Measuring salinity from space: The NASA Aquarius mission

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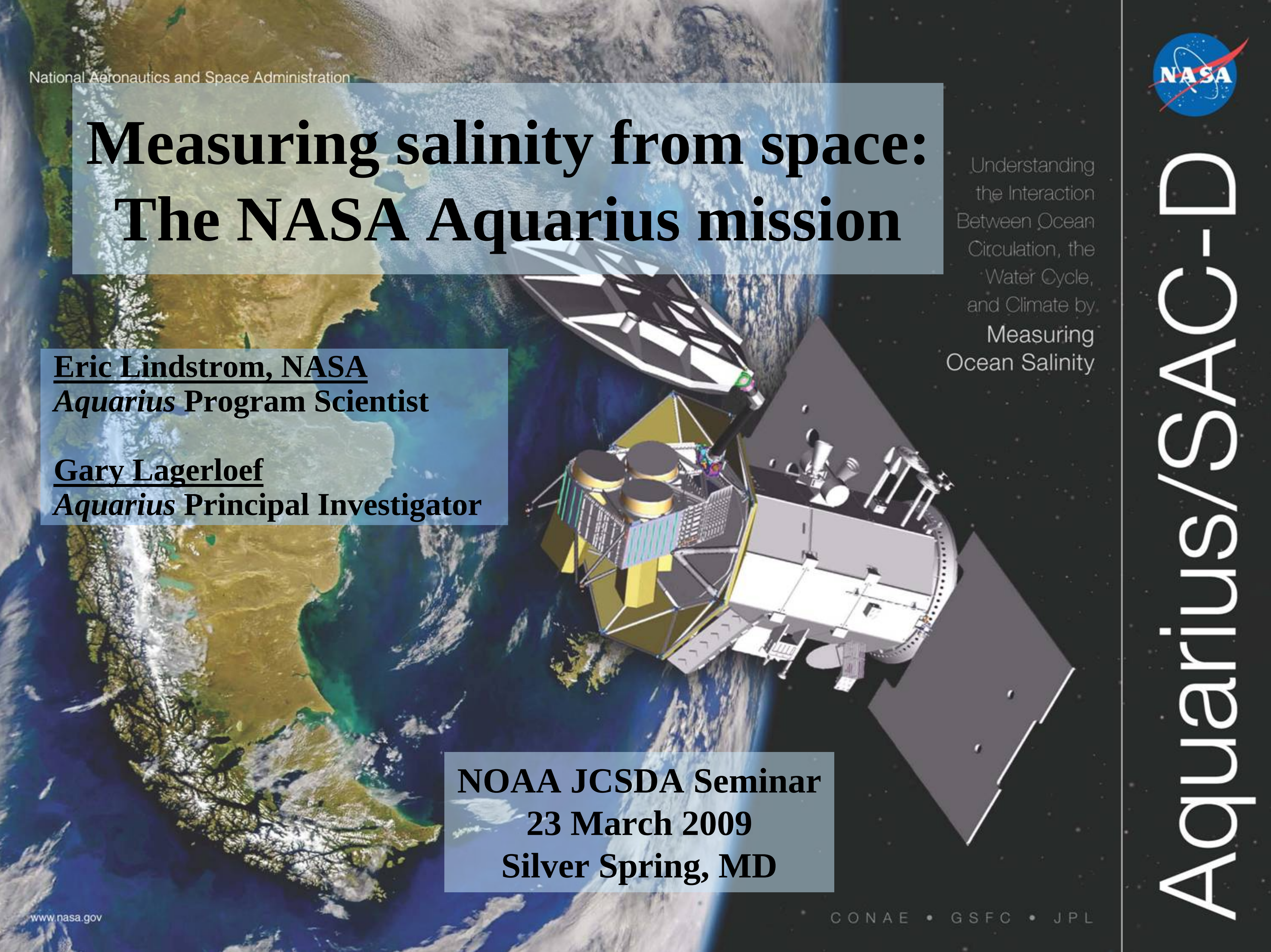
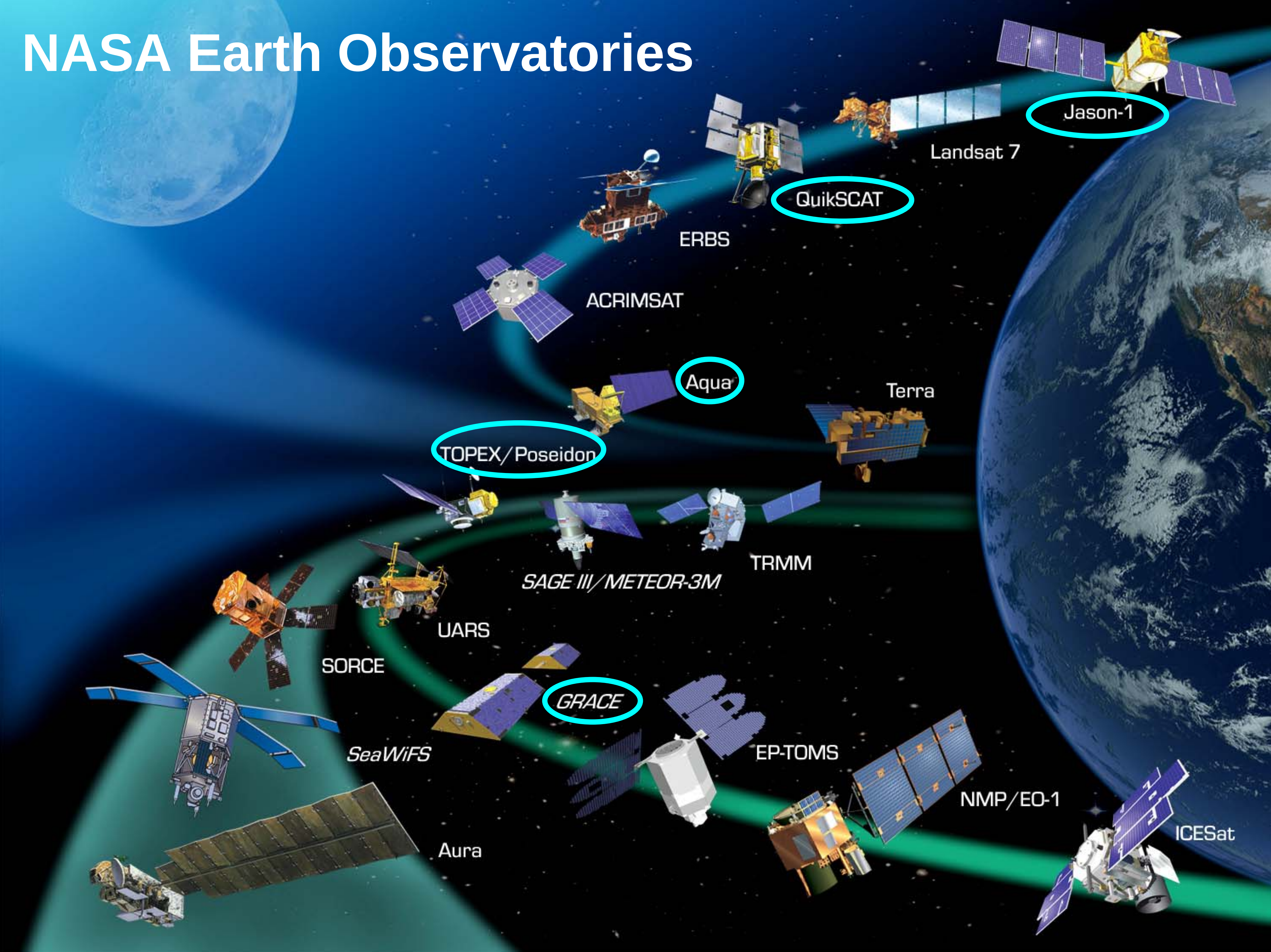
NOAA JCSDA Seminar
23 March 2009
Silver Spring, MD



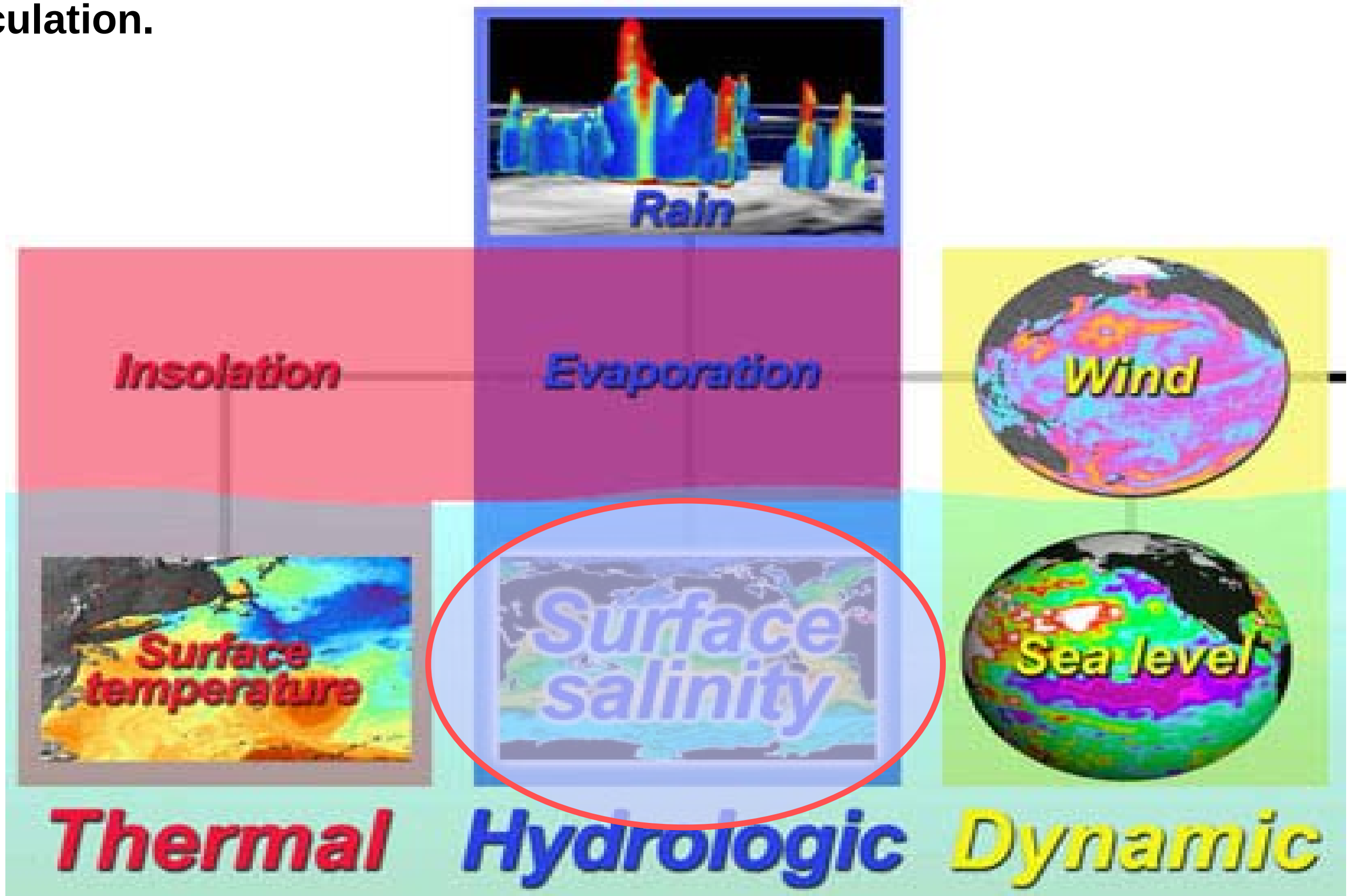
NASA Earth Observatories



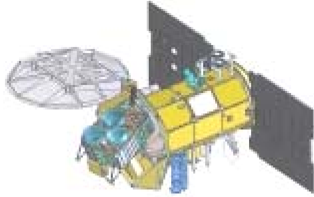
Salinity is Missing from the Satellite Measurement "Toolkit"

- Satellites measure sea level, surface wind, SST, insolation, rain rate, evaporation, ocean color, etc…

- Surface salinity is needed to link the hydrologic cycle to ocean dynamics and circulation.

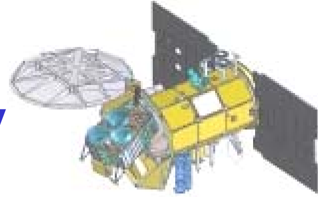


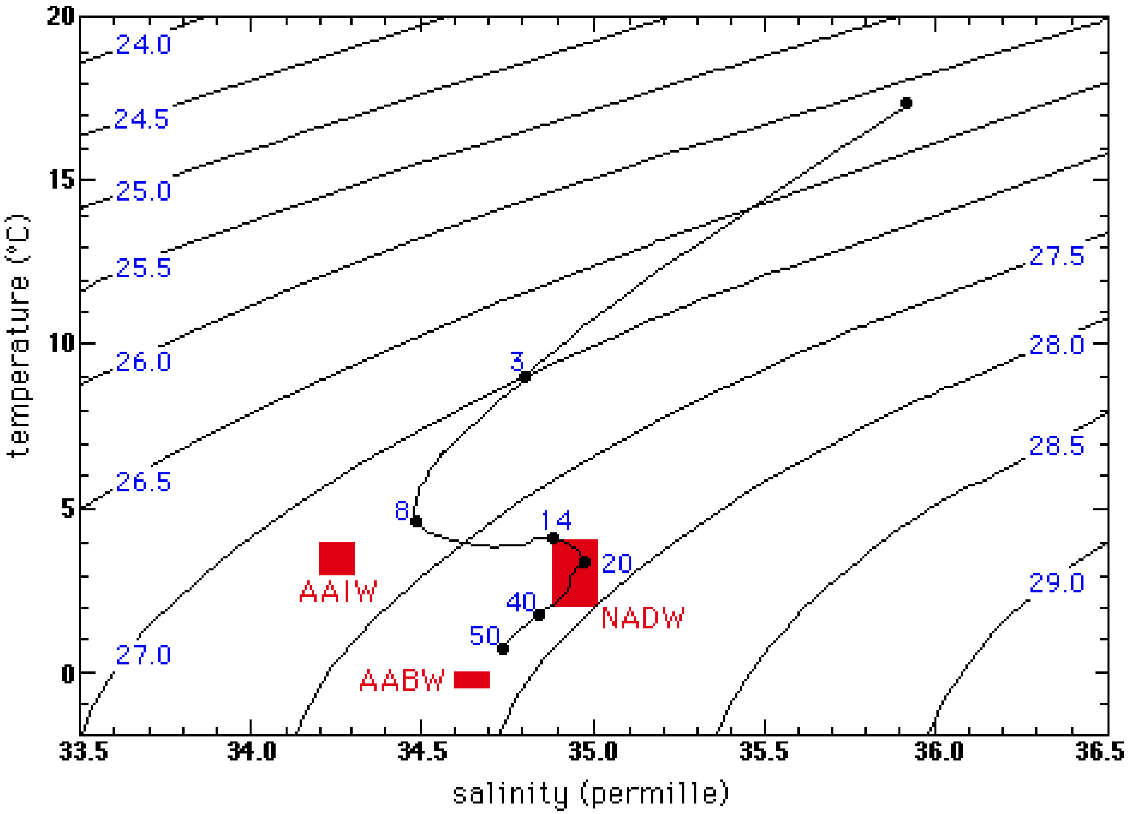
Outline



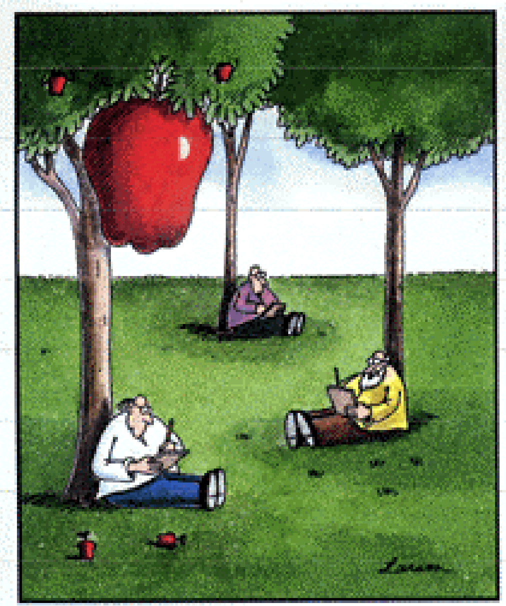
- Science – Why satellite SSS is required
- SSS remote sensing – How it works
- The Aquarius/SAC-D Mission
- Calibration and Validation
- Algorithms and simulators
- Ground System, data access

Temperature and Salinity determines water density





An example of a T-S diagram for observations at depths from 150 m to 5,000 m at 9°S latitude in the Atlantic Ocean. Dots represent individual seawater samples; numbers indicate depths in hundreds of meters. Red boxes represent the major subsurface Atlantic water masses. AABW = Antarctic Bottom Water; NADW = North Atlantic Deep Water; AAIW = Antarctic Intermediate Water.

