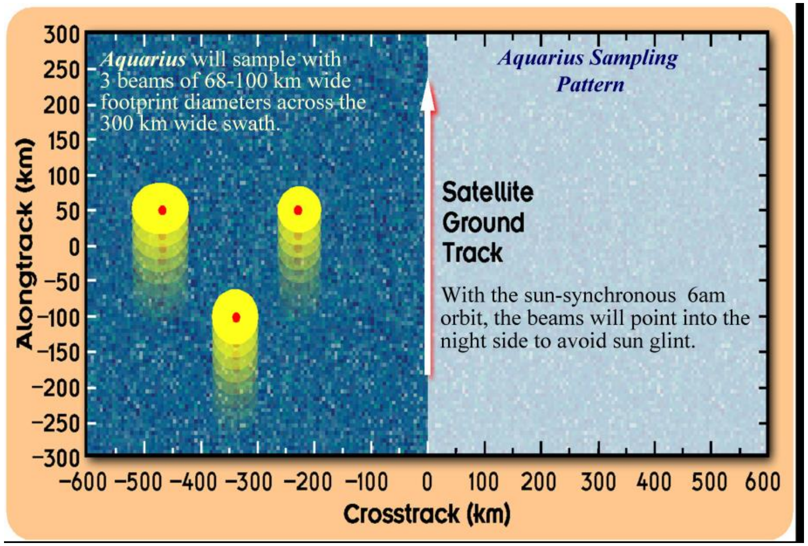
b) SMOS swath

Brightness temperature measurements at different incidence angles (0° – 60°)
Ground resolution: 35-80 km Global coverage every 3 days
Spot accuracy (instantaneous) ~1 psu

Aquarius/SAC-D

L band (1.4 GHz) radiometer with 3 incidence angles + L band scatterometer





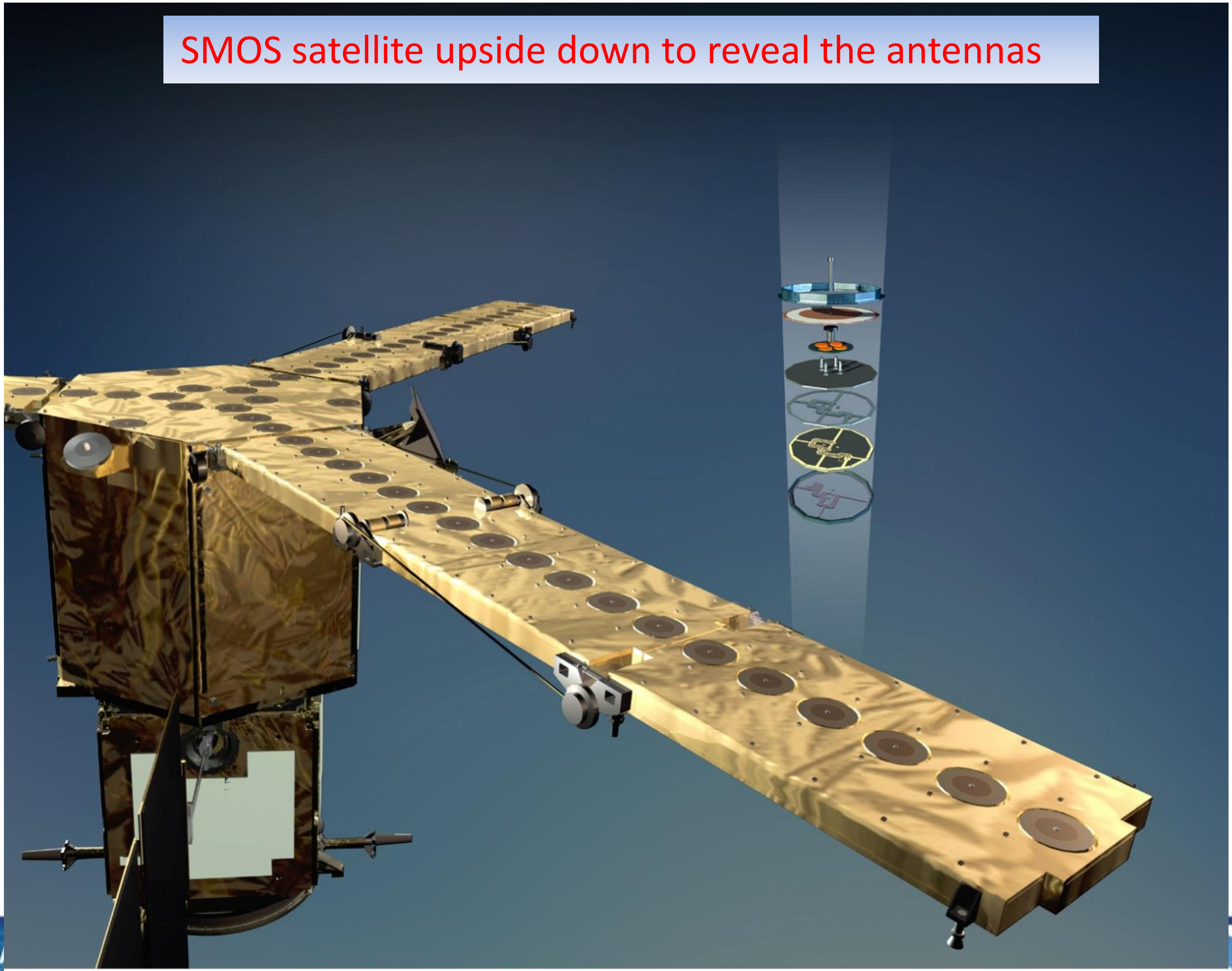
a) Aquarius artist view

b) Swath

Spatial resolution: 100 km every 10 days. Accuracy ~0.5 psu

MIRAS: AN INSTRUMENT FOR SALINITY REMOTE SENSING

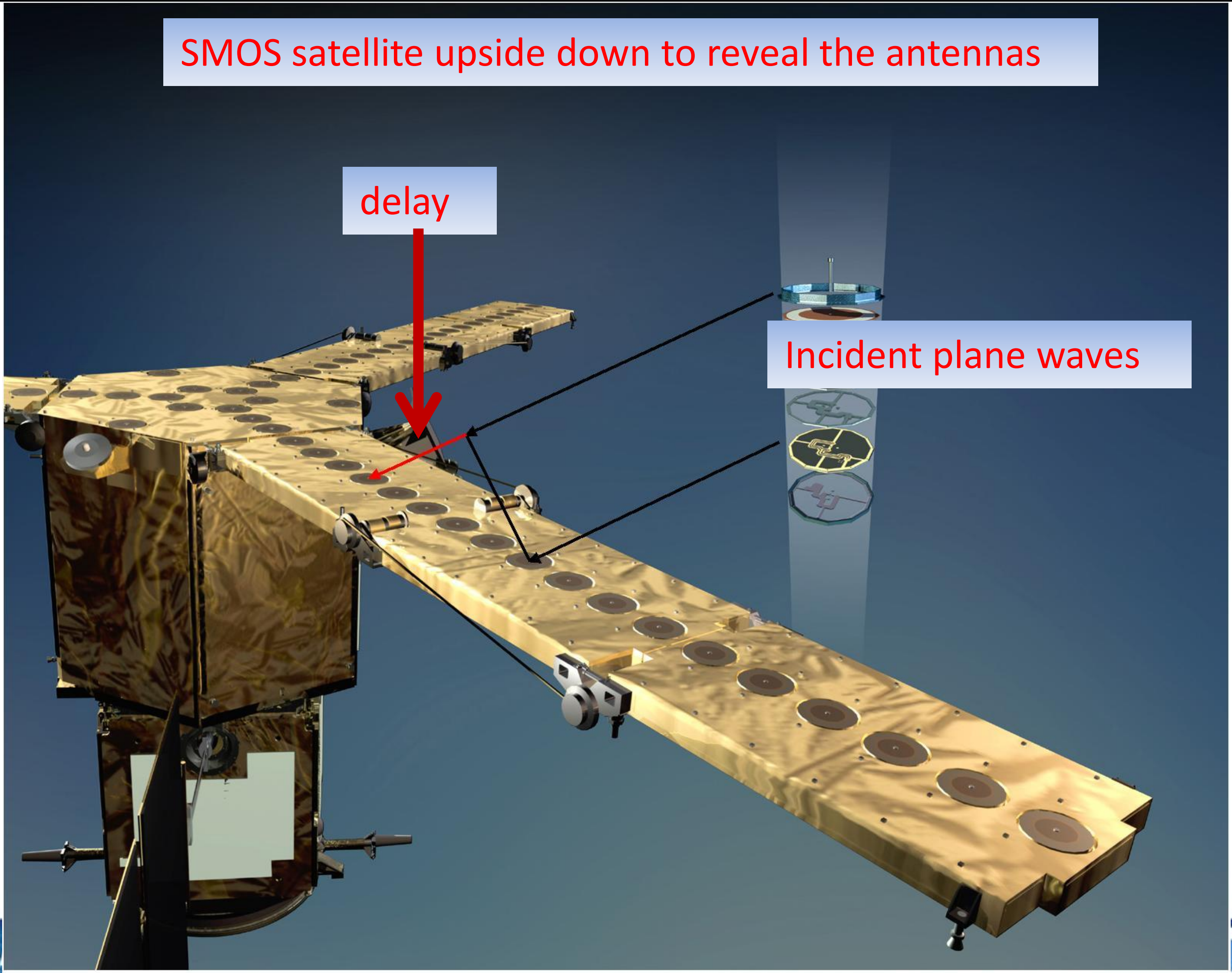
The interferometry technique was chosen in order to provide a large swath without the need for a large rotating reflector.



Patch antenna: each of the 69 antenna elements is based on a dual-polarization four-probe patch antenna in multi-layer microstrip technology.