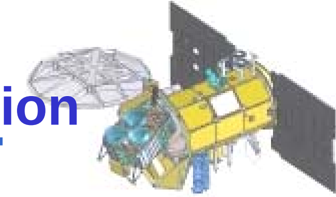


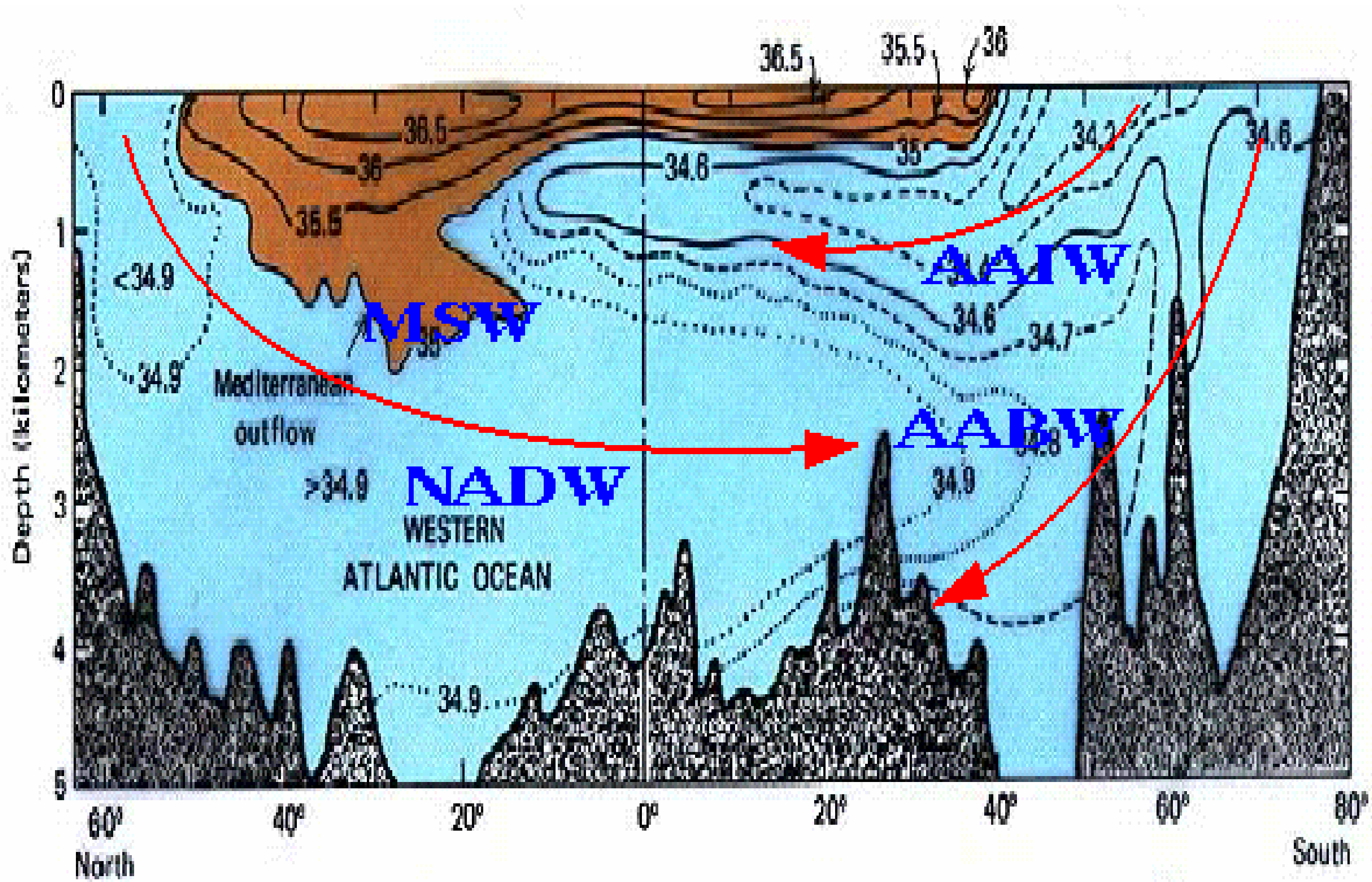
"Nothing yet... How about you, Newton?"

It is gravity that drives the ocean circulation

Temperature-Salinity Diagram (water masses)

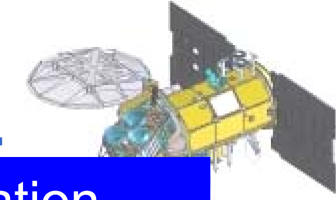
Salinity: An effective tracer of interior ocean circulation



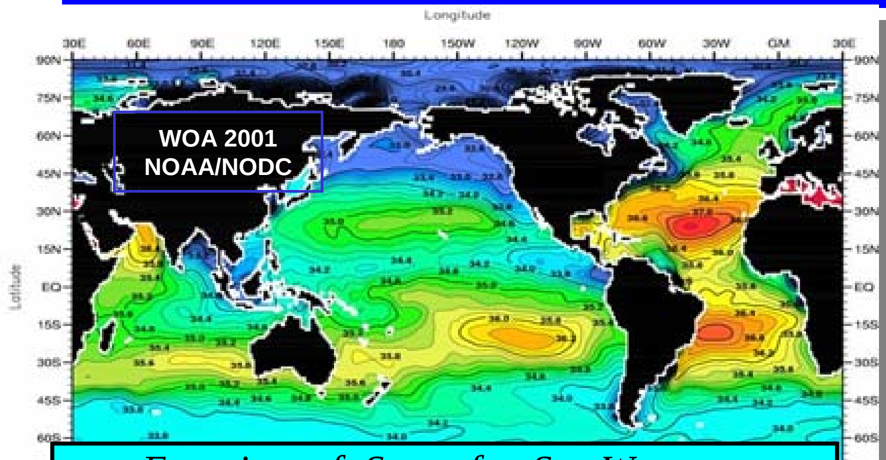


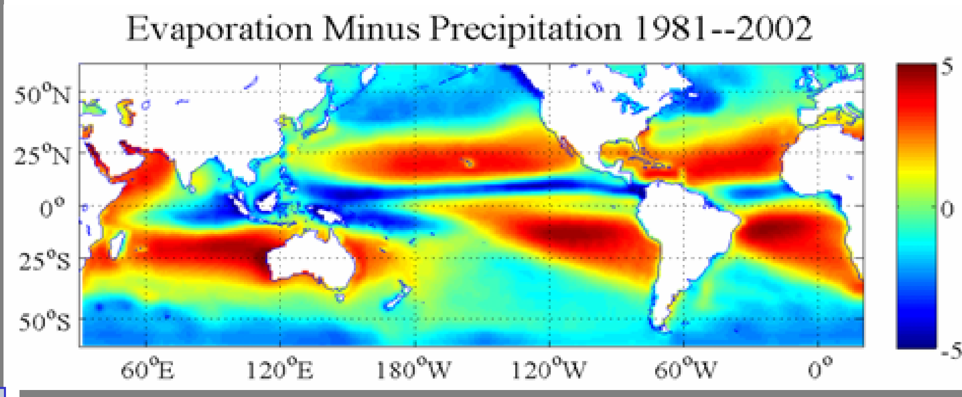
Vertical cross–section of salinity in the Atlantic basin

Aquarius Mission Science



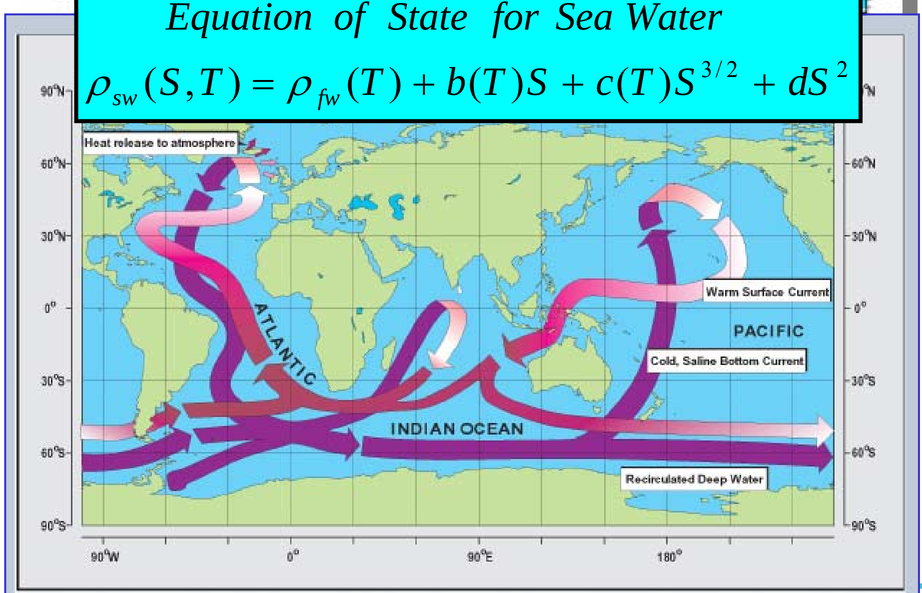
Understanding the Interactions Between the Ocean Circulation, Global Water Cycle and Climate by Measuring Sea Surface Salinity





Equation of State for Sea Water

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



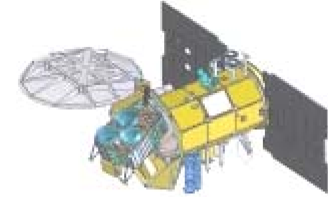
Global salinity patterns are linked to rainfall and evaporation

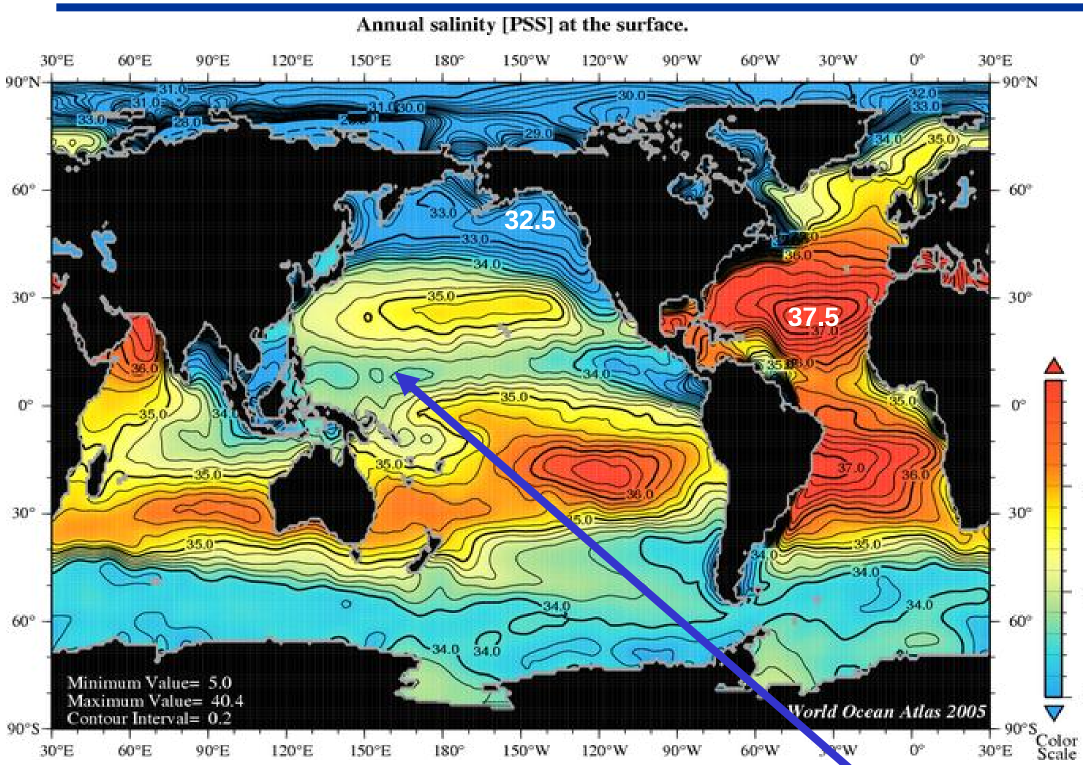
Salinity affects seawater density, which in turn governs ocean circulation and climate

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

Salinity variations are driven by precipitation, evaporation, runoff and ice freezing and melting

Dynamic Range and Accuracy





Mean Ocean SSS Dynamic Range is ~5 psu (32.5 to 37.5 open ocean)

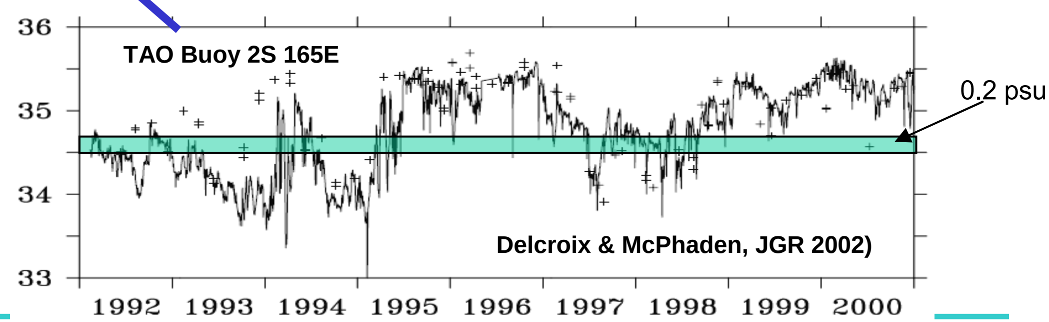
0.2 psu accuracy yields ~25:1 signal/error relative to mean field

Accuracy and signal/error improves with averaging interval (Table)

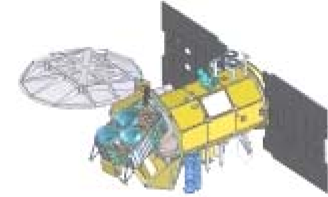
Random Error Reduction with Averaging Interval						
	Instantaneous	7 Days	28 Days	90 Days	1 Year	3 Years
Global RMS (psu)	0.87	0.33	0.20	0.09	0.05	0.03
Mean Signal/Error	6	15	25	55	110	190

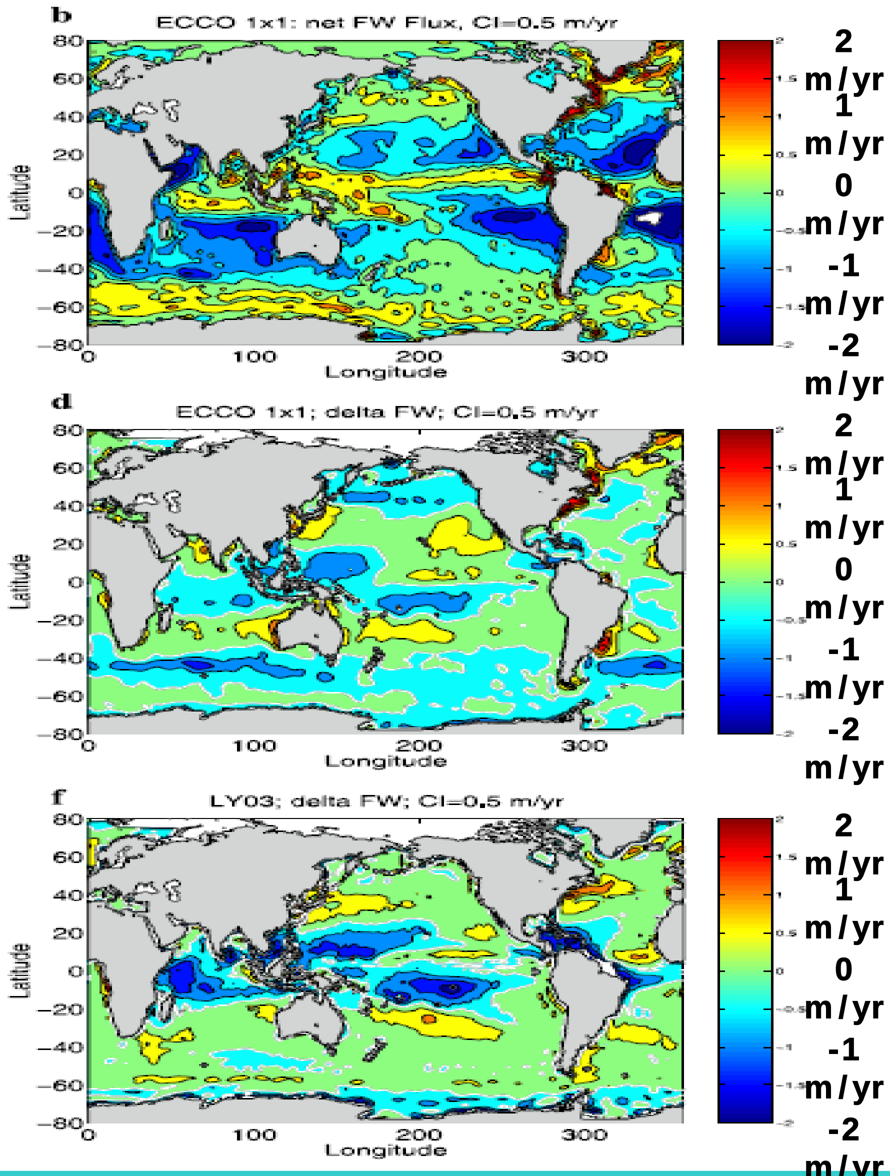
- Interannual SSS variability range is ~2 psu in the western tropical Pacific
- 0.2 psu monthly accuracy is at the detection limit of short time scales, and easily resolves the interannual signals related to El Niño

- Climatology maps based on the available historical data are interpolated over ~1000 km scales due to data sparseness.
- Aquarius' 150 km resolution will provide almost an order of magnitude improvement



Marine freshwater budget out of balance





The mean net freshwater flux fields to/from the atmosphere as they result from the ECCO ocean model optimization over the period 1992 through 2001 (m/year).