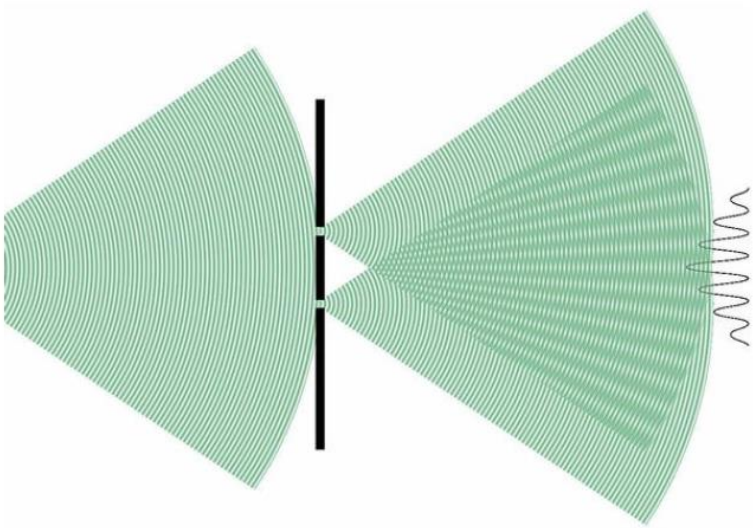
MIRAS: AN INSTRUMENT FOR SALINITY REMOTE SENSING

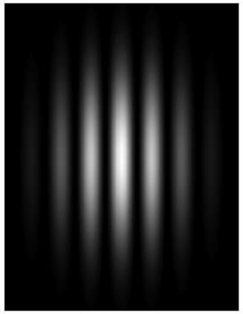
The basic idea is to exploit the fact that the delay (and thus the correlation) between signals from different receivers depends upon the direction of the incident radiation:

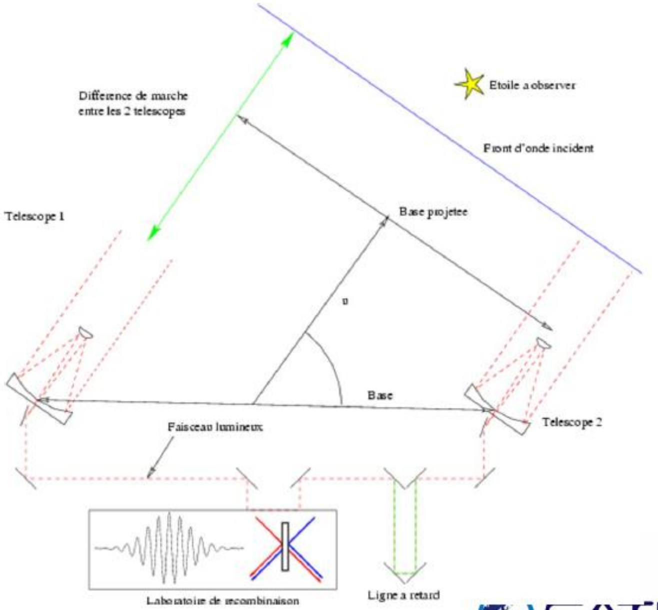


Patch antenna: each of the 69 antenna elements is based on a dual-polarization four-probe patch antenna in multi-layer microstrip technology.

The interferometric Principle







Young's double slit, 1801

Use by Fizeau, 1868 to build first interferometer to measure speed of light.

Allows to reach much higher spatial resolution by caracterising spatial frequencies

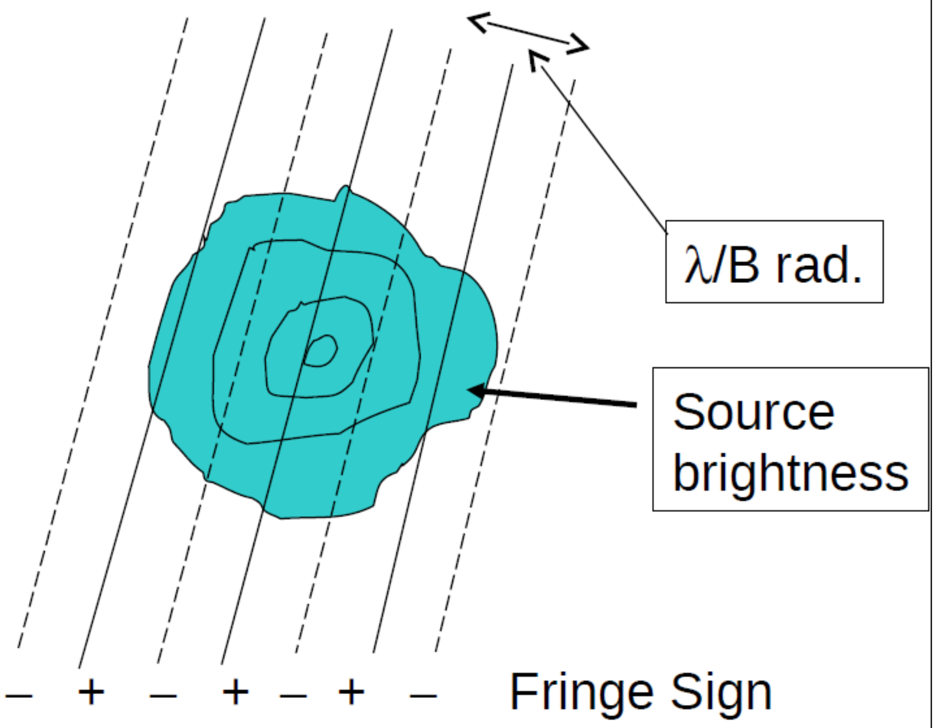
The interferometric Principle

Imaging through an 2D interferometer is equivalent to lighting the scene with an interference pattern.

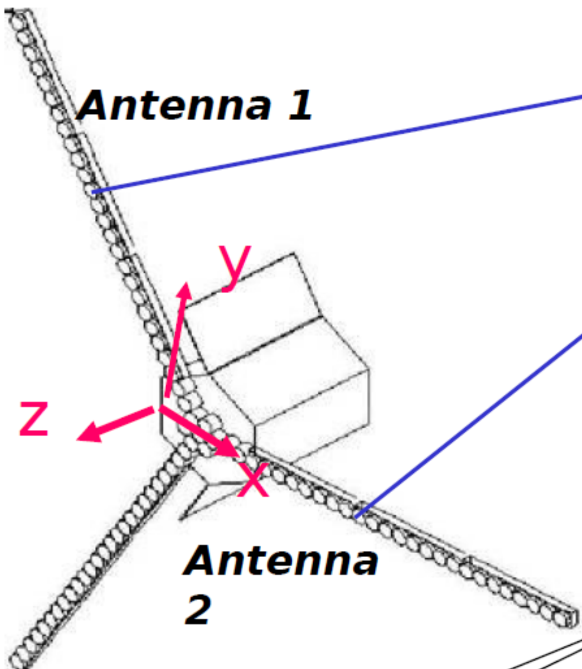
Fringe width depends on observation frequency and distance between antennas (baseline)

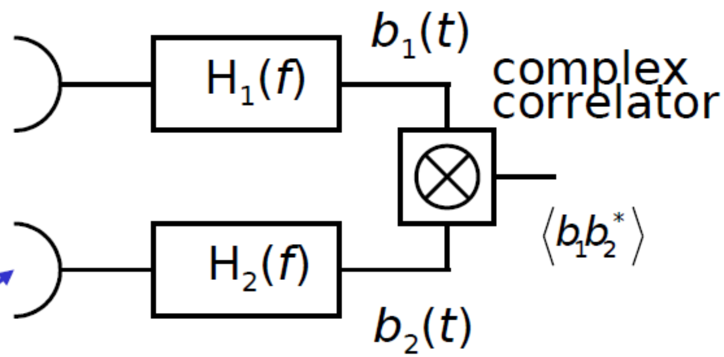
Correlation computation between a couple of antennas integrates radiance from the scene, weighted by the fringes.

This integral is characteristic of this baseline or spatial frequency.



The interferometry in SMOS





Complex Correlation

$$V(u,v) = \frac{1}{k_B \sqrt{B_1 B_2} \sqrt{G_1 G_2}} \frac{1}{2} \langle b_1(t)\, b_2^*(t) \rangle$$

Spatial coordinates

Boltzmann Constant

Noise bandwidths

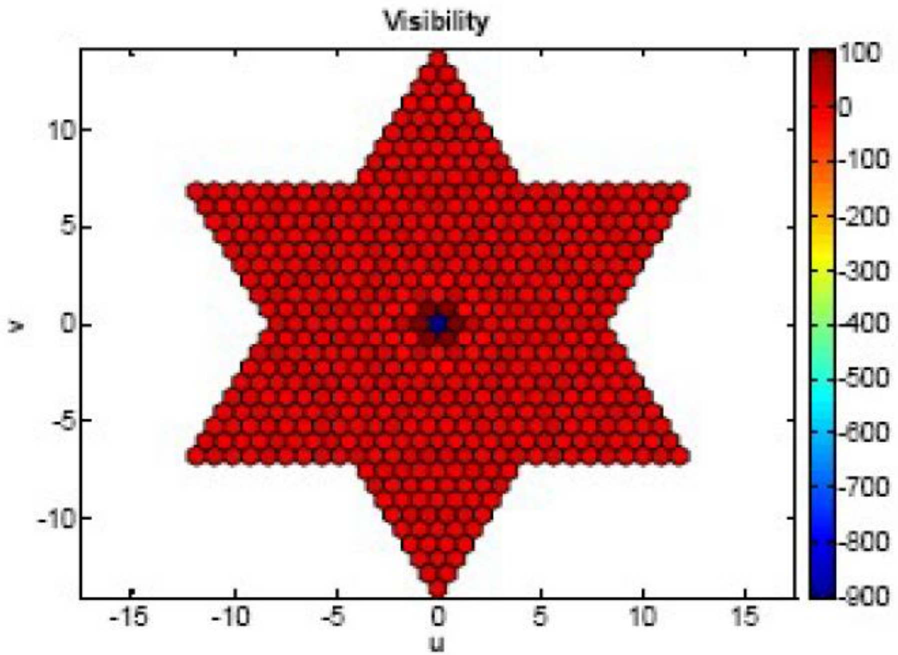
Available power gains

$$(u,v) = (\Delta x, \Delta y)/\lambda_0$$

Baselines in SMOS

Each pair of antennas constitutes a baseline, giving access to one specific spatial frequency: a visibility.

Pairing each antenna with all the others allows to map spatial frequencies within a specific region, linked to the arrangement of antennas in the antenna plane



Ideal Case

Assuming:

All antennas are identical

All filters have exactly the same sensibility, and infinitely thin

All correlators are identical

All measurement chains have identical gain

In this case:

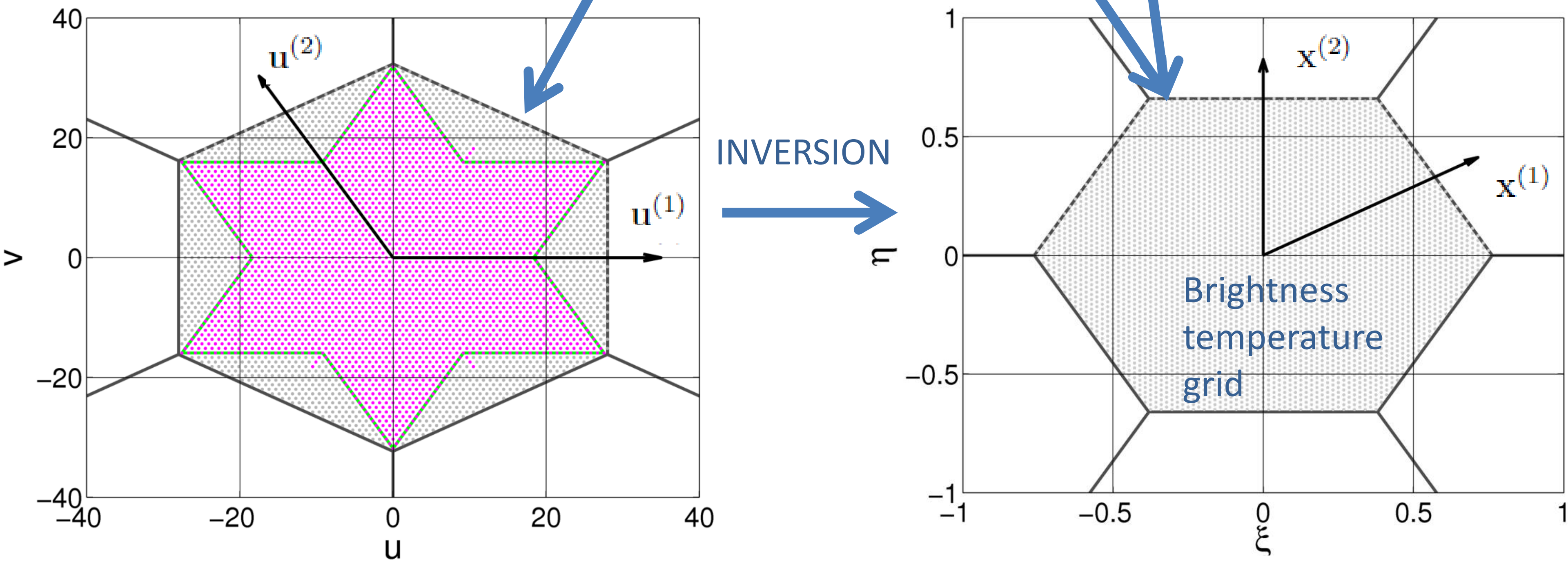
$$V(u,v) = \mathcal{F}\left[T(\xi,\eta)\right]$$

Visibilities — Fourrier Transform — Brightness Temperature image

But for us, not so ideal:

FROM VISIBILITIES TO BRIGHTNESS TEMPERATURE

Invert this equation: $\mathbf{V}(\mathbf{u}_{\mathbf{q}_{\mathbf{kl}}}) = \mathbf{G}_{kl}(\mathbf{x}_{\mathbf{p}})\,[\mathbf{T}_{xy}(\mathbf{x}_{\mathbf{p}}) - \mathbf{T}_{\mathbf{r}}]$



$$u_{kl} = \Delta x_{kl}/\lambda_o$$
$$v_{kl} = \Delta y_{kl}/\lambda_o$$

$$\xi = \sin\theta_s \cos\phi_s,$$
$$\eta = -\sin\theta_s \sin\phi_s,$$
$$\zeta = -\cos\theta_s.$$

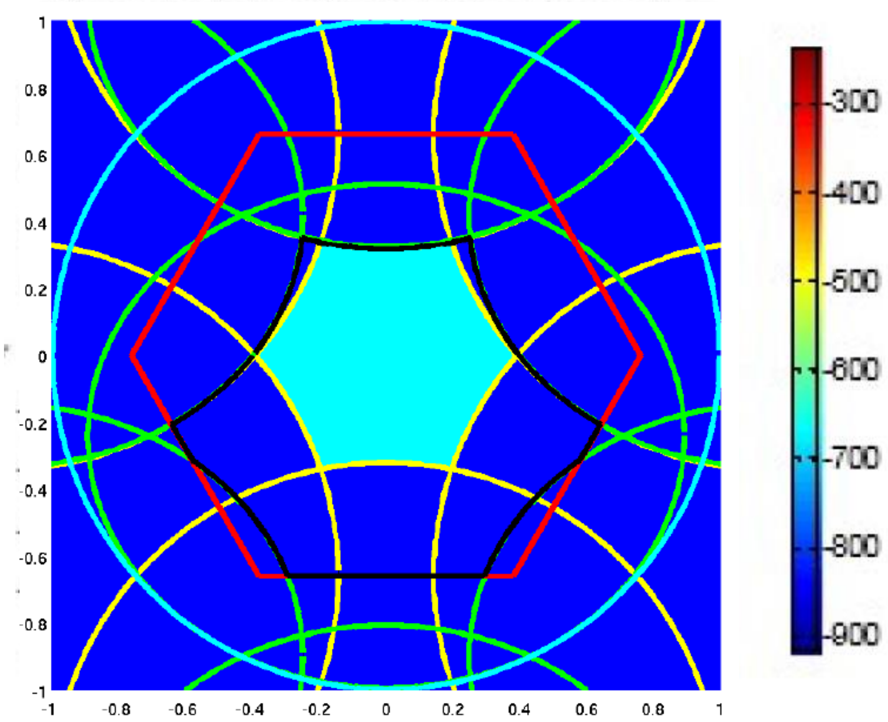
SMOS Aliasing

Spatial frequency given by each baseline depends on inter antenna separation.

But the sampling of the frequency plane is not compliant with Shannon condition.

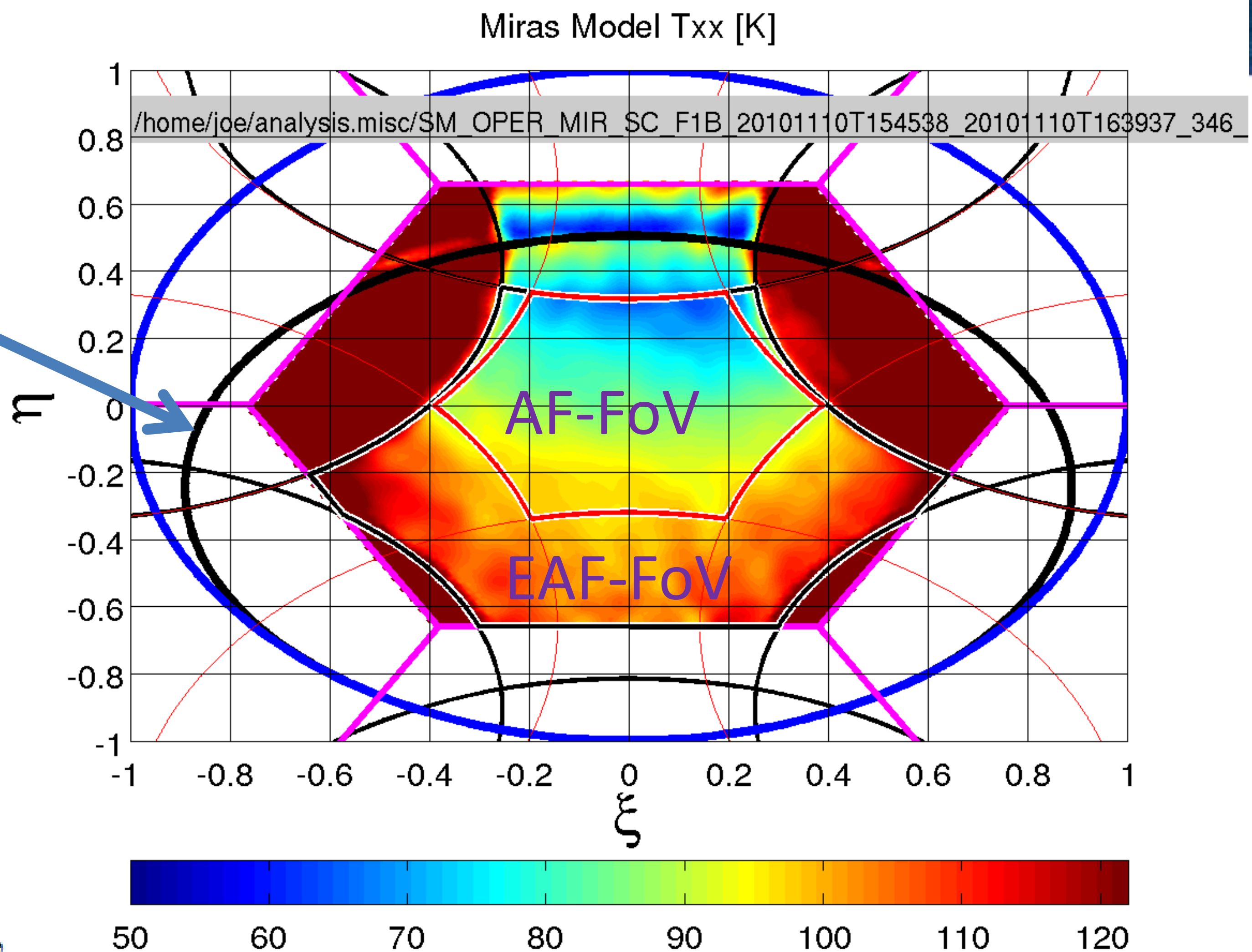
Each spatial frequency is not uniquely reconstructed, ambiguity exists, and leads to aliased images in the reconstruction.

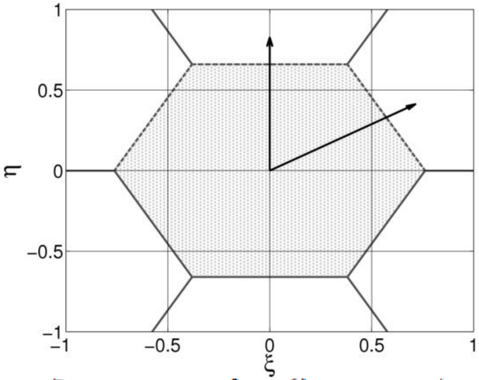
SMOS field of view is limited by these aliases, but extended to the areas where only sky image is aliased on top of earth image.