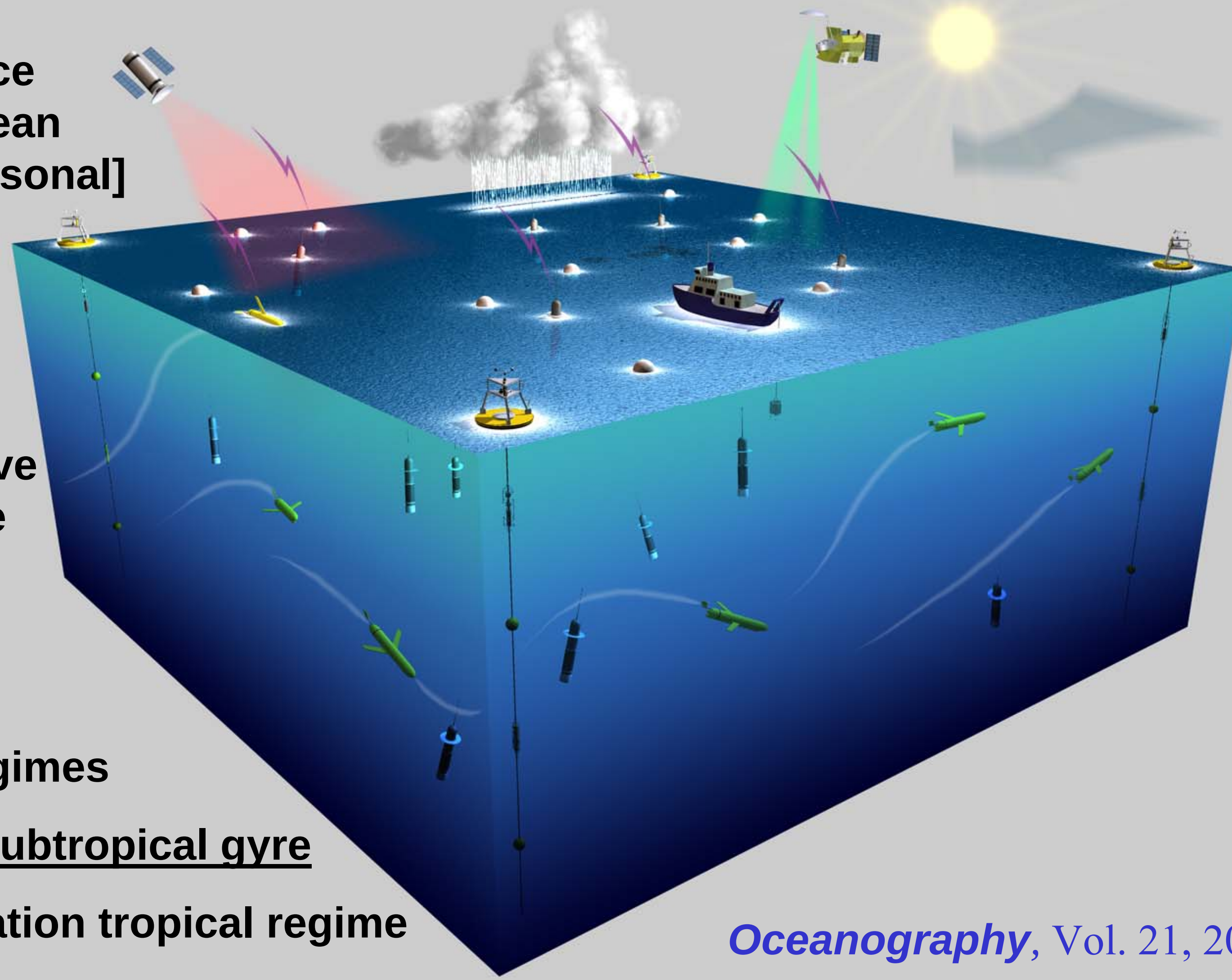
Mean difference between the net freshwater flux as determined from the ocean optimization relative to the NCEP fields estimated over the same period.

Mean fresh water flux difference between NCAR and NCEP for the period 1991–2000, illustrating the uncertainty range of different atmosphere analyses.

(Stammer et al, JGR-Oceans, 2004)

U.S. CLIVAR Salinity Working Group
Proposed Control Volume Experiment

Constrain the complete surface atmosphere/ocean hydrologic [seasonal] cycle based on observations



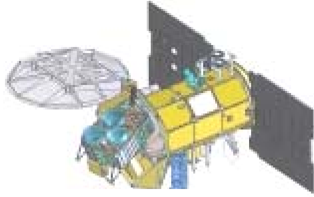
Test and improve coupled climate models

Alternative regimes

- **<u>evaporative subtropical gyre</u>**
- **high precipitation tropical regime**

Oceanography, Vol. 21, 2007

Potential Process Study in 2011



Air-Sea Freshwater Budget Study

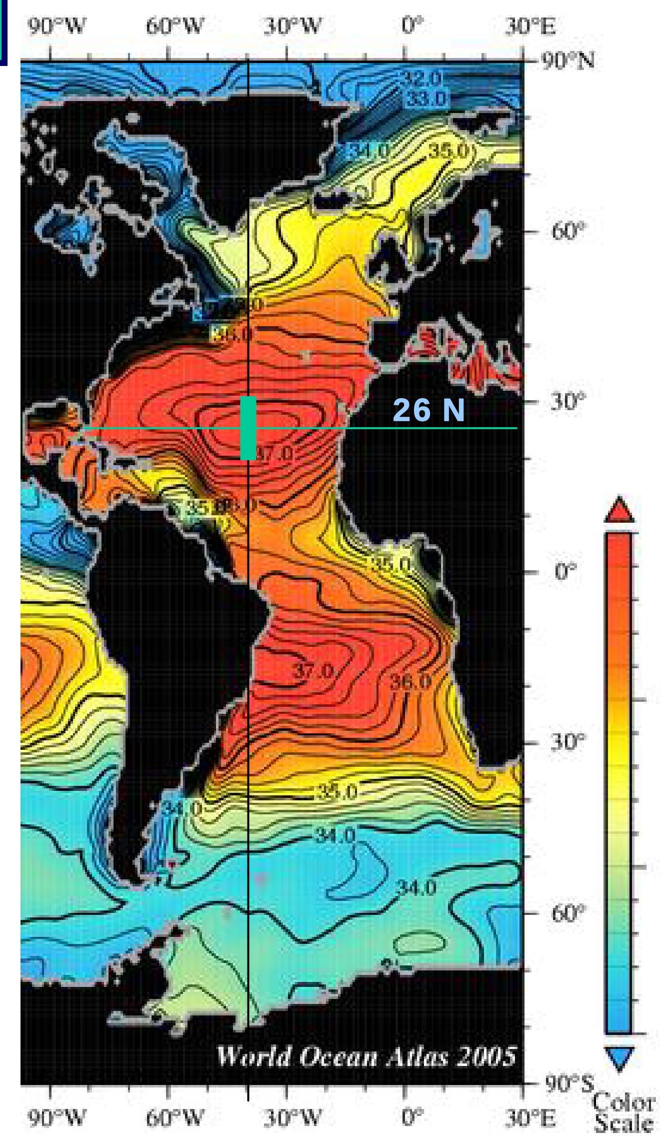
Discussion group meeting at WHOI 9-10 July 2008: Ray Schmitt, Eric Lindstrom, Steve Riser, Arnold Gordon, Bill Large, Jim Carton, Fred Bingham, Gary Lagerloef, Lisan Yu, David Fratantoni

Location advantages:

- Weak horizontal divergence
- Low precipitation
- Modest eddy activity

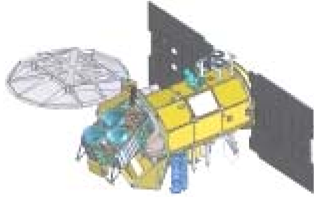
} 1D physics

- Source of water for northern tropical thermocline
- Stable SSS for satellite Cal-Val
- Warm SST (better for Aquarius accuracy)
- Leverages other resources: RAPID/MOC sections, Pirata Array, ESTOC time series (Canary Islands)
- Logistically tractable



Planning workshop in early 2009

Physical Principles



Salinity is Derived by Measuring Brightness Temperature at L-Band (1.413 GHz)

Microwave radiometers measure the emitted power of a surface in terms of a parameter called the radiometric brightness temperature (T_B), which is proportional to the ideal black body radiation.

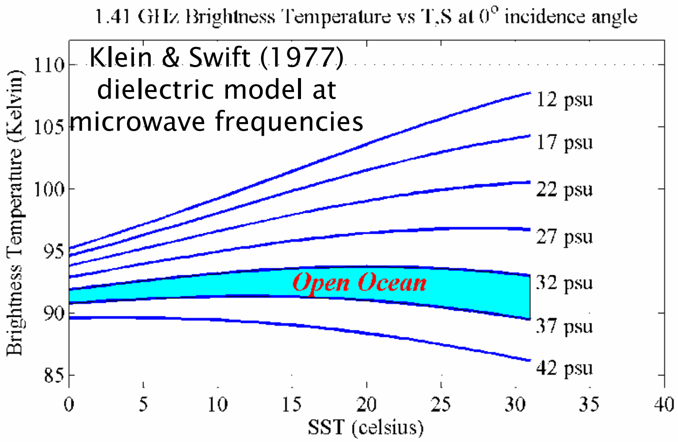
T_B is the product of emissivity (e) and absolute surface temperature (T) in Kelvins

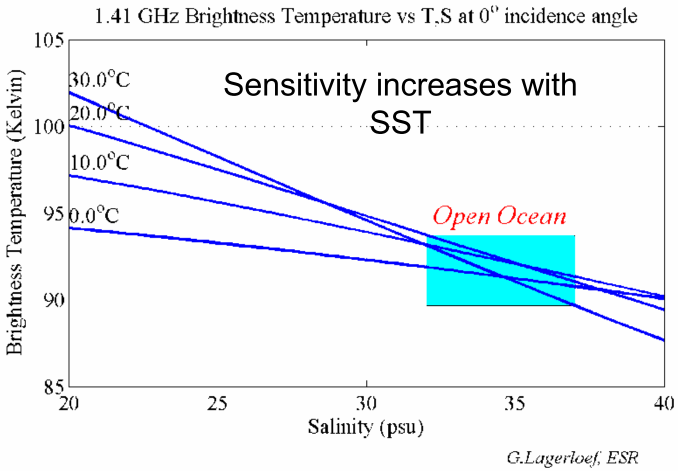
$$T_B = eT, \quad \text{where } e \leq 1$$

e is a function of dielectric coefficient ε , incidence angle θ, polarization H or V, and sea state

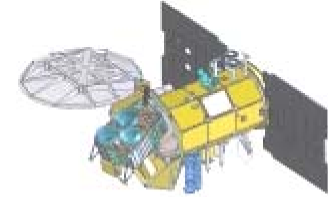
ε is the complex dielectric coefficient and depends on **S**, T, and radio frequency (f)

For sea water at S=35, T=288K(15C), θ=0, flat sea and f=1.413 GHz, the emissivity e≈0.3

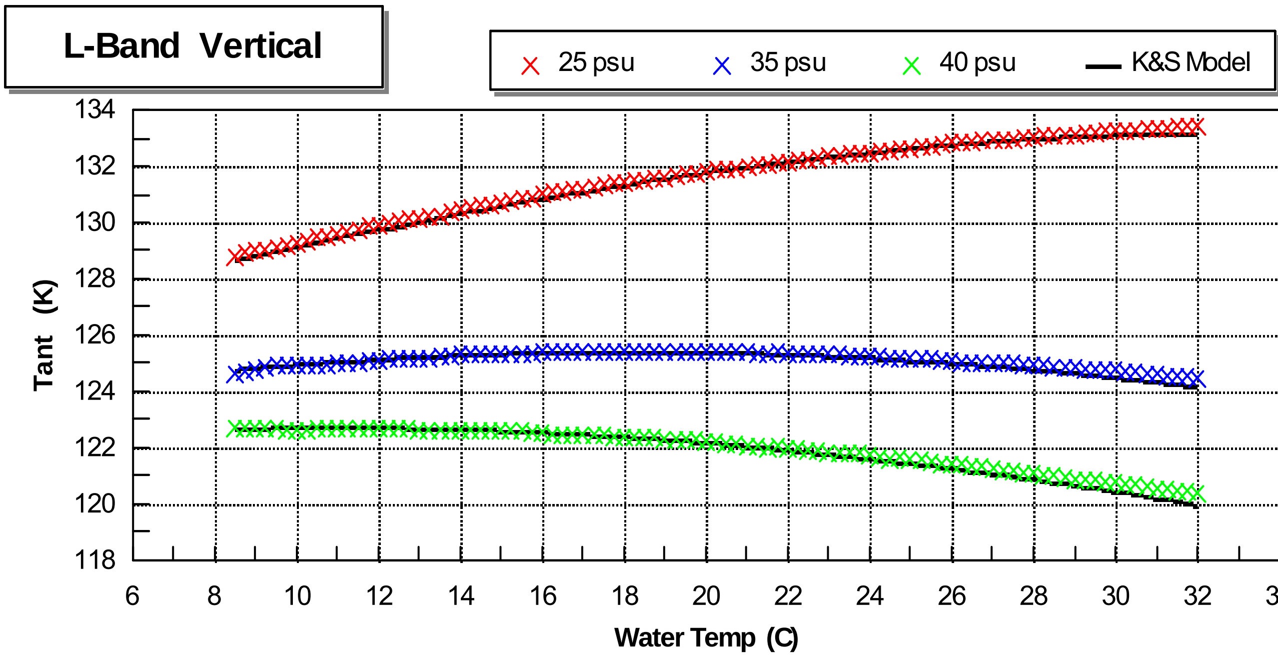




Physical Model Verification



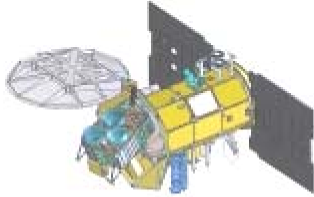
The Aquarius team has validated Klein and Swift theory with controlled experiments over a wide range of temperature & salinity.



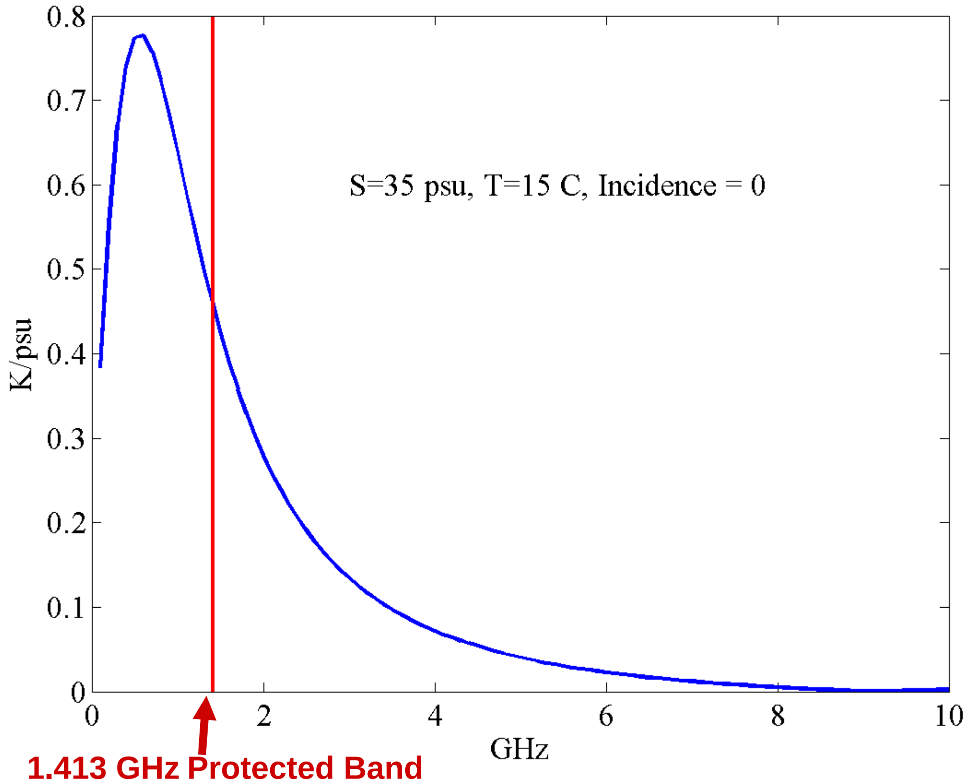
Passive/Active L-/S-Band Sensor (Wilson and Yueh, JPL, October 2001)

- New laboratory measurements of the sea water dielectric constant at 1.413 GHz are being made.

Why 1.413 GHz?



Sensitivity vs Radiometer Frequency



- It is a protected band (radio astronomy)
- Antenna size is manageable. Aquarius will have a 2.5 m antenna to yield a footprint ~100km.
- There is enough sensitivity to detect SSS signatures

  (~0.1K ≈ 0.2 psu)
- To achieve the required accuracy, the Aquarius radiometers are the most accurate ever developed for satellite.