THE FIELD OF VIEW AT ANTENNA LEVEL

The earth boundary passes outside fundamental hexagon (magenta) and thus earth aliases appear inside the fundamental hexagon.





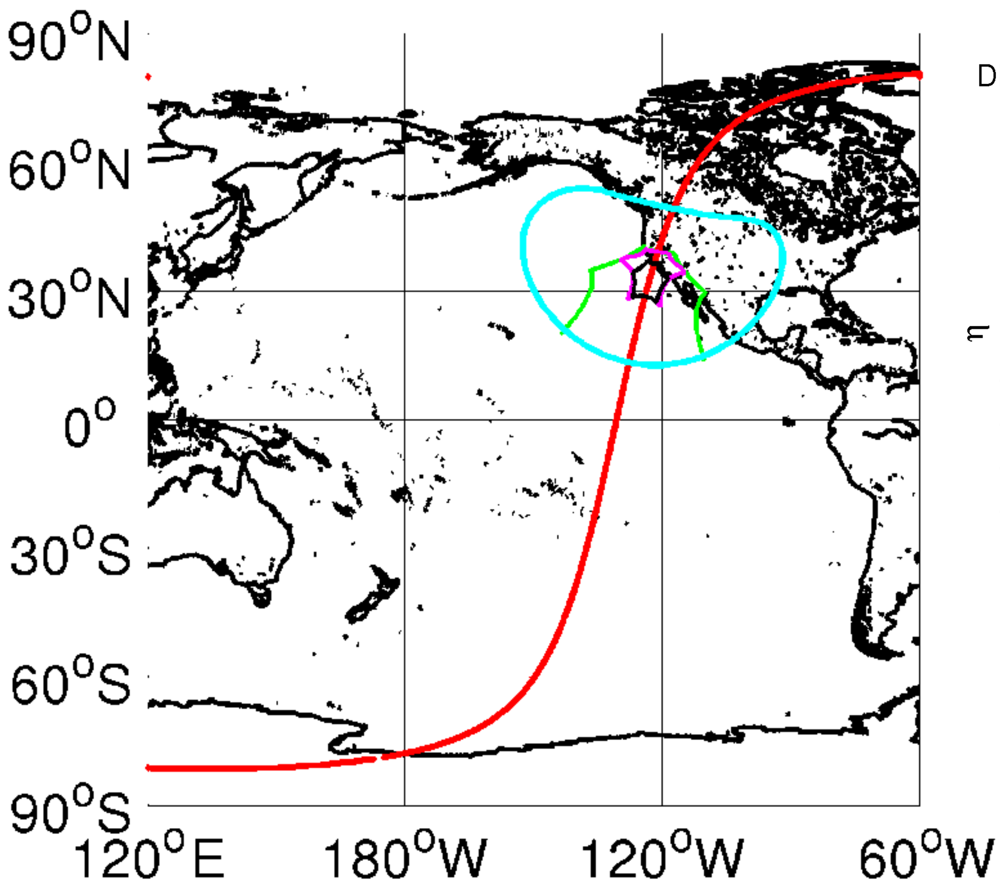
$$\xi = \sin\theta_s \cos\phi_s,$$
$$\eta = -\sin\theta_s \sin\phi_s,$$
$$\zeta = -\cos\theta_s.$$

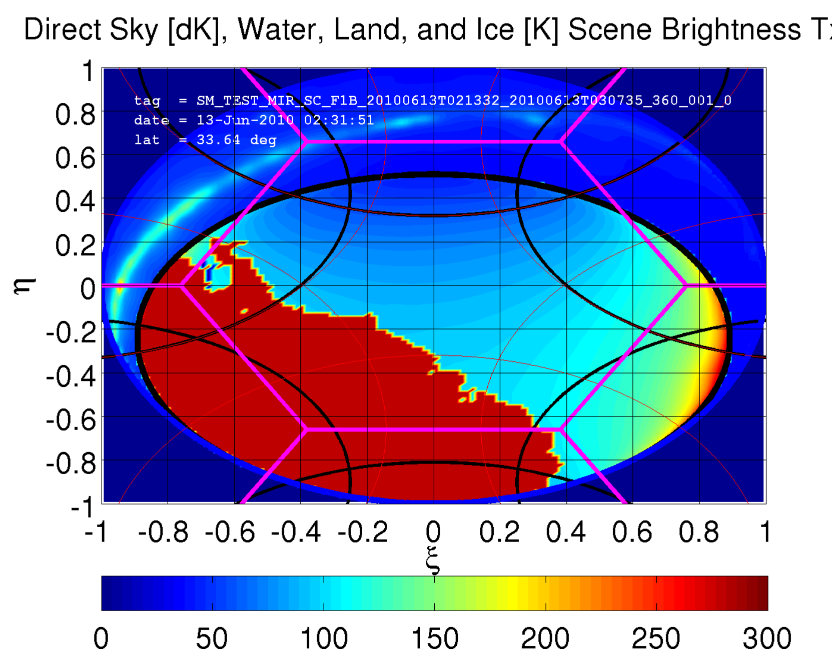
AF-FoV = alias-free field of view

EAF-FoV = extended alias-free field of view

EXAMPLE of SMOS BRIGHTNESS TEMPERATURE MAPS at antenna Level

Here is an example of the scene brightness model for one coastal snapshot. Direct celestial sky brightness has been multiplied by ten in the plot to show it more clearly, and land brightness temperature has been set to 280 K arbitrarily.



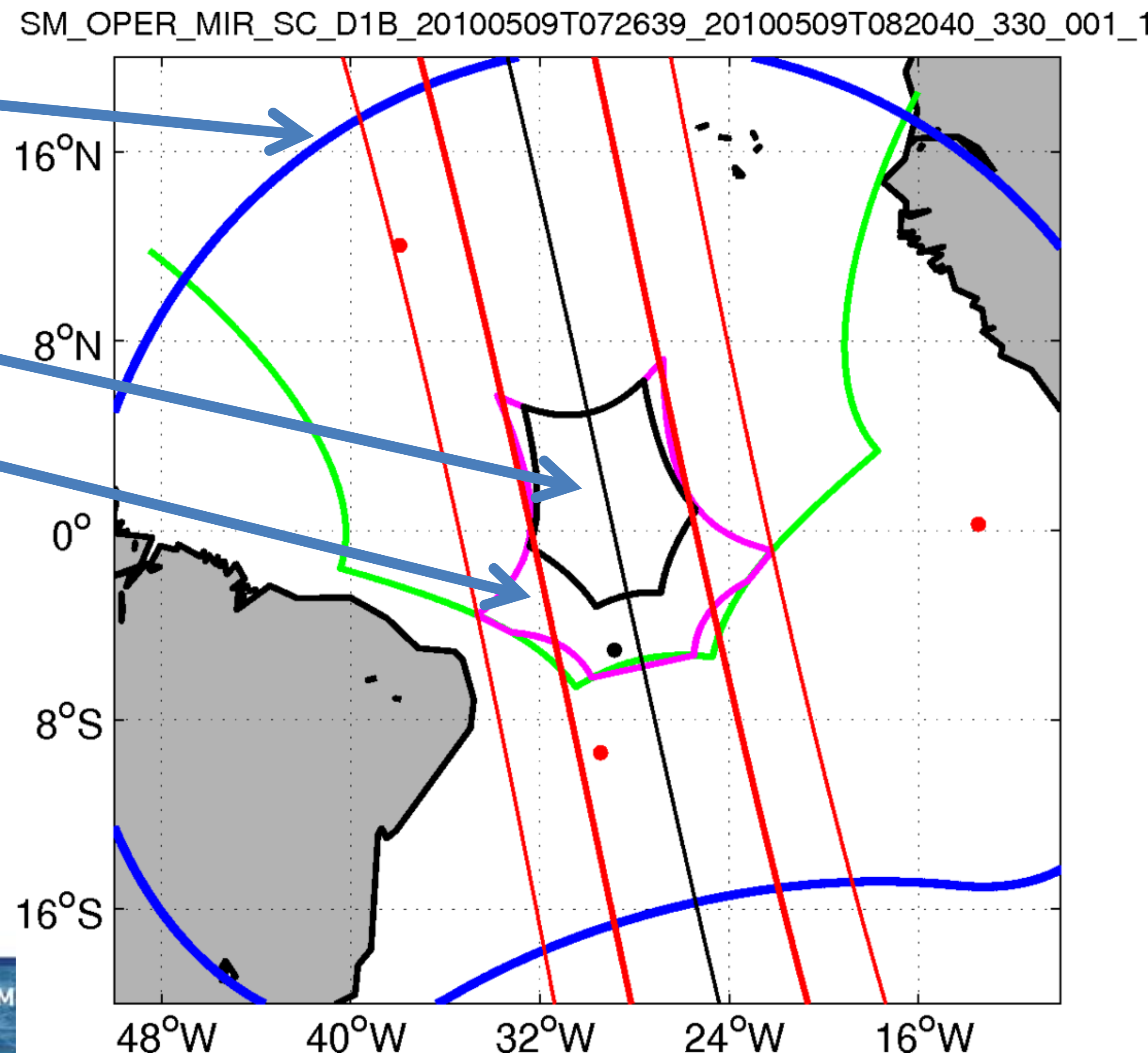


THE FIELD OF VIEW PROJECTED ONTO THE EARTH

Boundary of visible portion of earth

AF-FoV

EAF-FoV



SMOS Field of View on ground

Integrationtime is 1.2s. This is the time needed to record all visibilities with a satisfactory signal/noise ratio.

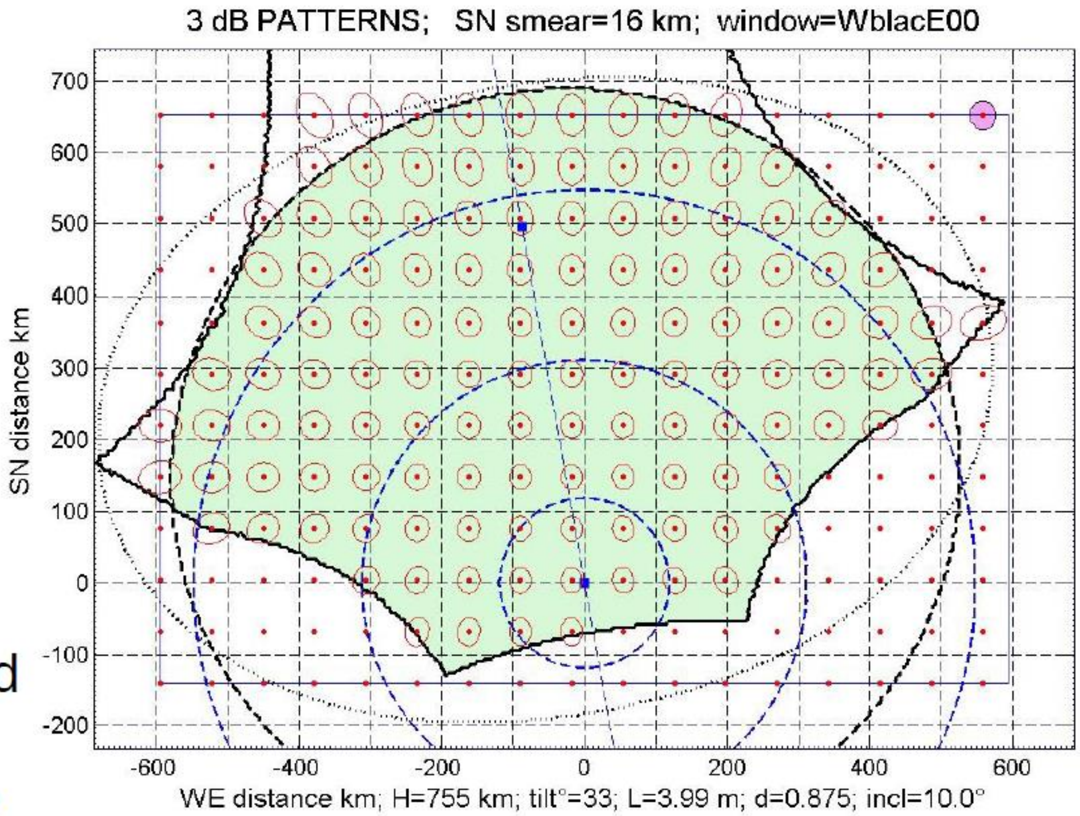
Antennas can only measure 1 polarisation at a time.

After that time, polarisation state of the antennas is changed to record another set of visibilities.

Complete polarisation recording takes up to 3.6s.

Meanwhile, spacecraft travelled about 25km.

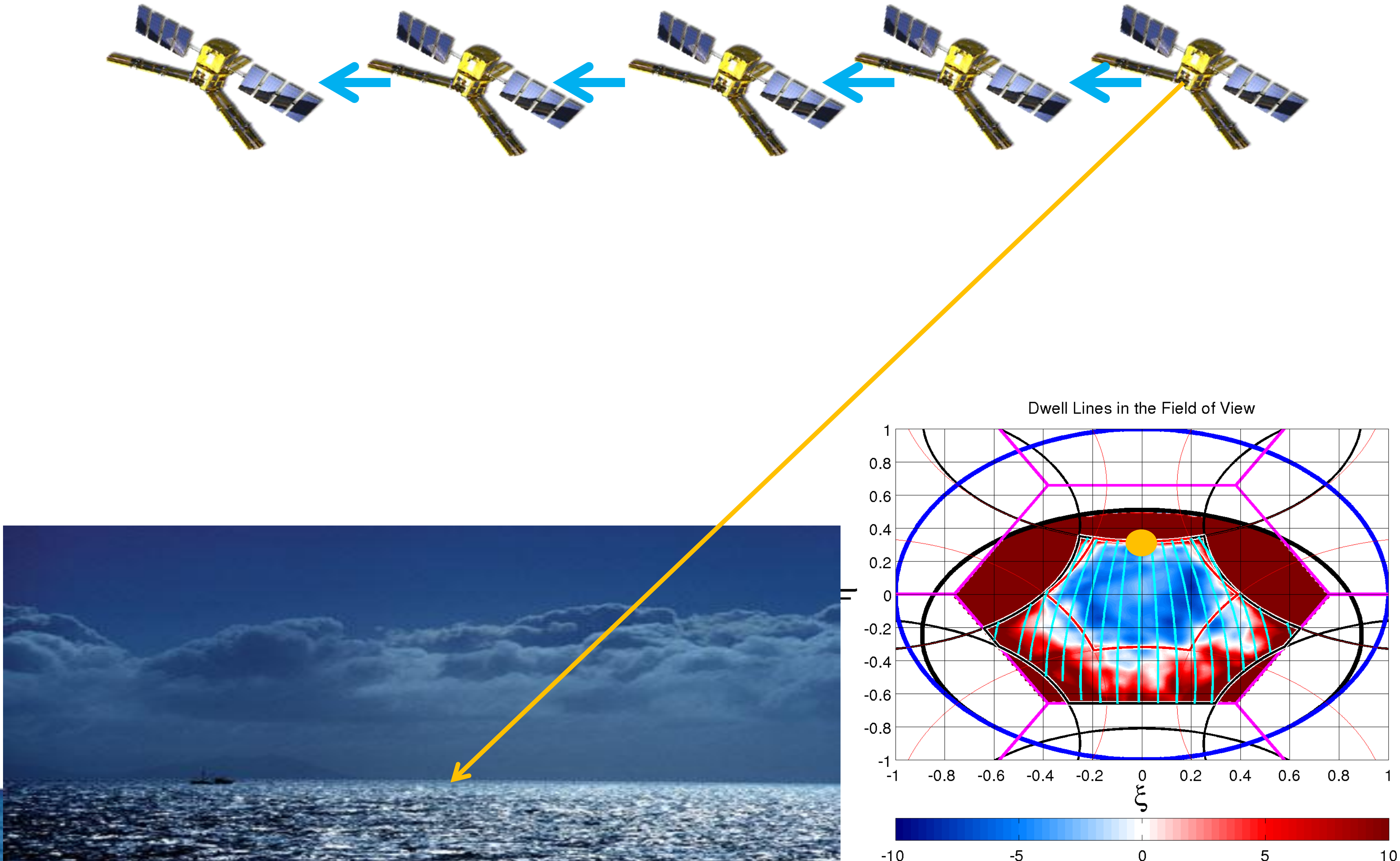
Two consecutive images show large overlap.



CONCEPT OF A DWELL LINE

THE CONCEPT OF A DWELL LINE

As the SMOS satellite propagates along its orbit, a given point on earth appears in many snapshots at a large range of incidence angles…



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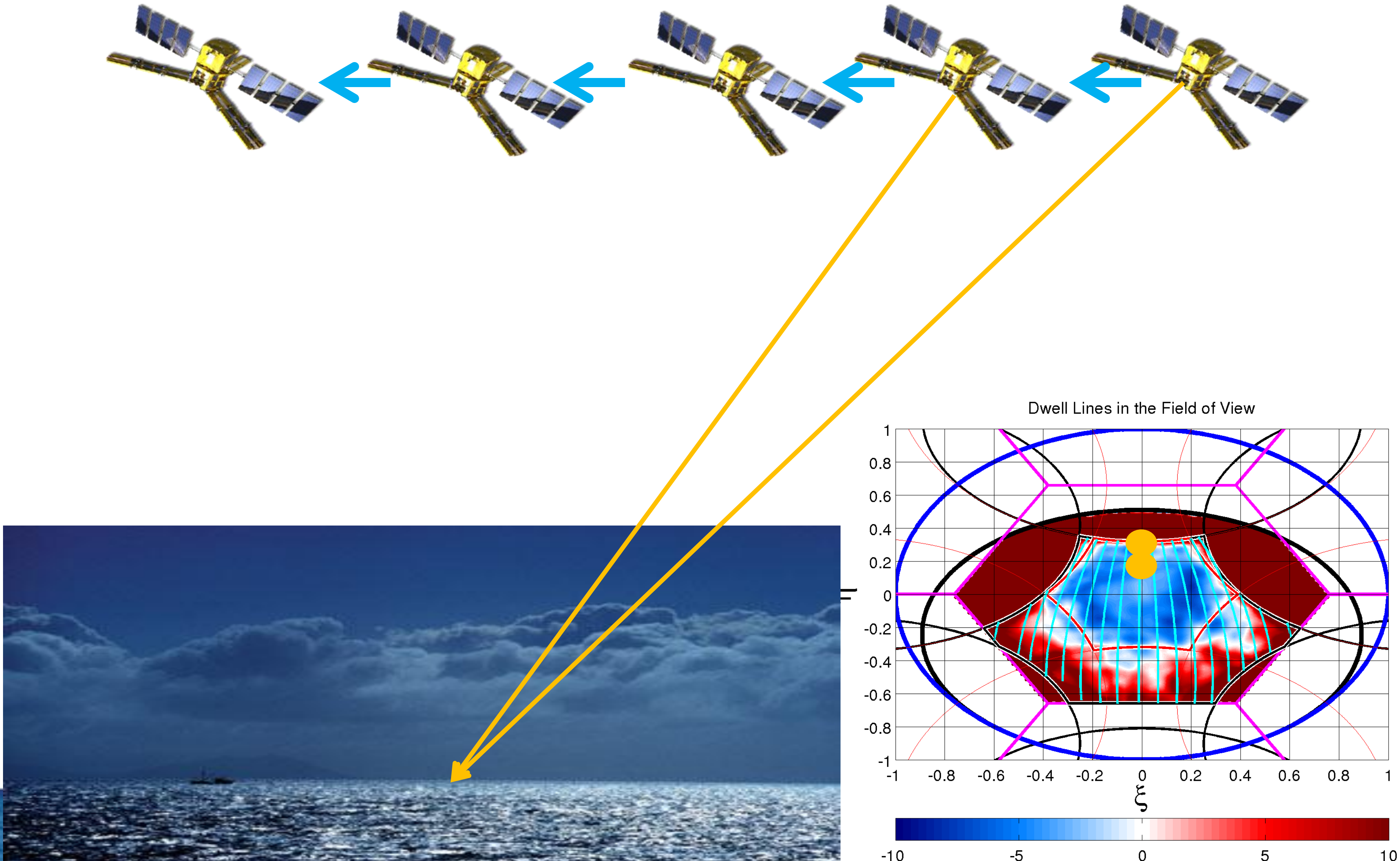