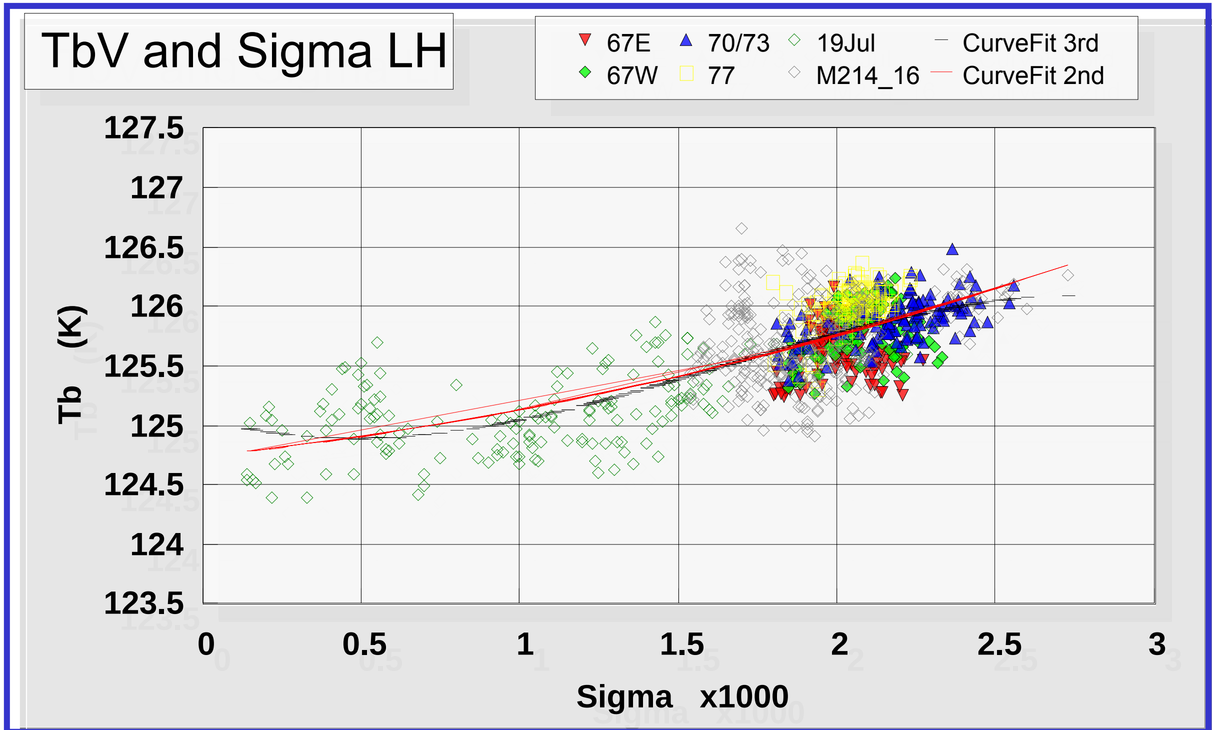
Instrument Requirements

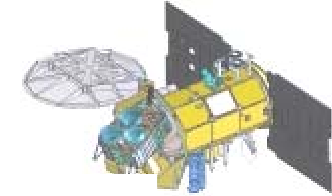
Aquarius **Will Carry a 1.26 GHz Radar Scatterometer to Correct for Surface Roughness**

PALS 2002 T_bV vs Scatterometer Data

2nd or 3rd order curve fit:

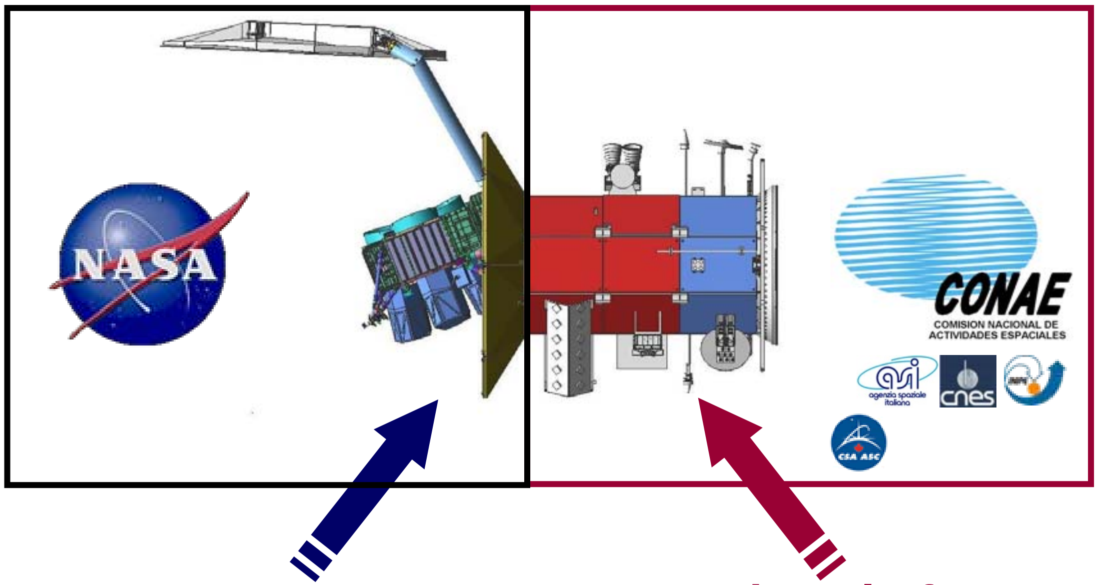
RMS error = 0.28 K





International Partnership between United States – Argentina

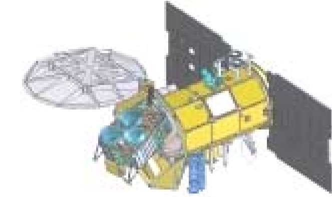
INVAP



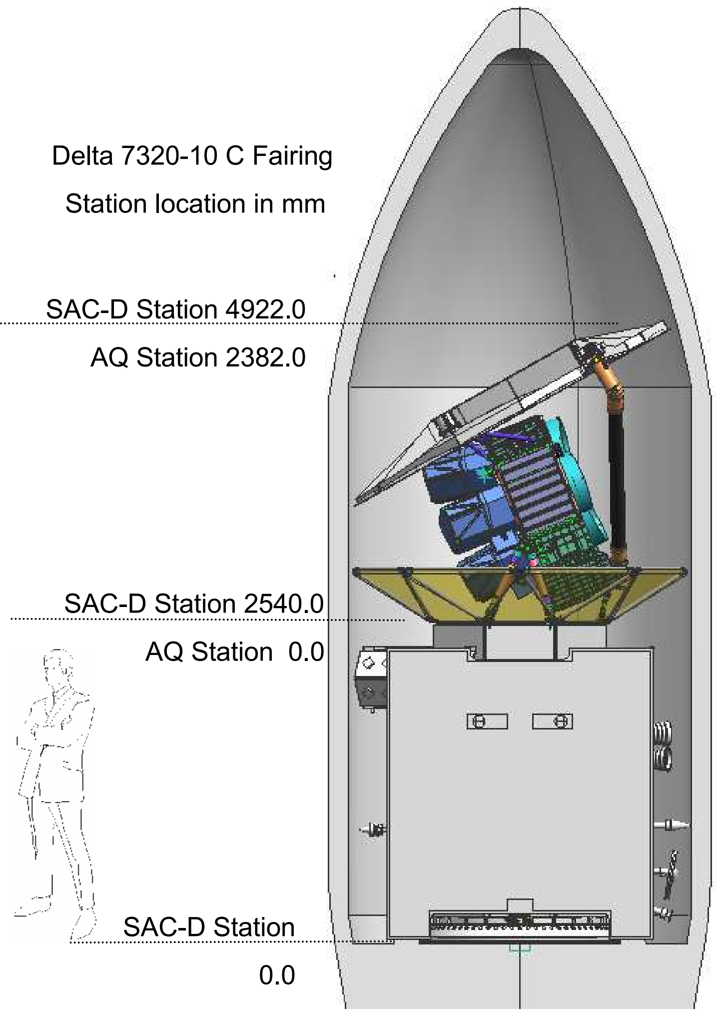
- Aquarius Salinity Microwave Instrument
- Launch Vehicle

- Service Platform and SAC-D Science Instruments
- Mission Operations & Ground System

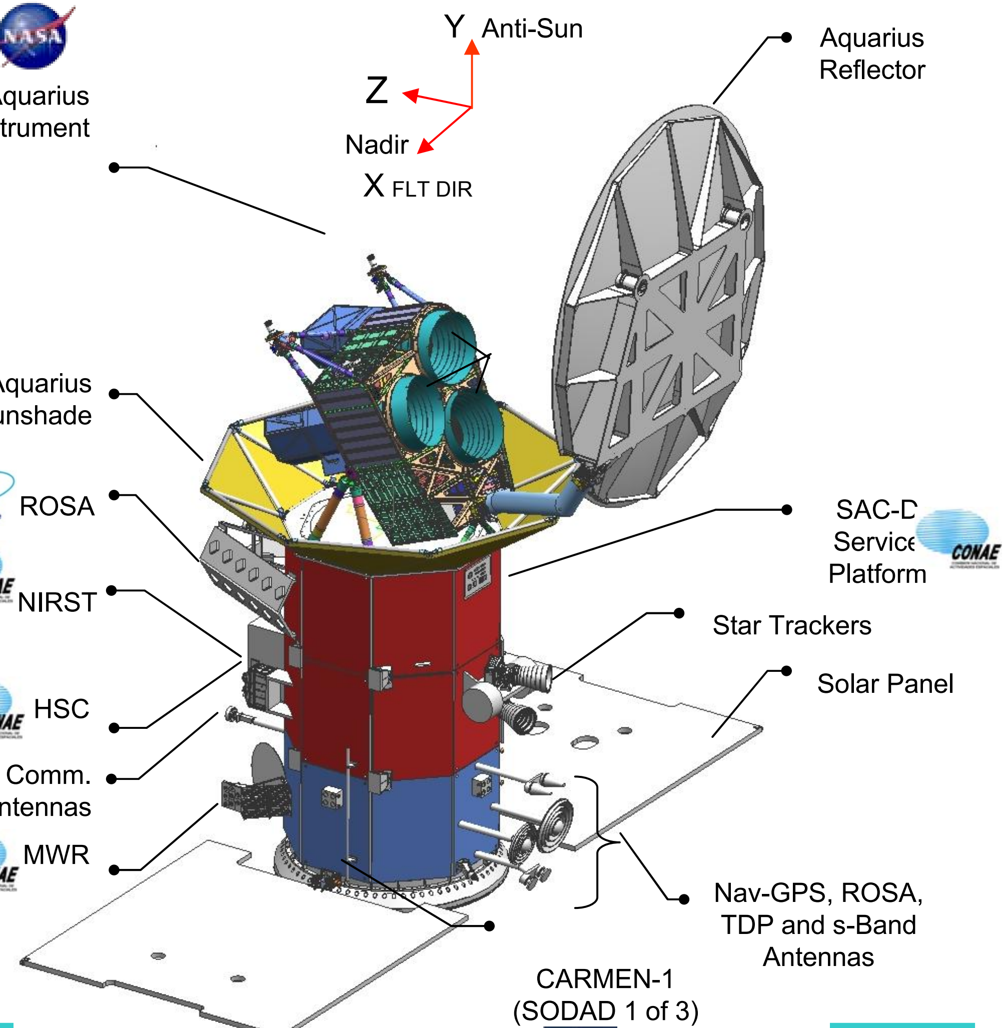
Observatory Configuration

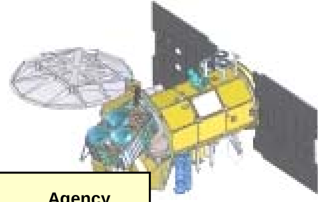


Stowed Configuration



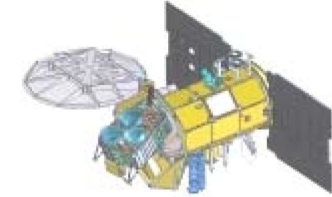
Deployed Configuration



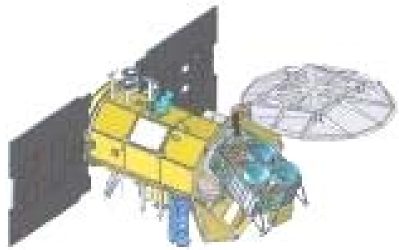


Instrument	Objectives for each instrument	Specifications	Resolution	Agency
Aquarius Integrated L- Band radiometer and Scaterometer	Sea Surface Salinity and Soil Moisture Meassurements	Integrated L- Band radiometer (1.413 Ghz) and scaterometer (1.26 Ghz) swath: 380 km	Three beams:76 x 94, 84 x 120, 96 x 156 km	NASA
MWR Microwave Radiometer	Precipitation rate, winds speed, sea ice concentration, water vapour, clouds	Bands: 23.8 Ghz V Pol. and 36.5 Ghz H and V Pol. Band widht: 0.5 and 1 Ghz swath: 380 km	Eight beams per frequency < 54 km	CONAE
NIRST New Technology Infrared Camera	Hot spot events(fires, volcanoes), sea surface temperature measurements	Bands:3,8, 10,85 y 11,85 um Instantaneous swath 182 Km extended swath 1000Km Pointing: ±30°	Space resolution: 350 m in temperature: 0.5°C less burned area detectable: 200 m²	CONAE CSA
HSC Hight Sensitivity Camera	Urban lights, electric storms, polar regions ,vessel detection, snow cover	Pancromatic: 450-610 nm Swath: 700 Km	200-300 meters	CONAE
DCS Data Collection System	Data Collection System of Environmental and meteorological	401.55 Mhz uplink	2 contacts per day with 200 platforms	CONAE
ROSA Radio Occultation Sounder For Atmosphere	Determination of Atmospheric temperature, pressure, humidity	GPS Occultation Techniques	Horiz: 300 Km Vert: 300m	ASI
CARMEN I ICARE & SODAD	Effects of cosmic radiation in electronic devices, distribution of micro-particles and space debris	I: three Si detectors, Si/Li S: four MOS sensors	I: 256 channels spectra S: Sensitivity: 0.5 u part. at 10Kkm/sec	CNES
TDP Technological Demostration Package	Position, velocity and time inertial angular velocity determination	GPS receiver Inertial Unit Reference	Position: 20m, velocity:1m/sec Angular Random Walk: 0.008 deg/sqrt h	CONAE

Mission Design and Sampling Strategy

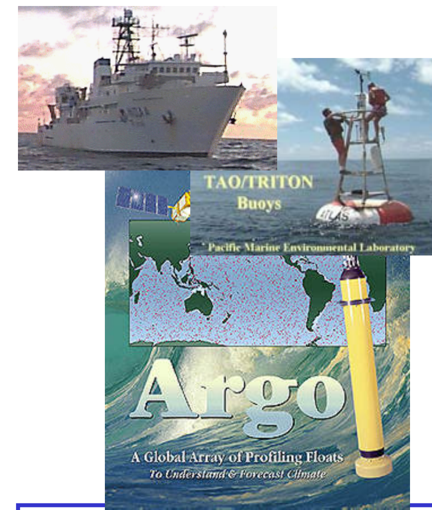


Sun-synchronous exact repeat orbit
6pm ascending node
Altitude 657 km



- ***Global Coverage in 7 Days***
- ***4 Repeat Cycles per Month***

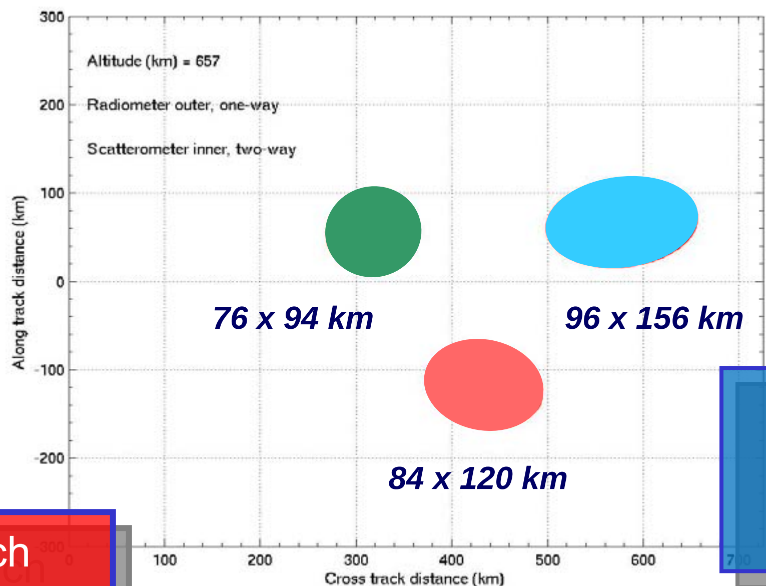
Beams point toward the night side to avoid sun glint