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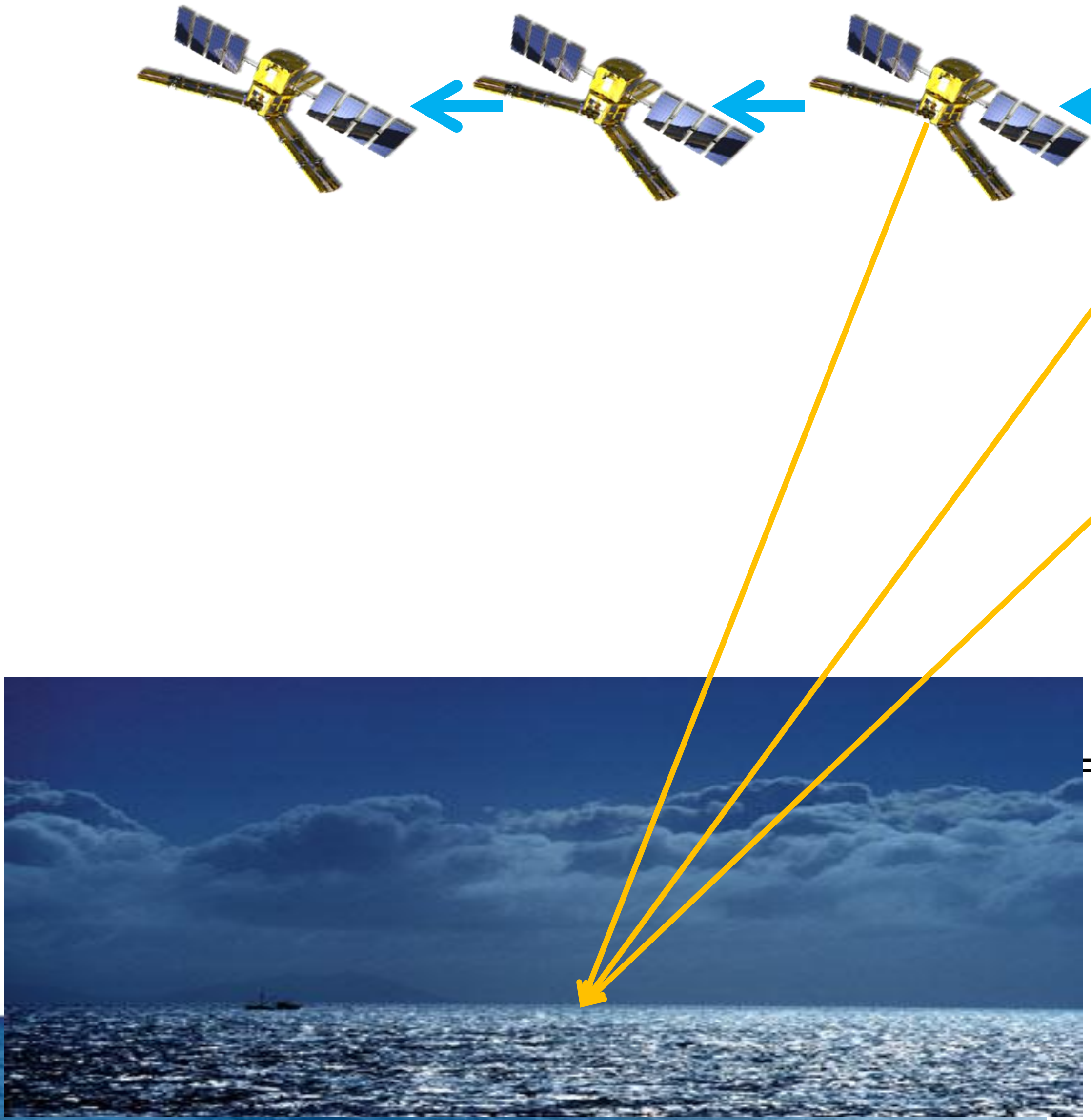

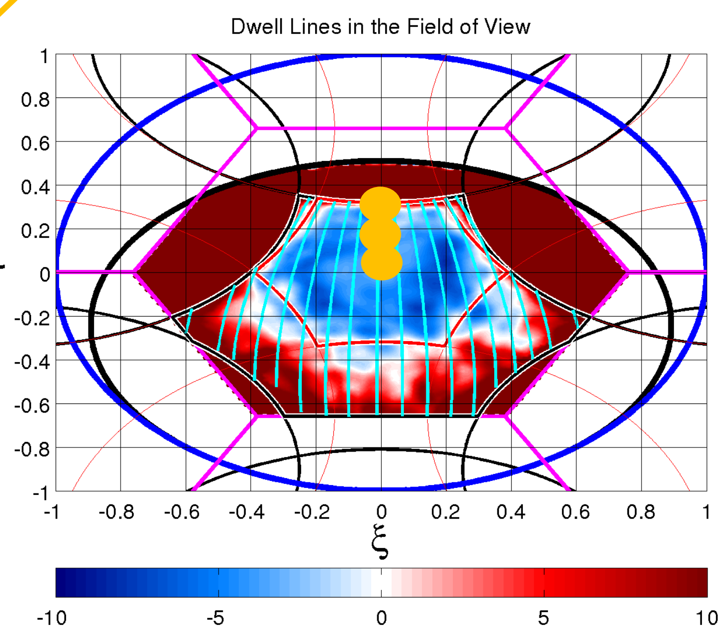

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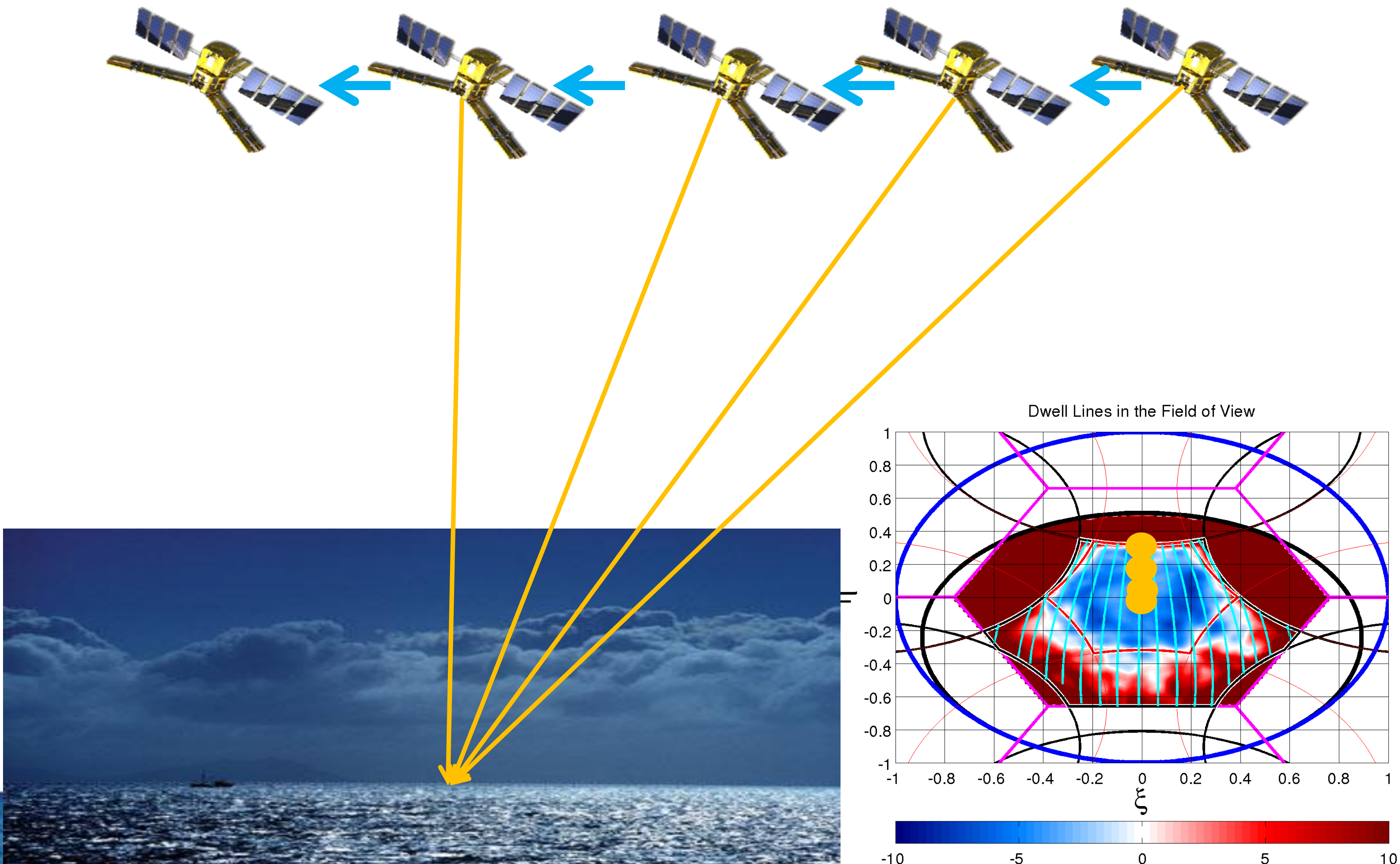