Surface Validation

In Orbit Check out

***3 beams** 390 km wide swath.*

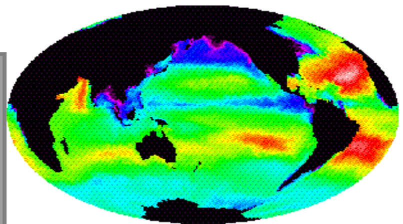


Aquarius Ground System

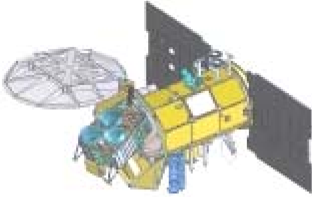
Launch
22 May 2010

Salinity Data

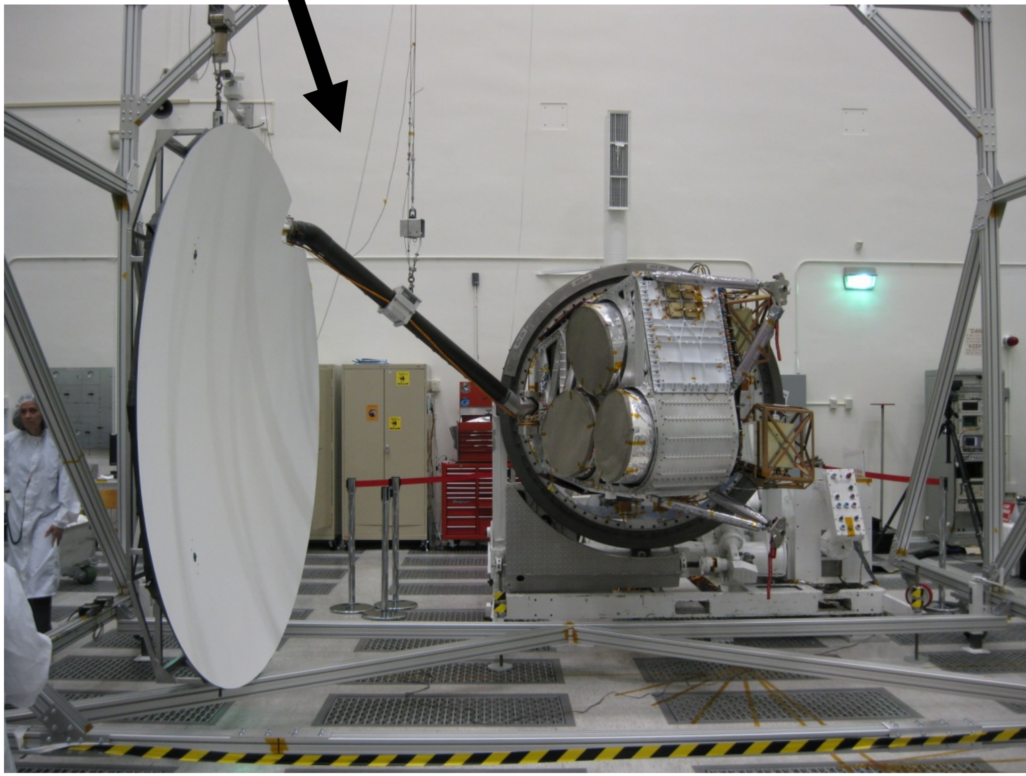
150km, Monthly, 0.2 (pss)



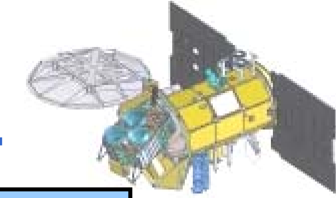
Boom & Reflector Installation and Deployment Tests

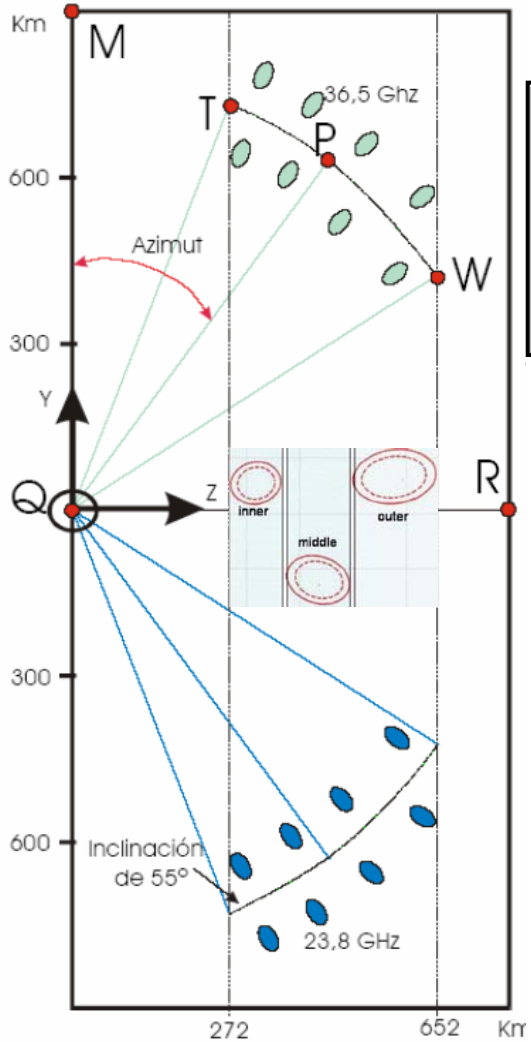


1. Boom and Reflector installation complete & stowed configuration (3 Nov 2008)
2. Deployment test complete (10 November 2008)



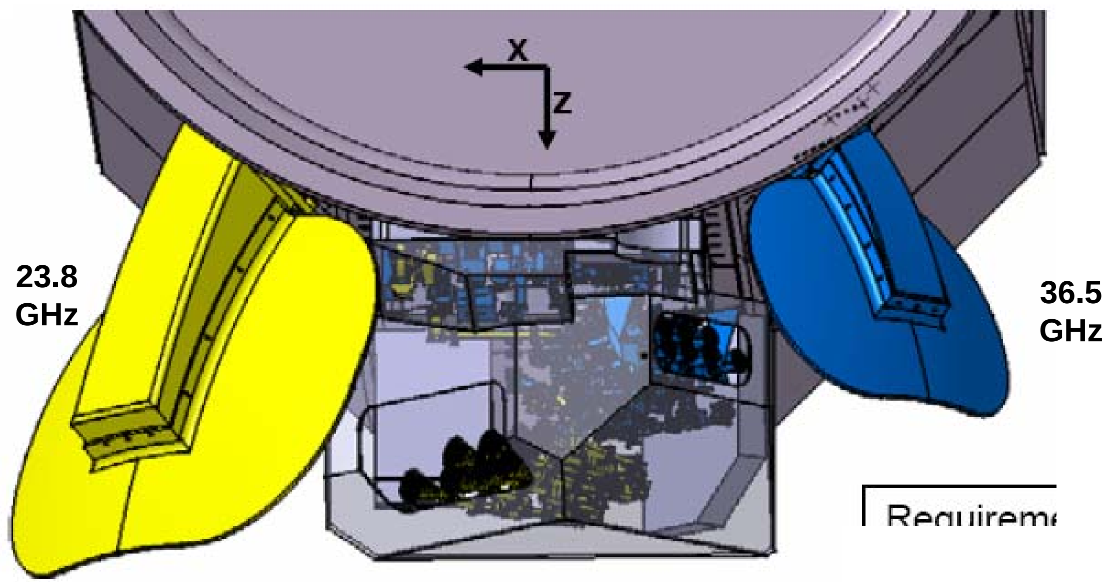
CONAE MicroWave Radiometer (MWR)



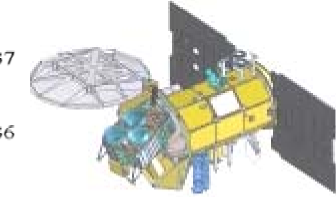


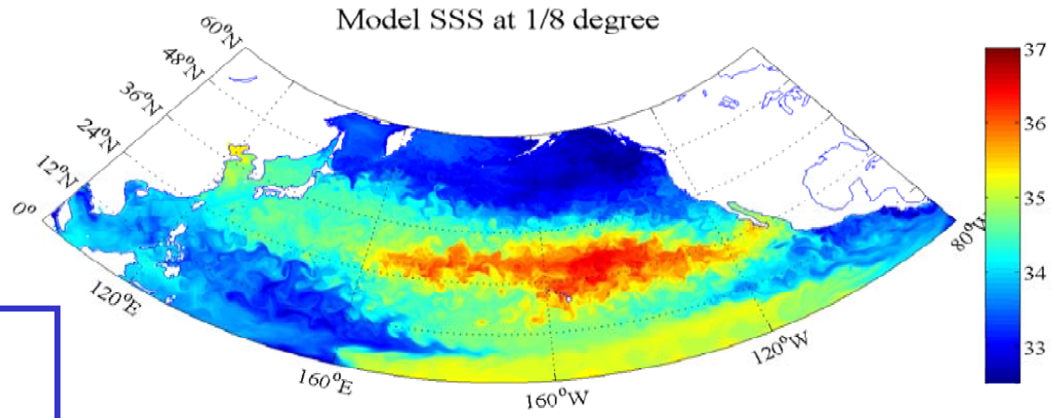
Rain, Wind, Sea ice

Instrument	Objective	Description	Resolution	Source
MWR: Microwave Radiometer	Precipitation, wind speed, sea ice concentration, water vapor	23.8 GHz and 36.5 GHz; 36.5 polari-metric; 23.8 V-pol; 390 km swath	50 km	CONAE



Each radiometer has a cluster of 8 offset feeds



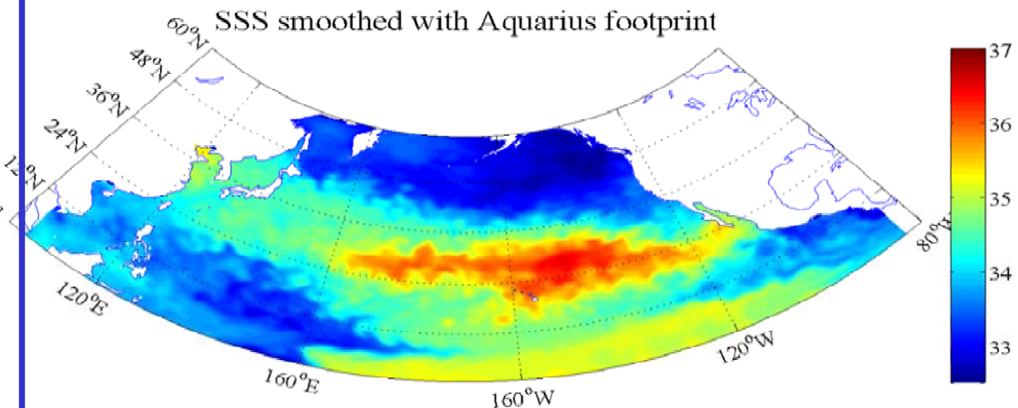


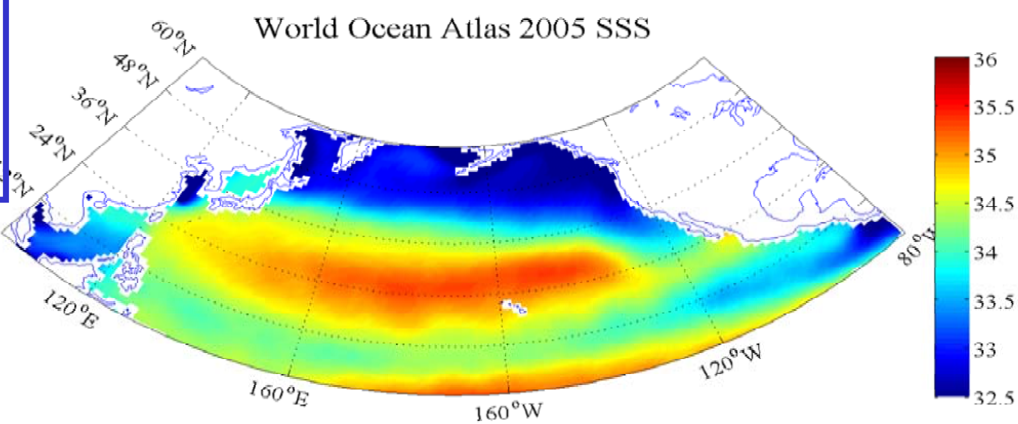
Basin scale spatial resolution provided by the Aquarius footprint:

•**Top:** Snapshot of a 1/8 degree OGCM SSS field.

•**Middle:** The same field with a 150 km Gaussian filter applied to simulate the Aquarius spatial resolution, removing much of the eddy scale structure while preserving good spatial resolution of basin and gyre scale structures.

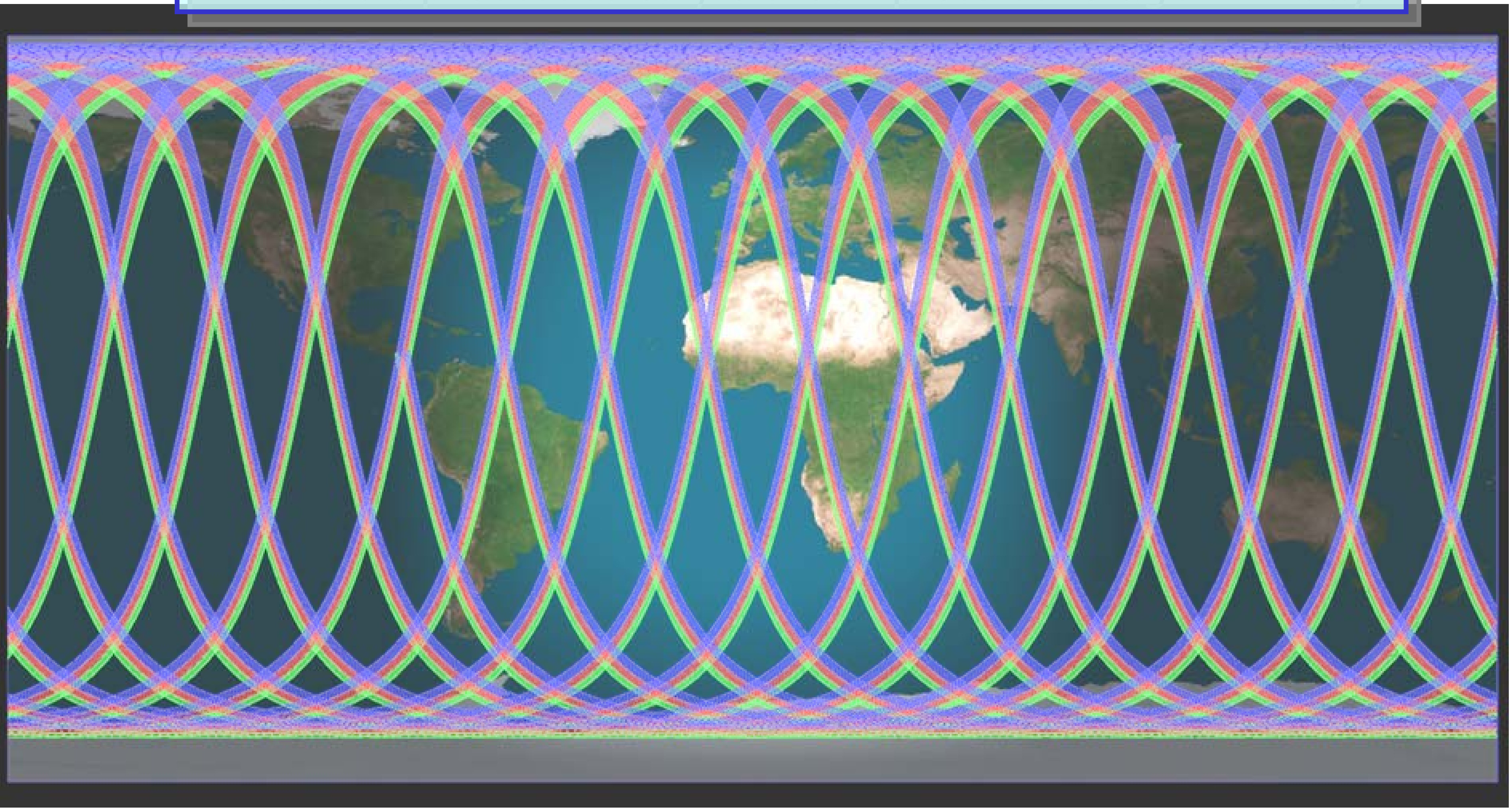
•**Bottom:** Mean annual SSS from World Ocean Atlas 2005.



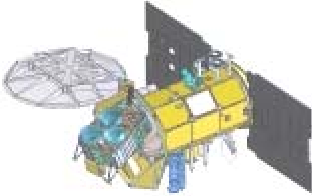


Single Day Orbit Swath Pattern

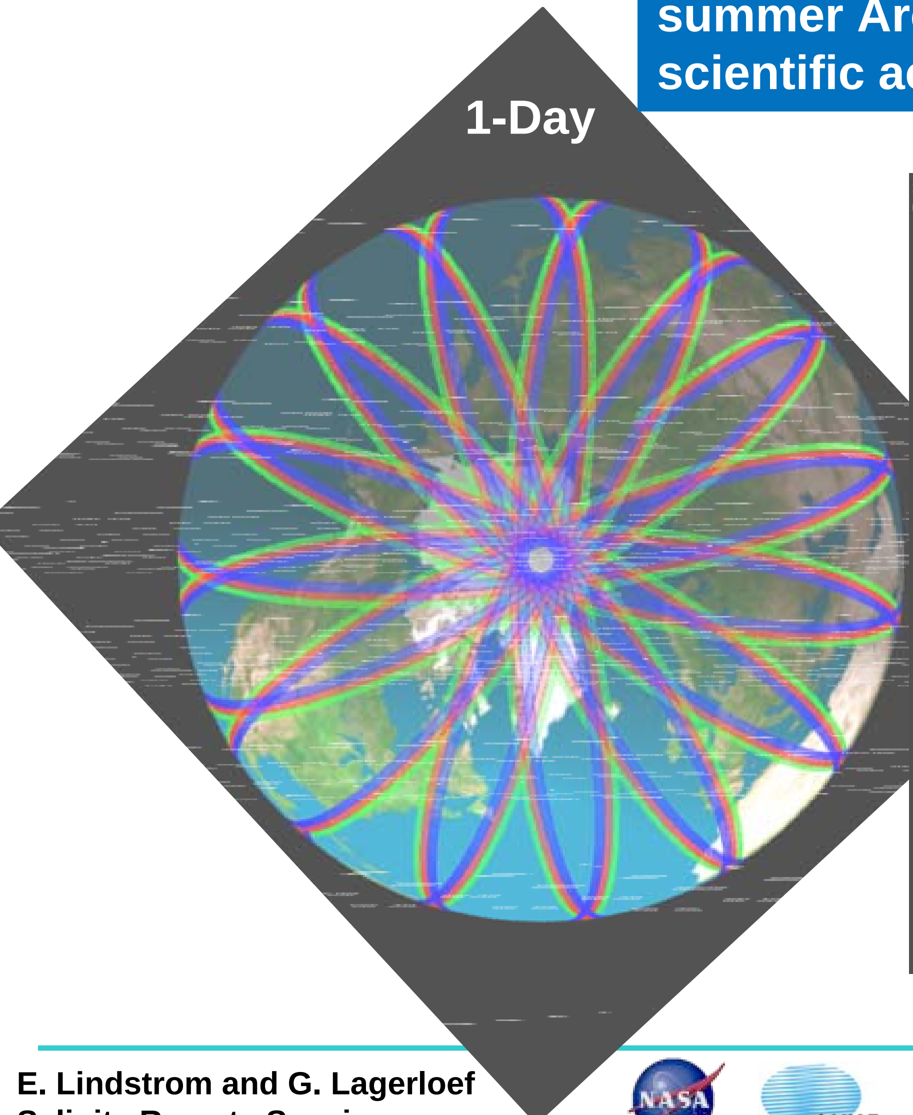
The orbit precesses to yield complete coverage in 7 days

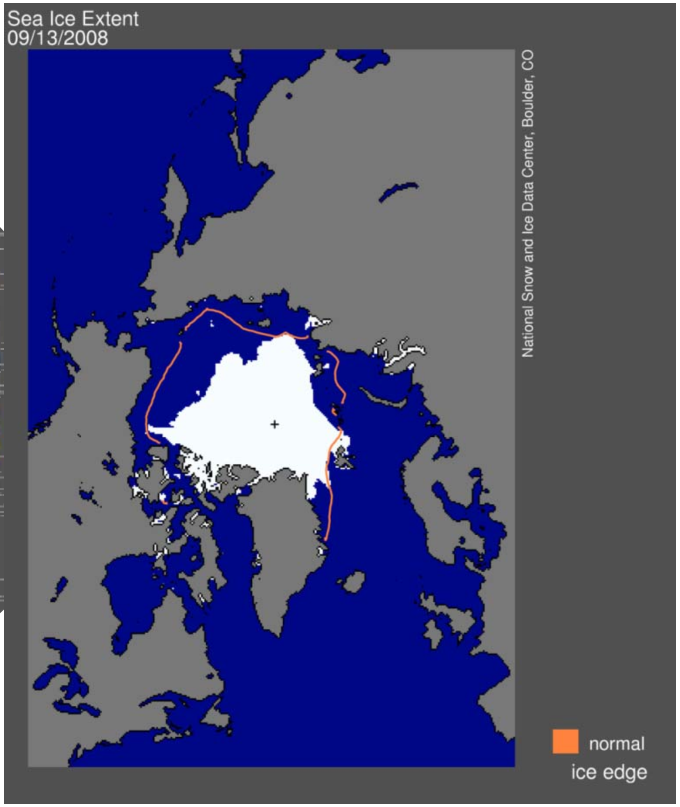


Arctic Ocean Coverage

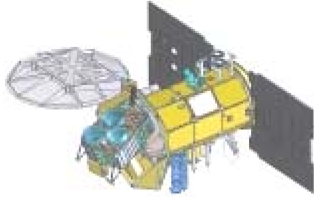


Measuring surface SSS conditions during in the summer Arctic ice melt may become an important scientific achievement for Aquarius.

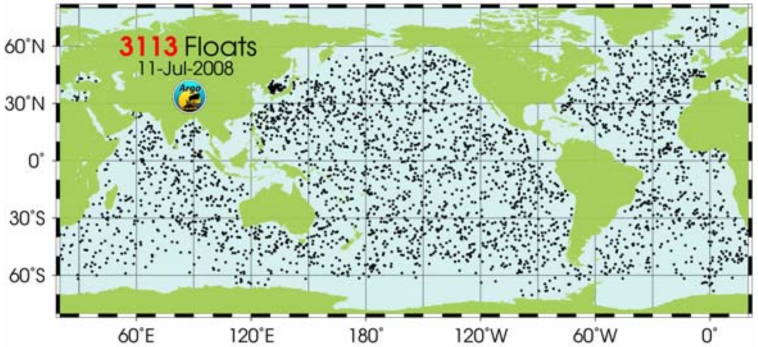




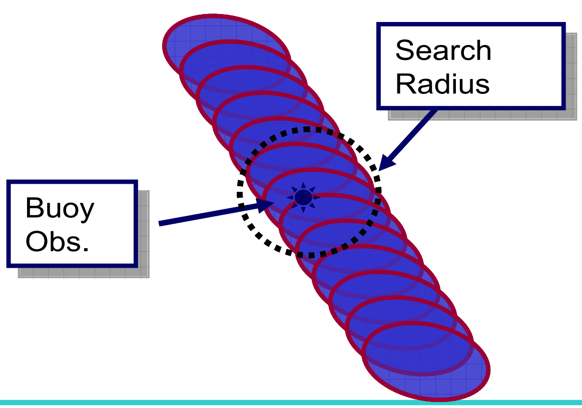
Cal/Val Approach



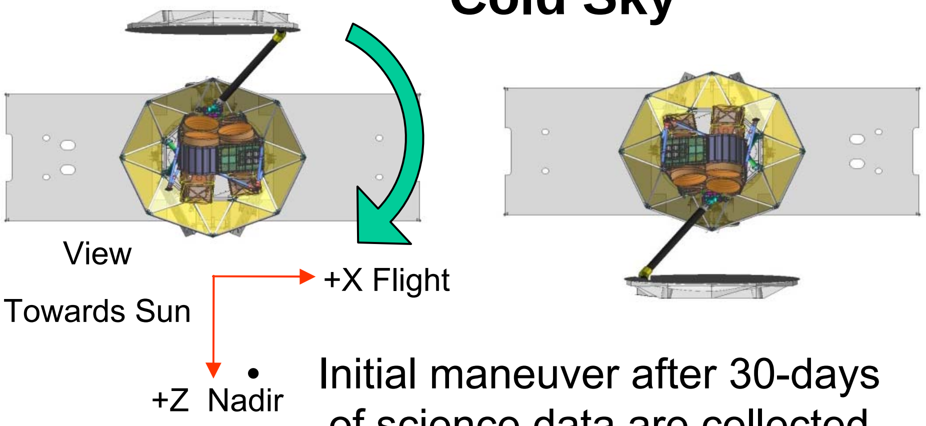
In situ



- Individual matchups
- Independent calibration of each radiometer – bias and drift
- Algorithm fine-tuning

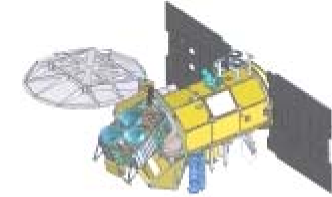


Cold Sky



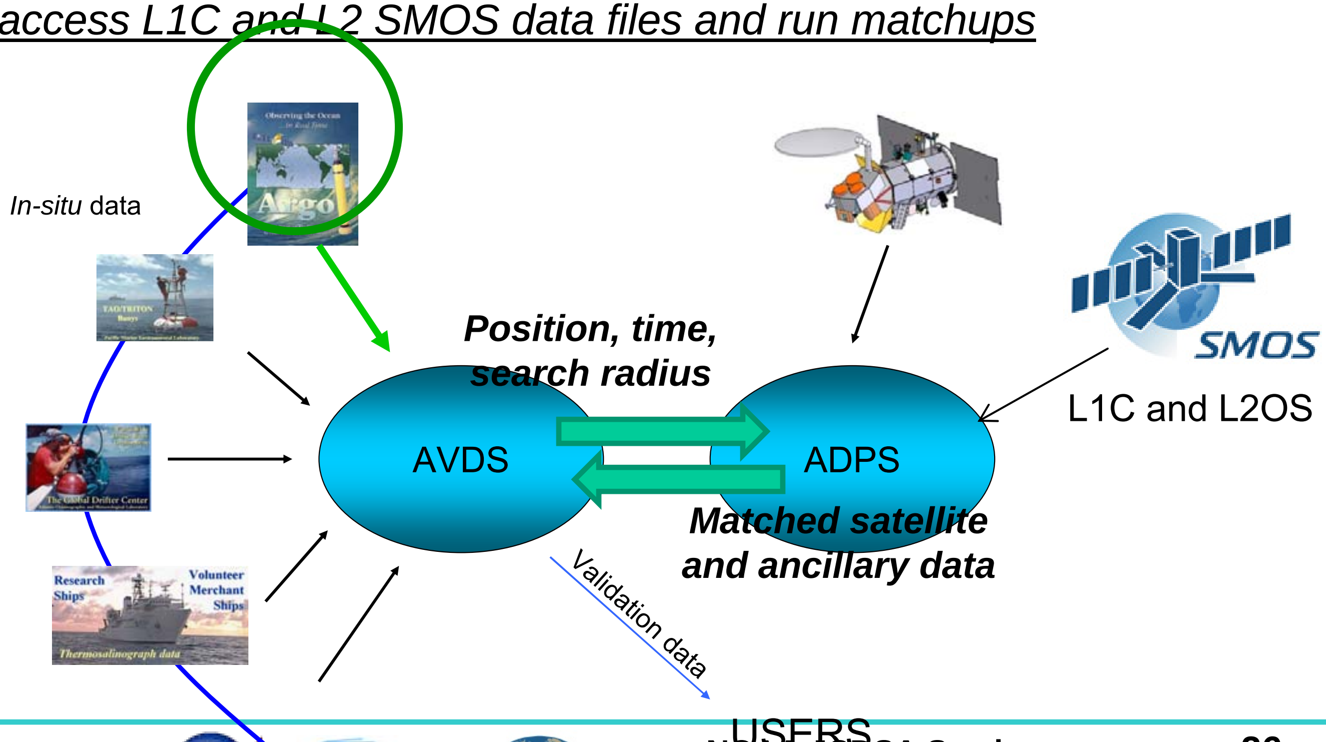
- Initial maneuver after 30-days of science data are collected
- Subsequent maneuvers as needed; Maximum frequency 1/month
- Opportunities vary seasonally depending on galactic plane orientation
  - Objectives:
    - Bias correction
      - Linearity
    - Calibration drift
    - Antenna back lobes (ocean-land transition)

AVDS and ADPS Roles

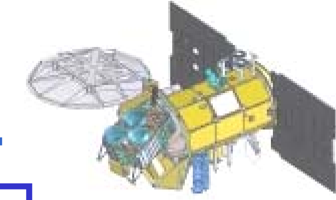


Aquarius Validation Data System (AVDS) and Aquarius Data Processing System (ADPS)

- AVDS Purpose is to collect all available *in situ* validation data, quality control, format and distribute for Aquarius Cal/Val
  - AVDS ↔ ADPS interface testing with 30-day simulation data: Testing Underway
  - AVDS daily Argo *in situ* data access: Operational
  - *ADPS will access L1C and L2 SMOS data files and run matchups*



Initial Operations Phase Science



- "At Launch" algorithm

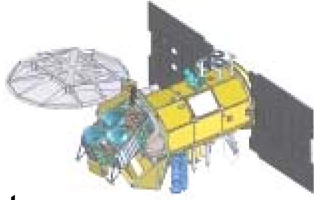
$$S = a_o + a_1 T_V + a_2 T_H + a_3 W + \dots$$

  - Coefficients a_i depend on SST and incidence angle and are tuned with the pre launch simulator
  - Initial operational ADPS processing will use ancillary wind input (NCEP winds and WISE model)
  - As the scatterometer and MWR are calibrated, terms for those data will be added to the retrieval algorithm equation.
  - Each beam SSS retrieval will undergo a simple least squares orbital bias correction with *in situ* matchups to release daily "quicklook" maps

Aquarius Data Products

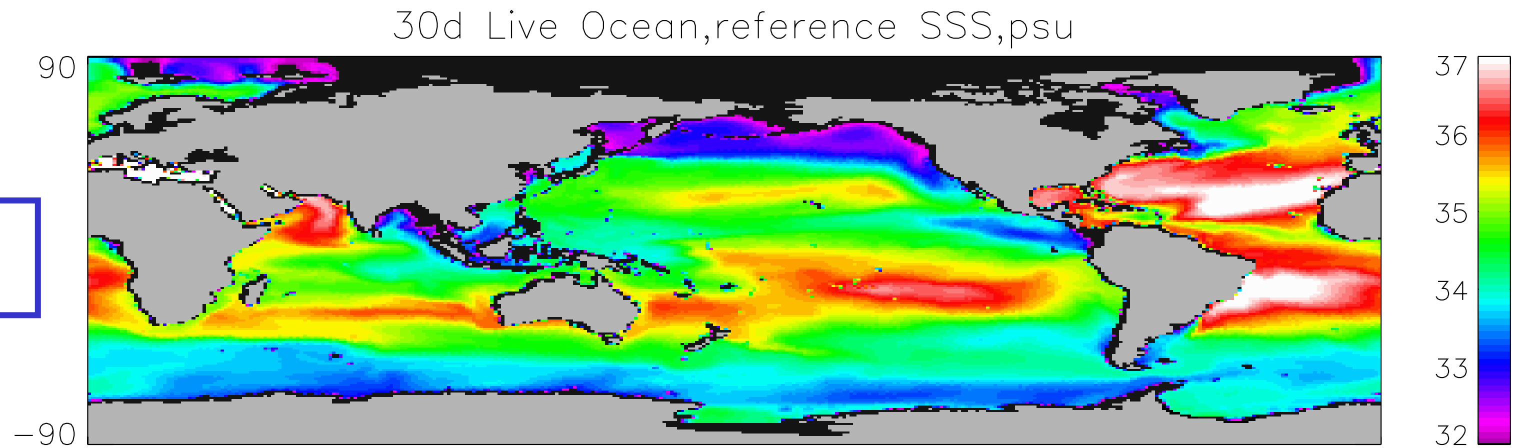
Data Product	Description
Level 1a	Reconstructed Unprocessed Instrument Data
Level 1b	Calibrated Sensor Units
Level 2	Derived Geolocated SSS
Level 3	Time-space averaged SSS on a standard Earth Projection.