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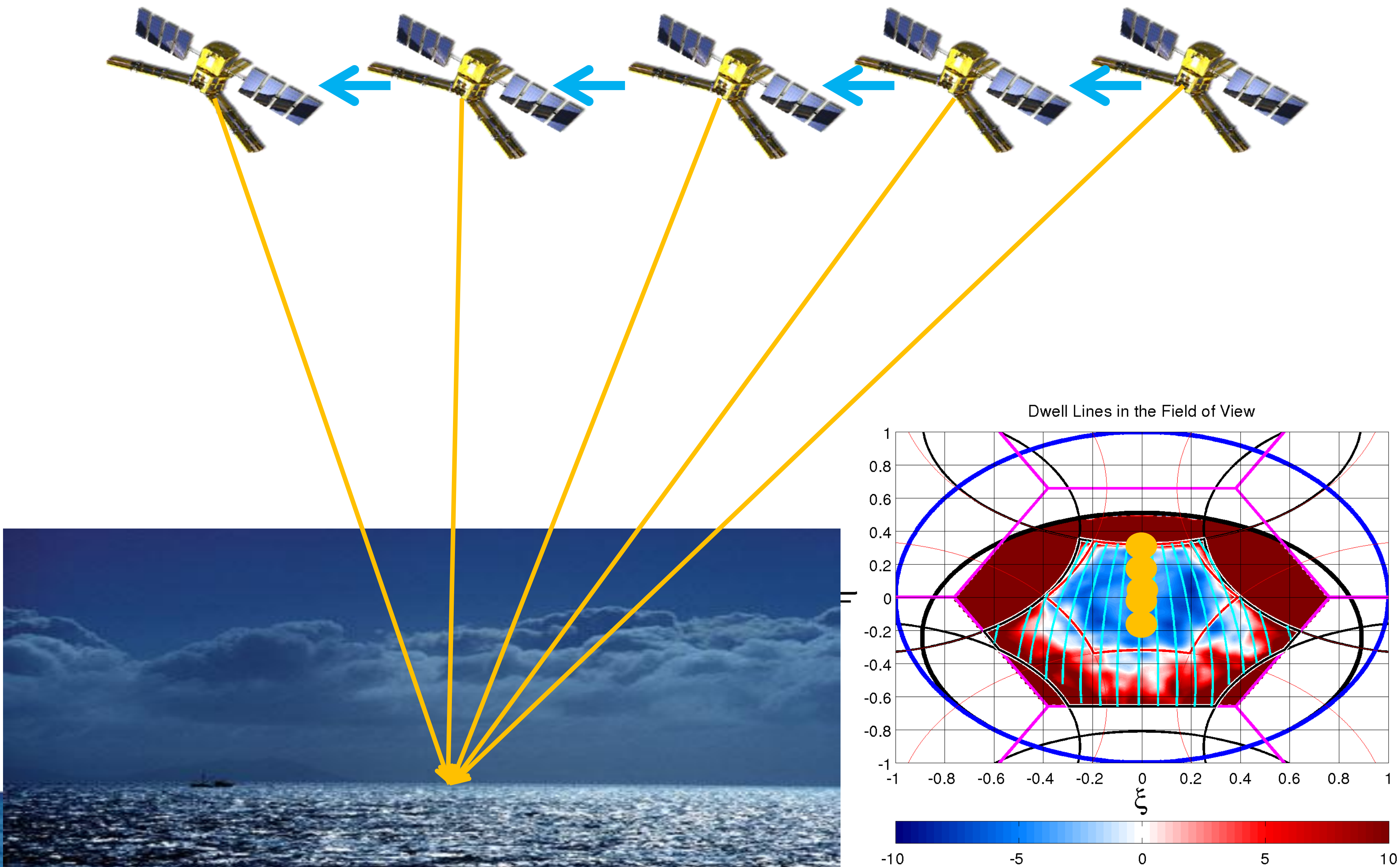

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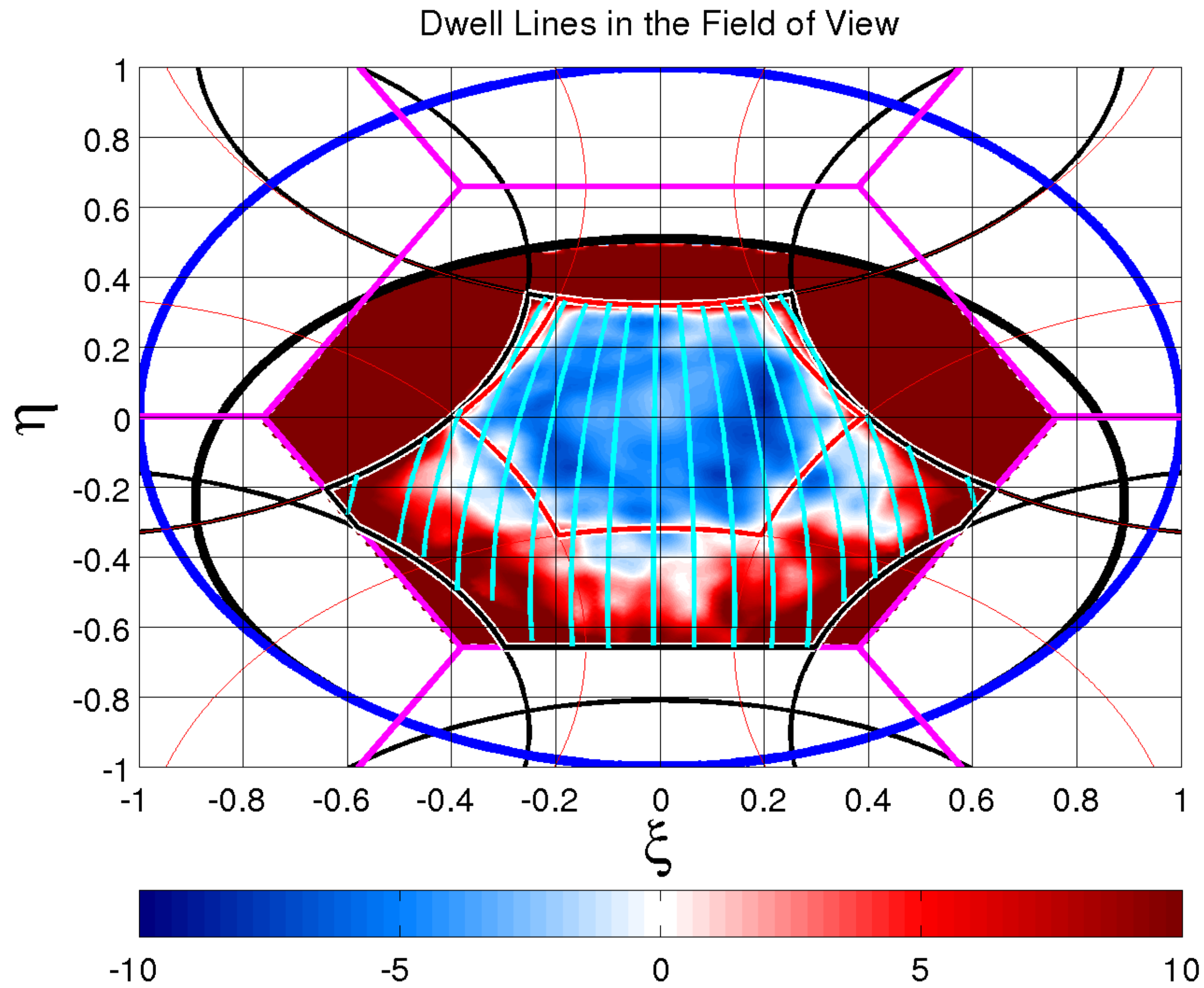
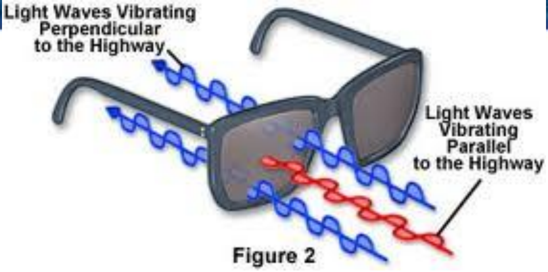


The SMOS Aquisition Polarization



Dual polarisation

1 image is acquired with all antennas in X mode

1 image is acquired with all antennas in Y mode

Gives access to Stokes parameter 1 and 2 (I and Q) but stored as X and Y.

Full polarisation

1 image is acquired with all antennas in X mode

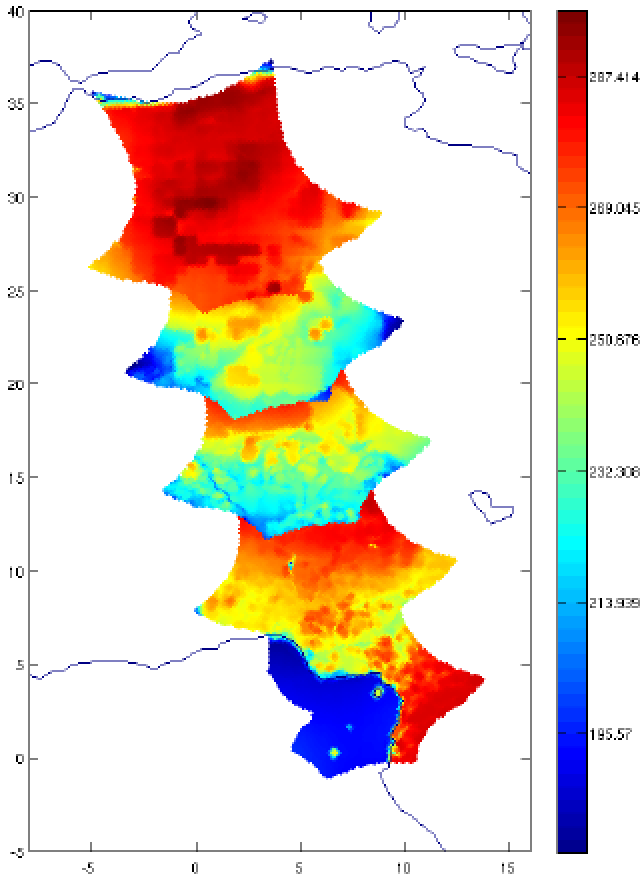
1 image is acquired with 2/3 antennas in X mode and 1/3 in Y mode, alternating within the integration time