SSS 30-day Retrieval Simulation

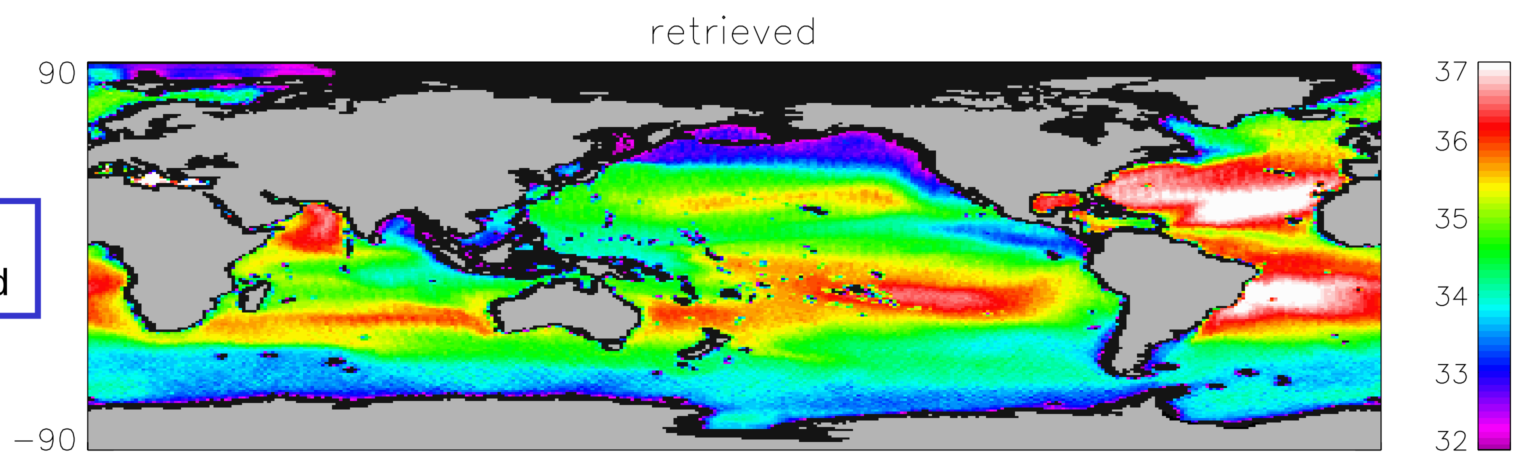


Representing both ascending and descending at Aquarius 3 horn footprints

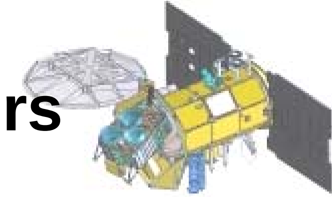
30 day mean
Input SSS field



30 day men
Retrieved SSS field

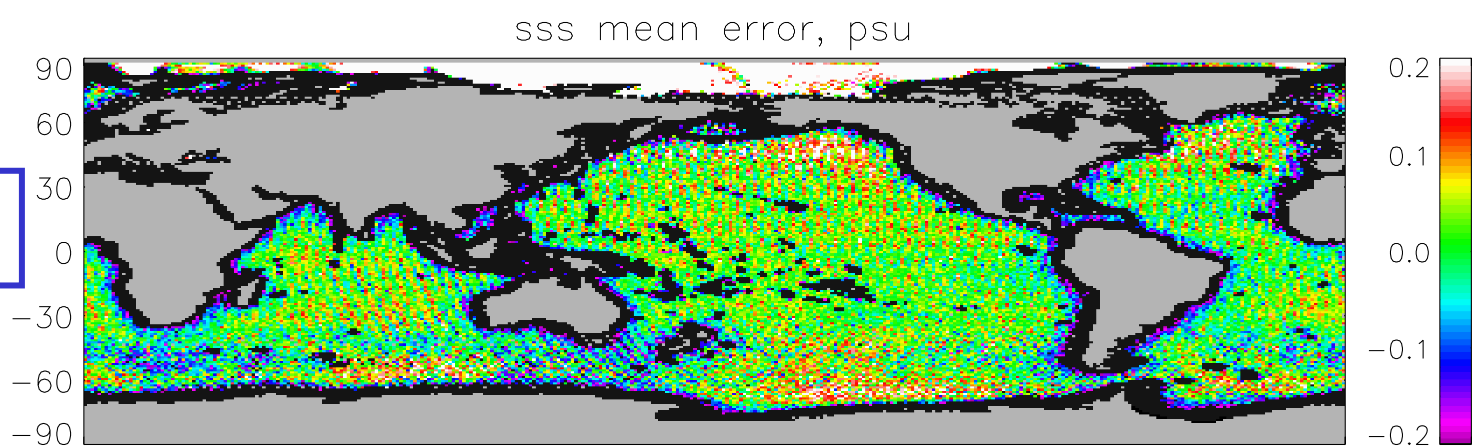


SSS Retrieval Simulation Mean and Standard Deviation Errors



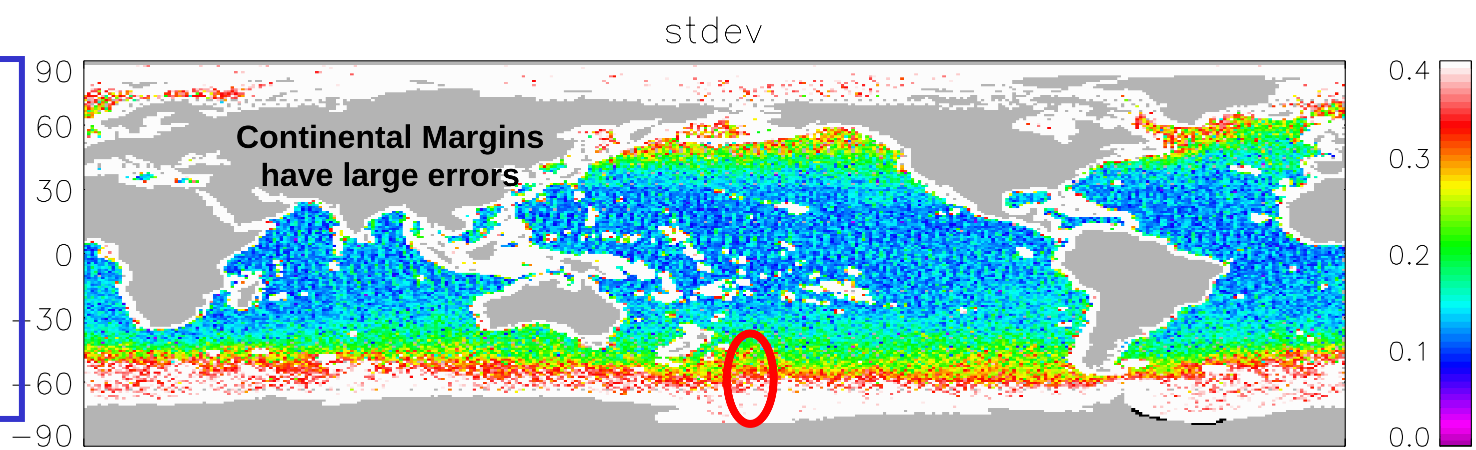
Representing both ascending and descending of all 3 horns

30 day SSS retrieval bias

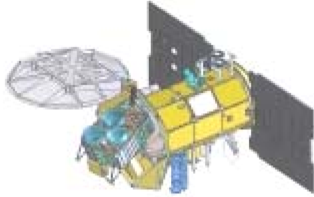


30 day SSS retrieval error standard deviation

Note degradation in high latitudes, especially southern ocean



Breakdown of Simulated Retrieval Errors by Latitude Band

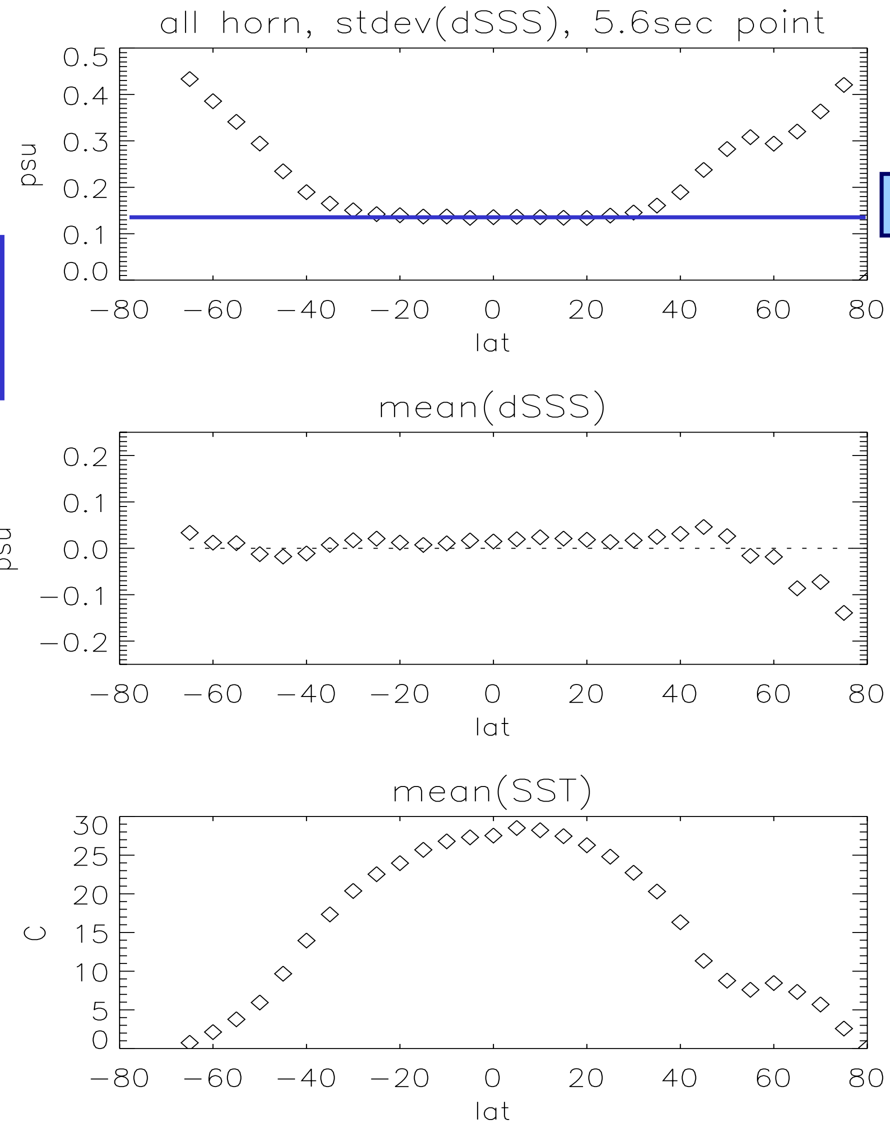


Individual 5.6 second sample standard deviation error

While these simulator results look very promising, we are certain to have overlooked something...

Mean bias error

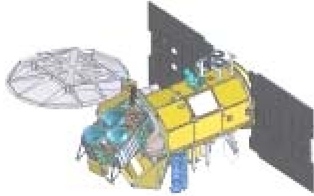
Zonal mean SST



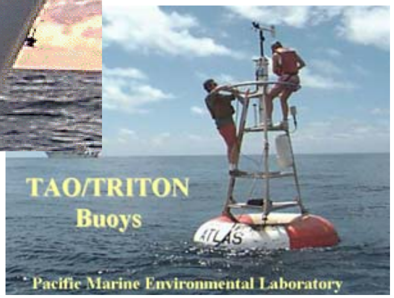
<0.15 psu

Frank Wentz and Sab Kim, Remote Sensing Systems;
Aquarius Algorithm Development Team

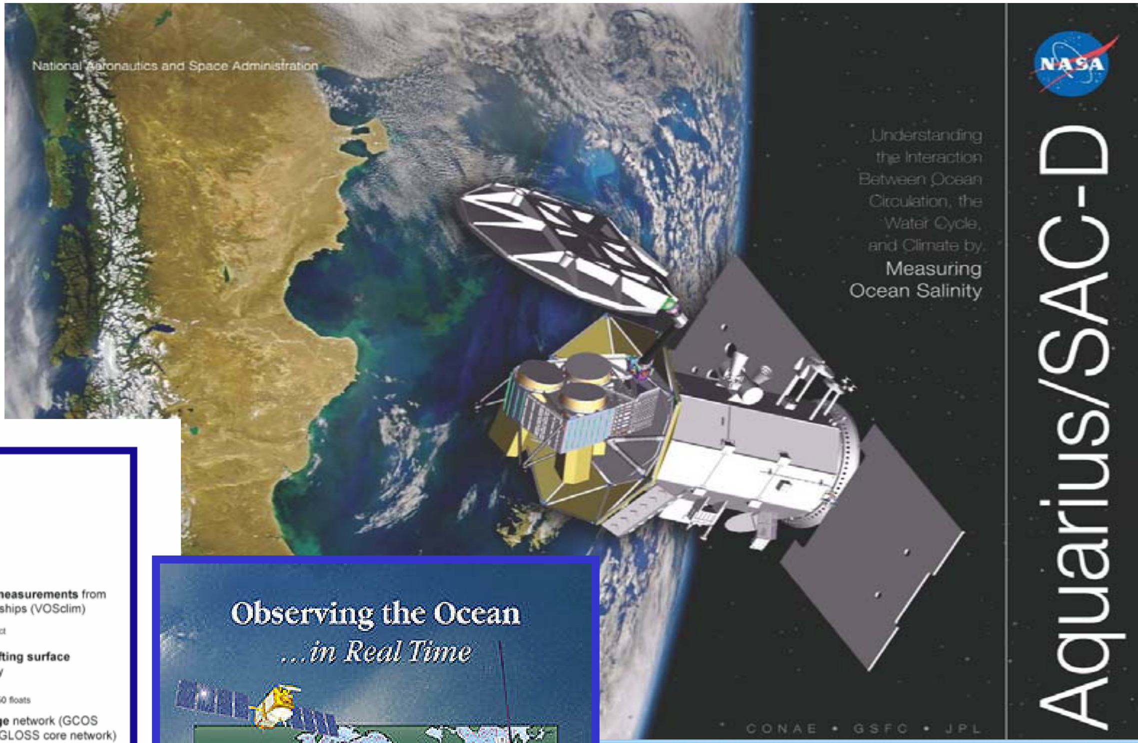
Aquarius will Rely on *In Situ* Observations that are Heavily Supported by NOAA

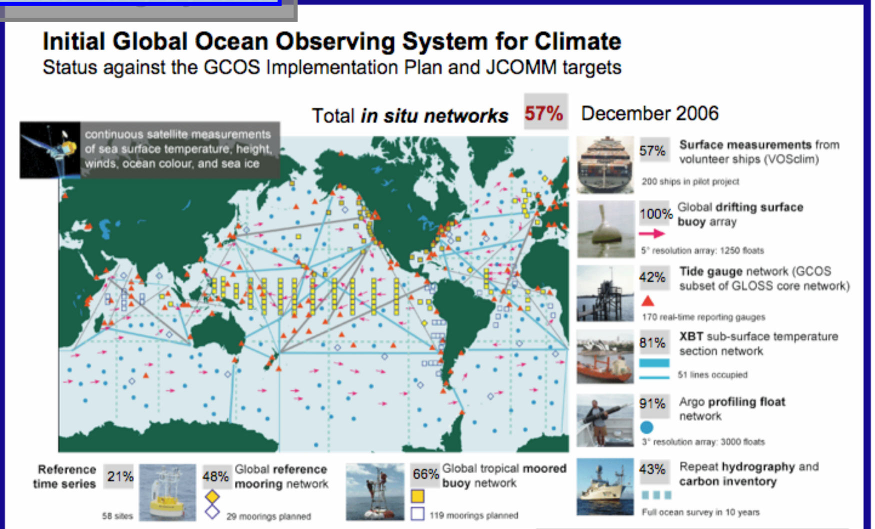


Surface Validation

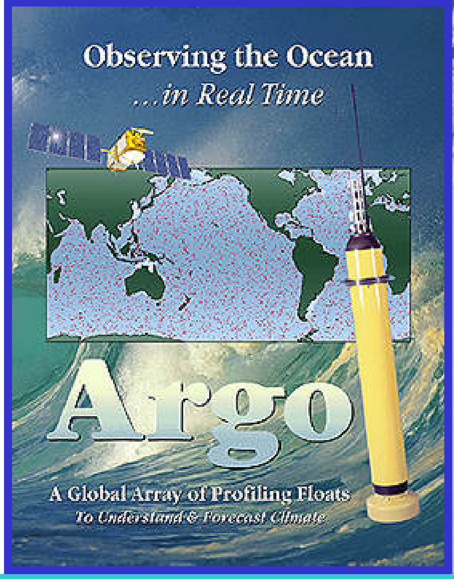


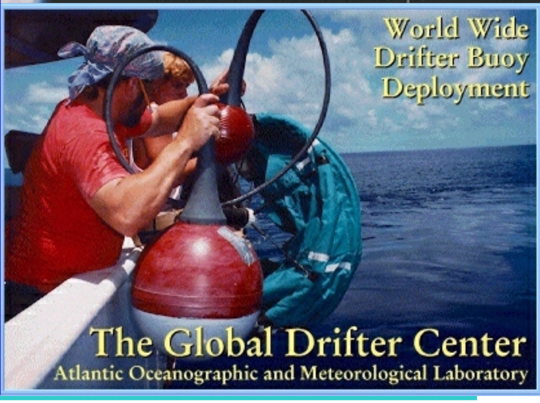
Integrated Satellite + *in situ* Salinity Observing System



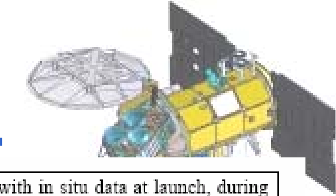


- A total of 5540 platforms are maintained globally.
- The U.S. supports 2798, of which 2631 are sponsored by NOAA.





Drifters SSS: COSMOS 2005 Field Test, Bay of Biscay



Reverdin et al., JTech, 2007


a
b

9-month drifts <~0.06

SVP Drifters

Ready for more extensive SSS trials

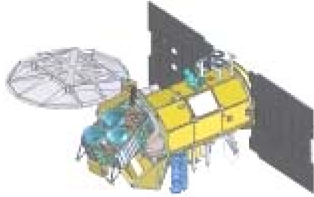
Parallel effort at WHOI

Table 2: Estimated salinity biases (pss-78) by comparison with in situ data at launch, during the COSMOS2 cruise and later encounters with research vessels (© close encounter with R.V; (f) far encounter with R.V.; (d) deployment from R.V. for SIO-56365). Estimates based on the intercomparison of nearby drifters are also indicated, as well as date of recovery (and estimated bias when available), and post-recovery estimates.