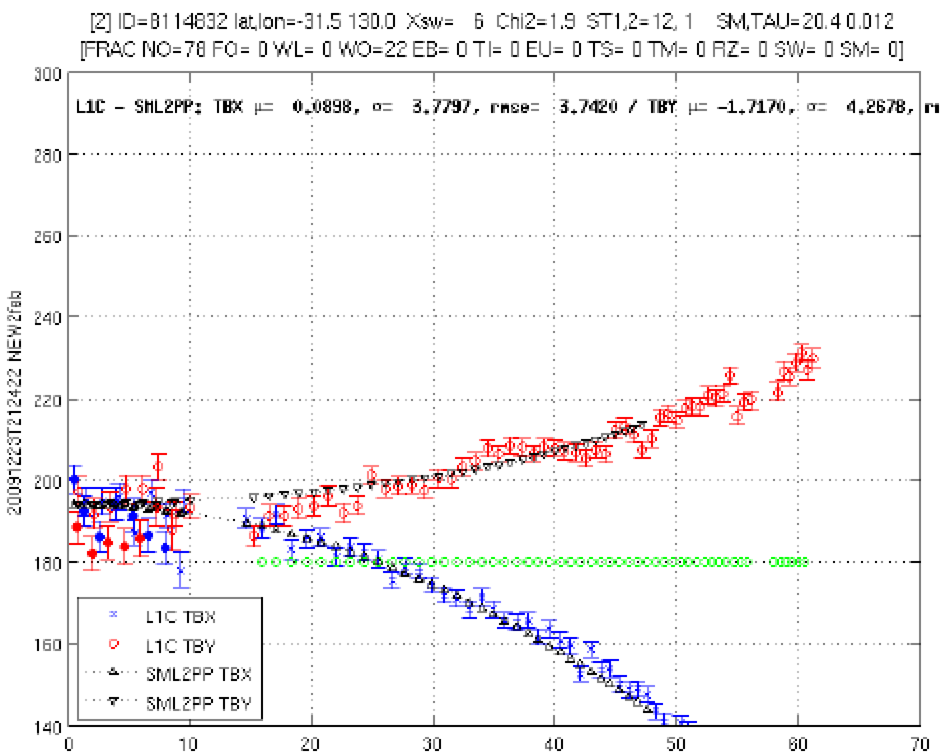
1 image is acquired with all antennas in Y mode

1 image is acquired with 2/3 antennas in Y mode and 1/3 in X mode, alternating within the integration time

Gives access to all 4 Stokes parameters (I, Q, U, V) at the expense of slightly reduced sensitivity.

THE MultiAngular SMOS Aquisition





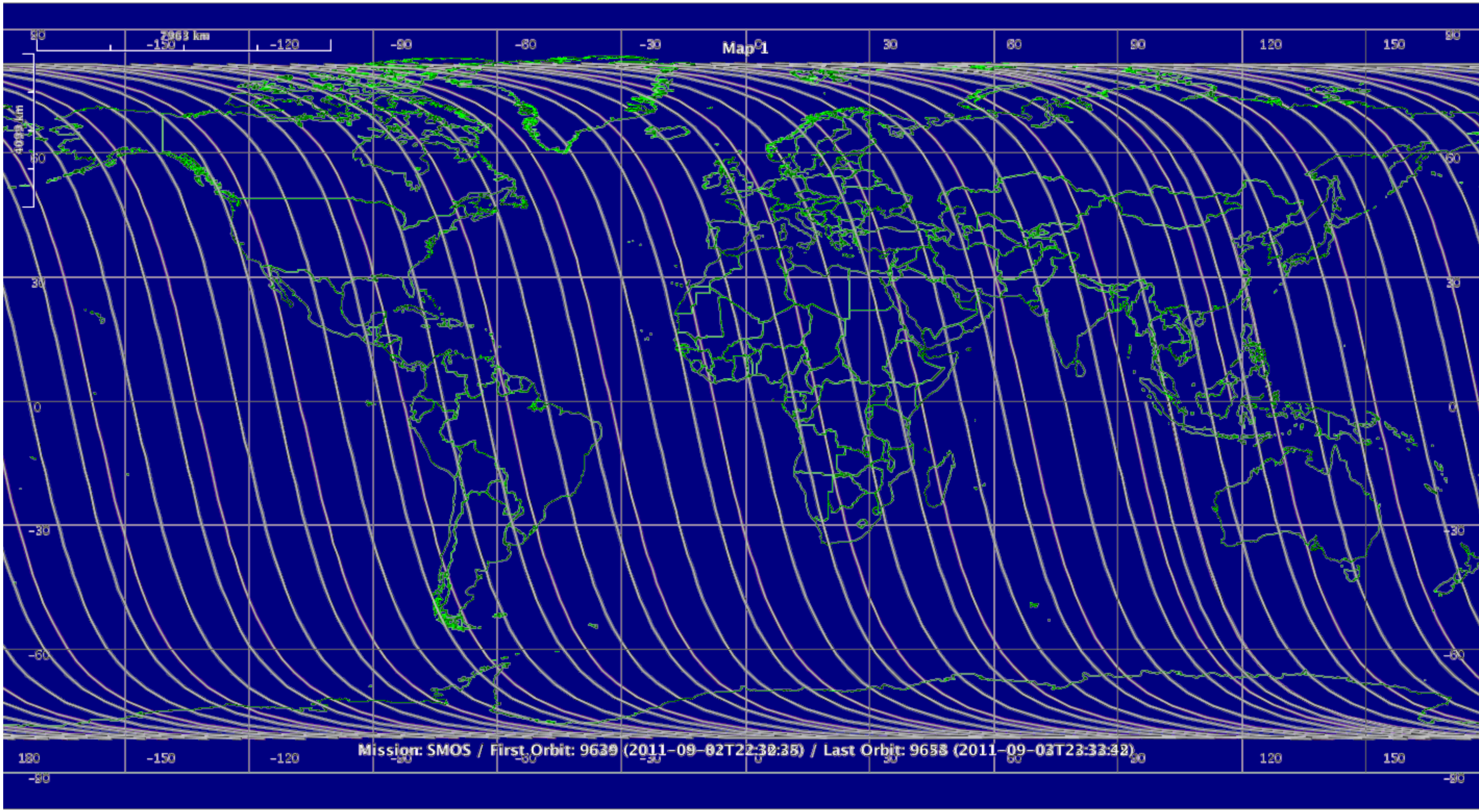
SMOS orbital characteristics

Morning ascending passes

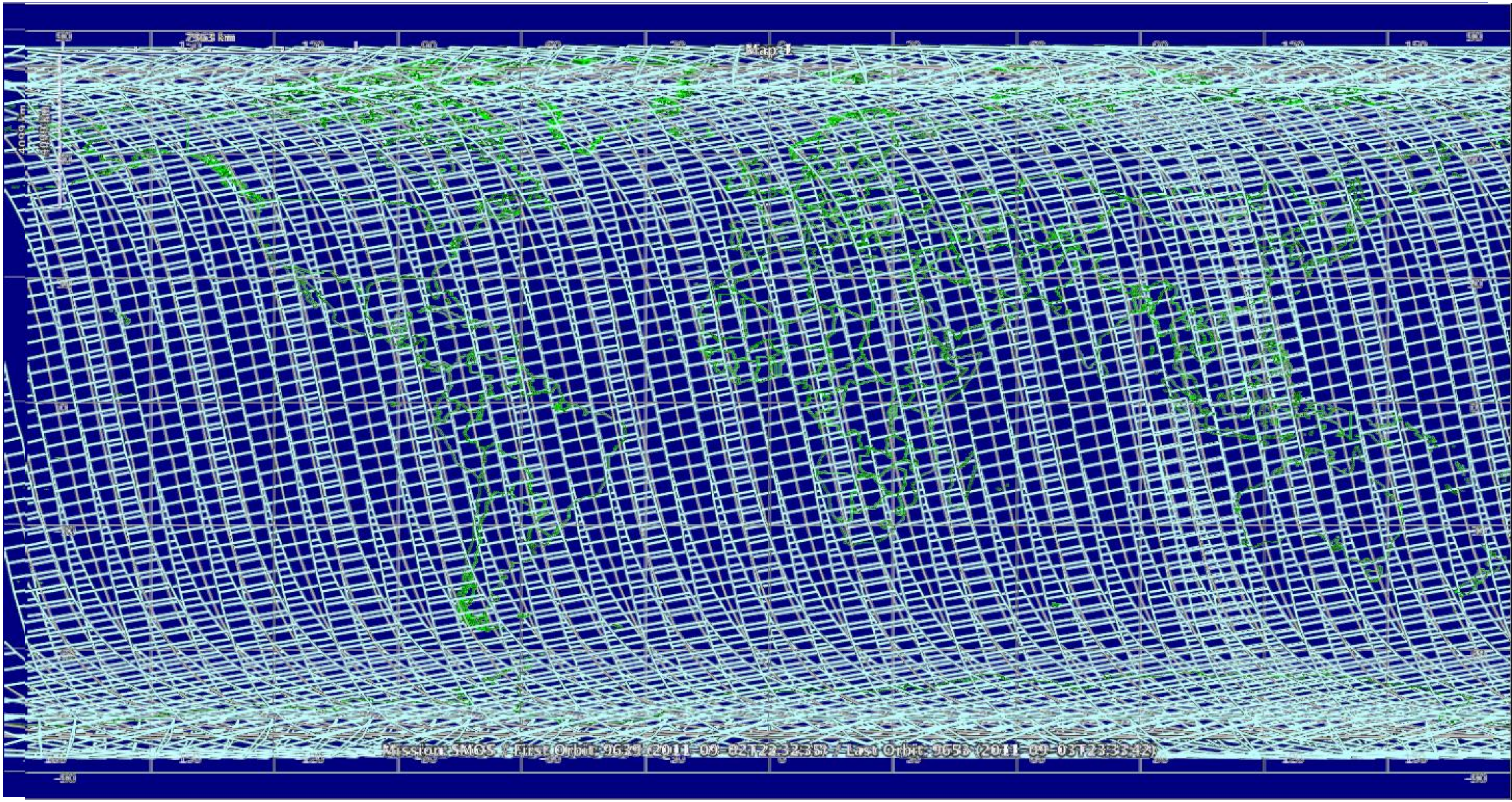
Over terminator to minimise sun contamination

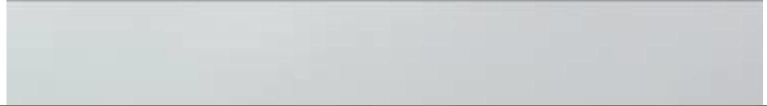
Parameter	Mean Value
Semi-major axis	a = 7134.552 km
Eccentricity	e = 0.00116
Inclination (sun-synchronous)	i = 98.445°
Argument of perigee	ω = 90°
Mean Local Solar Time	Ω = 06:00 AM
Repeat cycle / cycle length	149 days, 2144 orbits
Orbital duration	6004.478 s

SMOS 3 days orbital coverage



SMOS 3 days swath coverage





Payload construction without too much issues

Launched quasi-perfect

(fuel consumption)

Pointing & stability OK

First Images in X and Y pol