Apr Jun Aug-Sep Dec

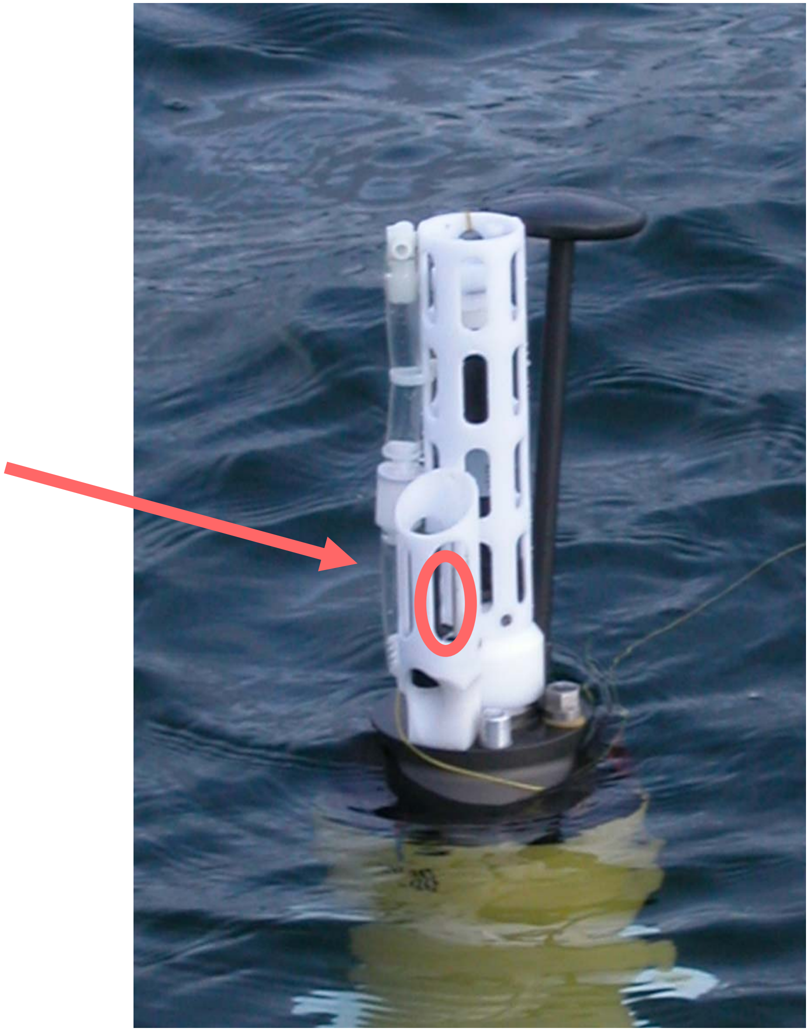
Drifter	Launch Date/bias	COSMOS2 22-28/06	R.V. TSGs Date/bias	Other drifters Date/bias	Recovery/ loss date bias	Post-recovery bias
SIO-56362	2/04 -0.010	-0.008	7/09 -0.030 (f)	7/08 13/08 -0.030	3/12	28/01/2006 -0.066
SIO-56363	2/04 -0.012	-0.029	31/08 -0.030 (c)		29/09	28/01/2006 -0.061
SIO-56364	1/05 -0.026				11/03/2006 (grounded)	
SIO-56365	2/04 -0.020	-0.0028	28/08 -0.090 (d)		03/10 (loss)	
SIO-56366	2/04 -0.015	-0.016			19/08 grounded	
SIO-56367	1/05 -0.017	-0.027	6/09 -0.040 (f)	12/12 -0.020		
SIO-56368	1/05 0.009	-0.009			7/12 -0.005	2-4/02/2006 -0.011
SIO-56369	2/04 -0.020	-0.031			17/09 grounded	
SIO-56370	2/04 -0.019	-0.028	4/09 -0.010 (f)	7/08 -0.030	23/09	5-7/12 -0.034
SIO-56371	2/04 -0.019	-0.020		13/08 -0.025	5/11	5-7/12 -0.028
SIO-56372	1/05 -0.007	-0.015	8/09 -0.025 (c)		16/11	5-7/12 -0.051
SIO-	2/04				8/04	

Argo Enhanced SSS Float Trials

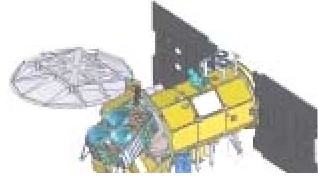


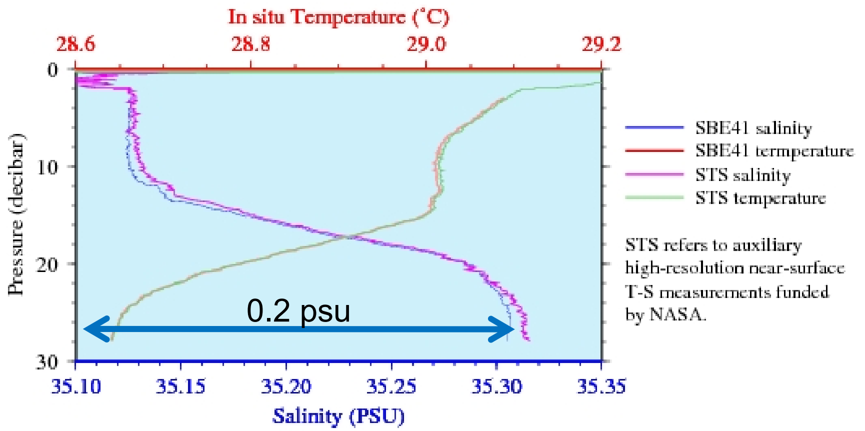
Purpose: To obtain "skin" salinity and upper 5m gradient statistics

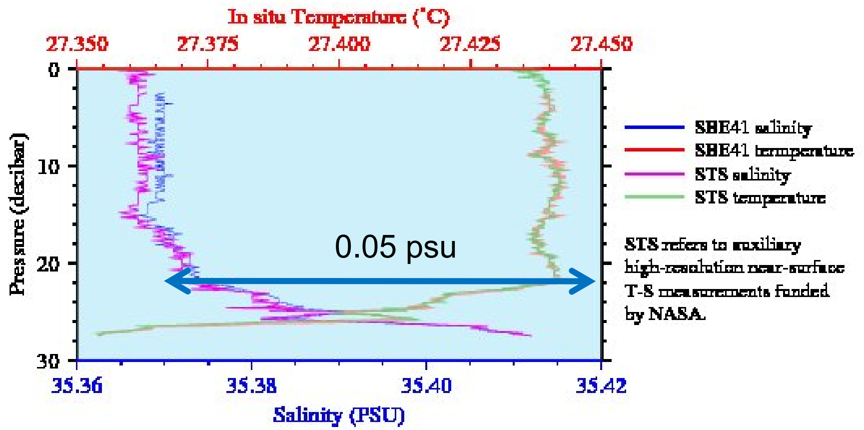
- Argo CTD nominally shuts off at ~5m
- Steve Riser and Gary Lagerloef are assembling experimental Argo floats each with a secondary CTD sensor to profile to the surface. The primary CTD will shut off at ~5 m per normal operations.
- Sea-Bird developed a specialized "Surface Temperature Salinity" (STS) sensor which is programmed to profile the upper ~30 m and is inter-calibrated with the primary CTD
- We deployed the first at the HOT site near Hawaii late summer 2007.
- Others are being deployed in the equatorial Pacific in 2008, including one in the warm pool.
- Development of at least 20 are being funded by NASA during the next 2 years.

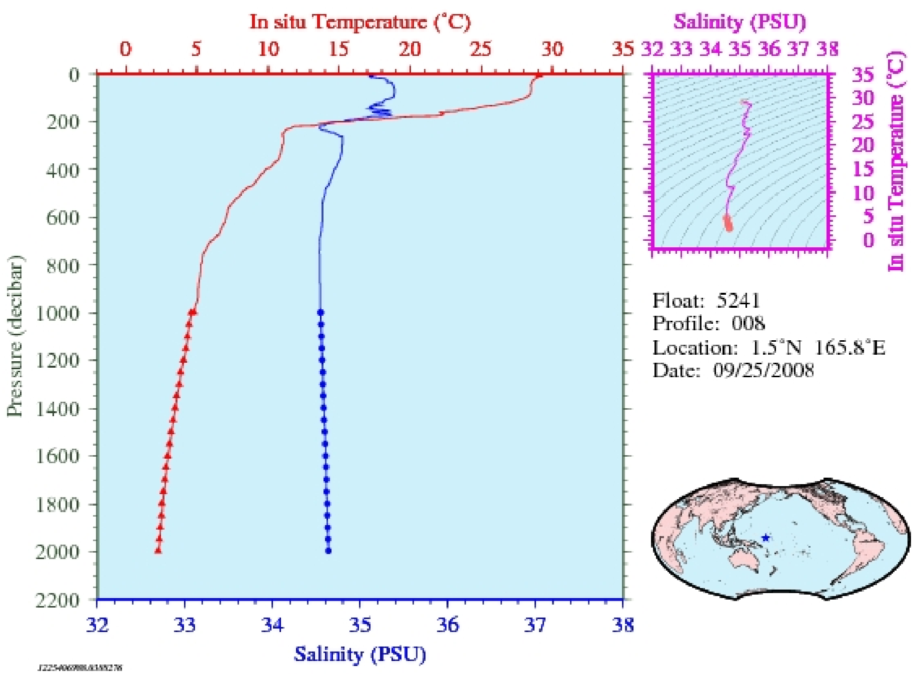


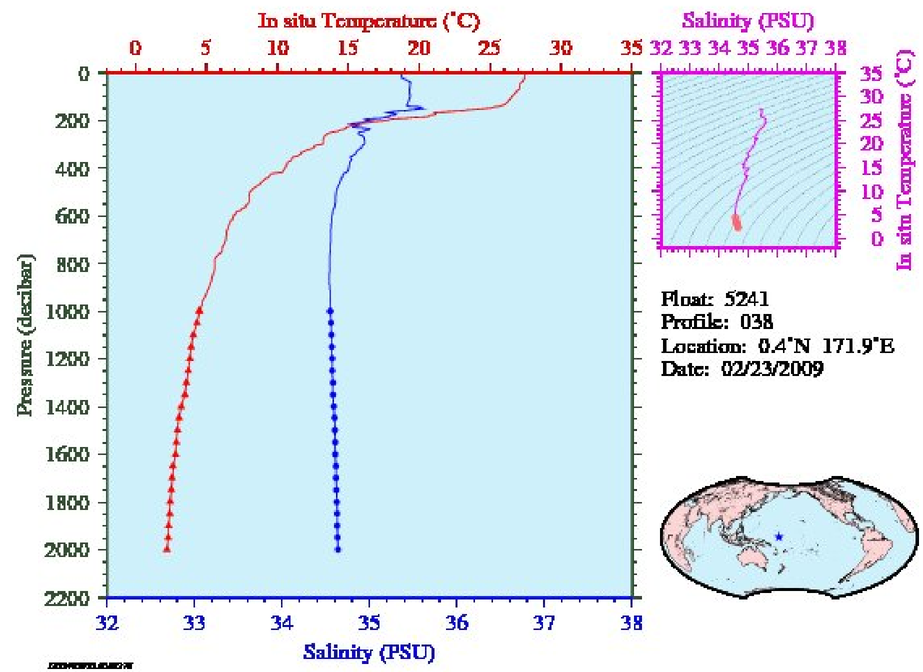
Small gradients relative to satellite resolution



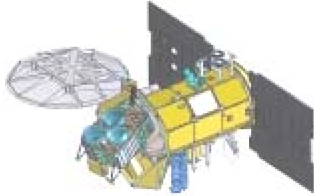


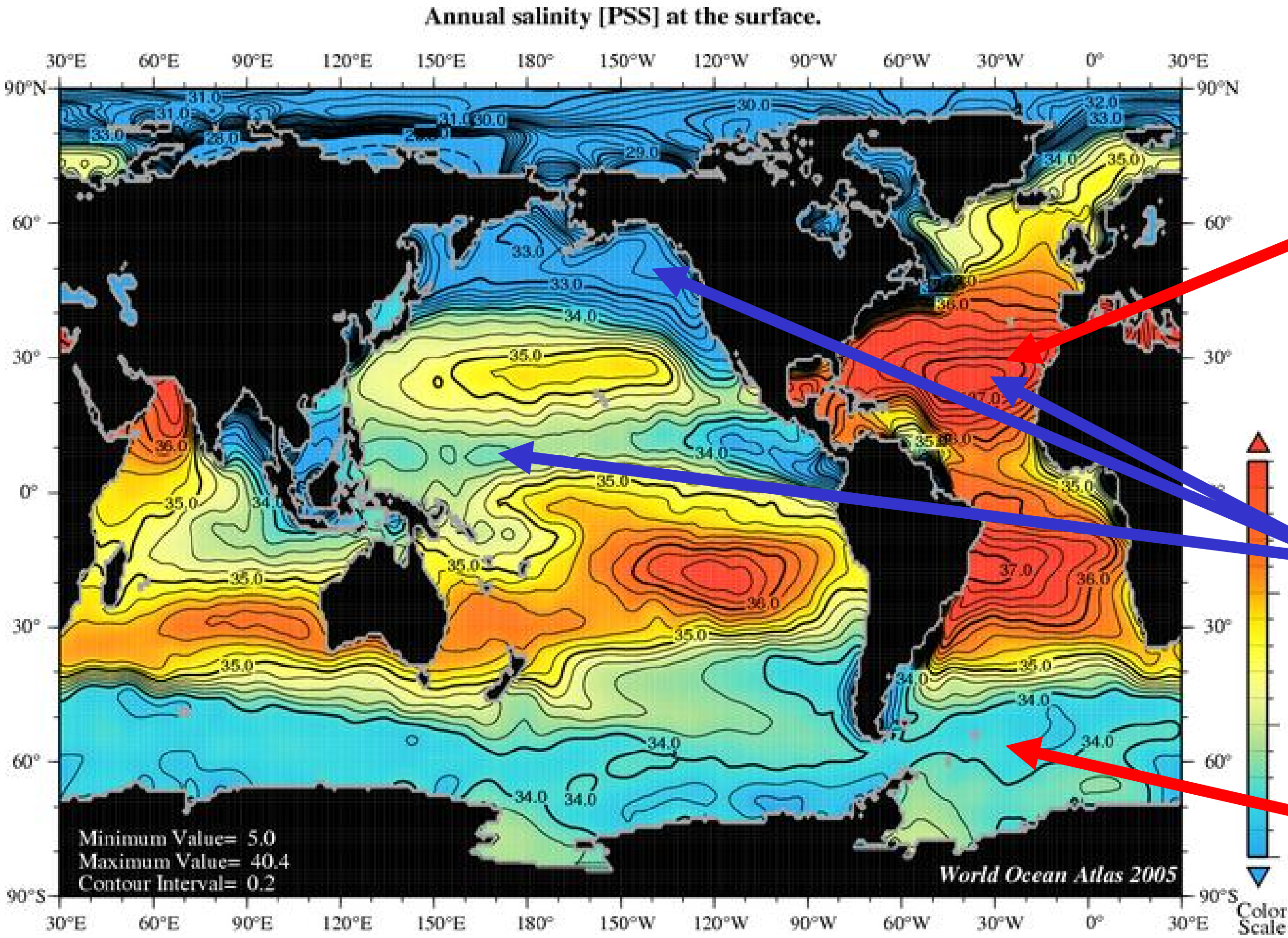






Priorities for Aquarius SSS Cal/Val and Ocean Process Studies



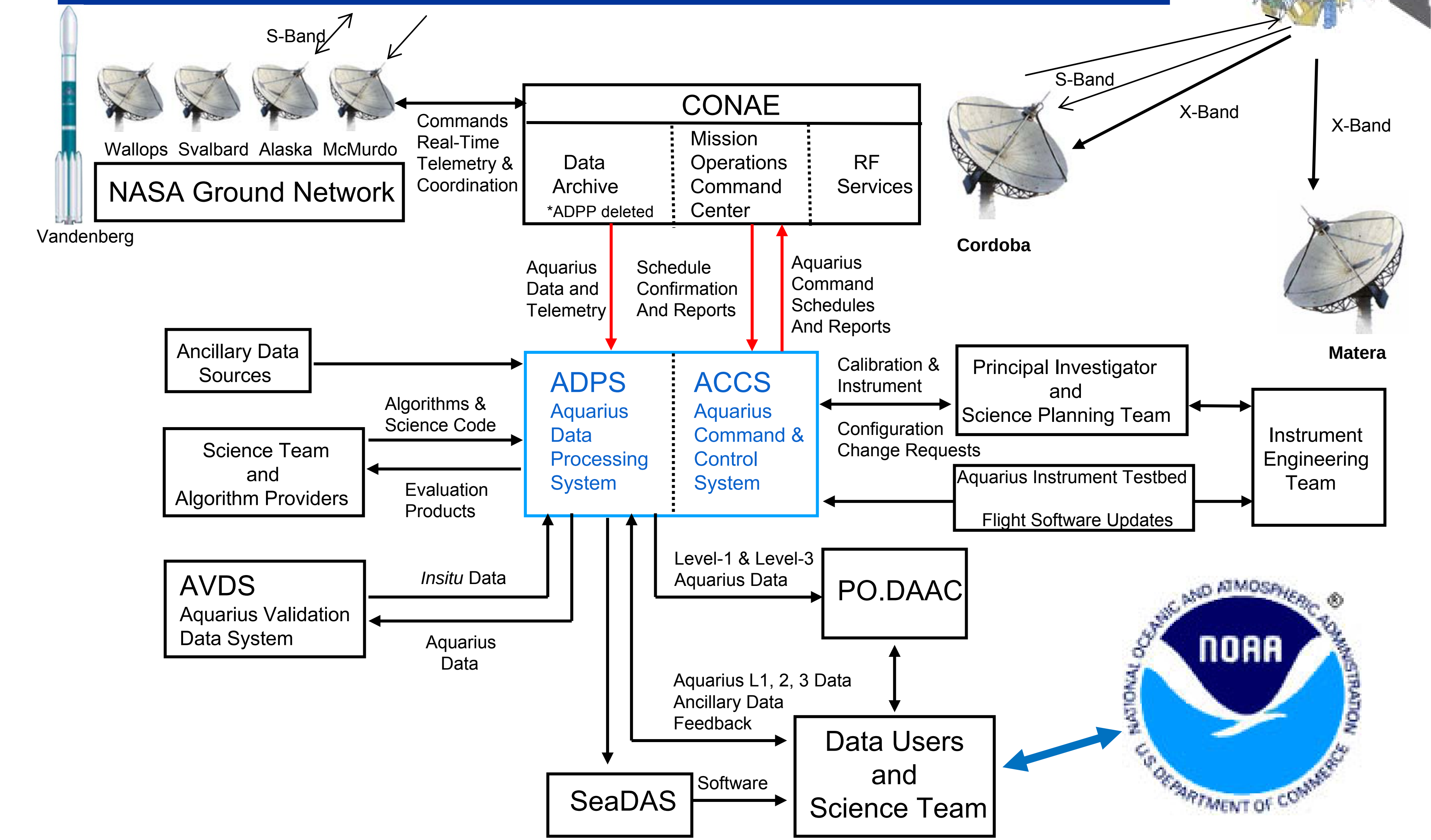


50-100 SSS Drifters in the N. Atlantic Subtropical gyre by 2011.

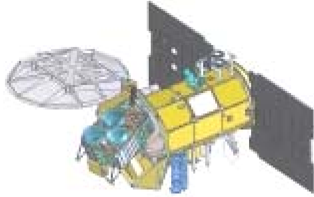
~50 Enhanced STS Argo in high rainfall and high evaporation regimes.

~50 SSS Drifters in the Southern Ocean (large satellite error)

Ground Data System

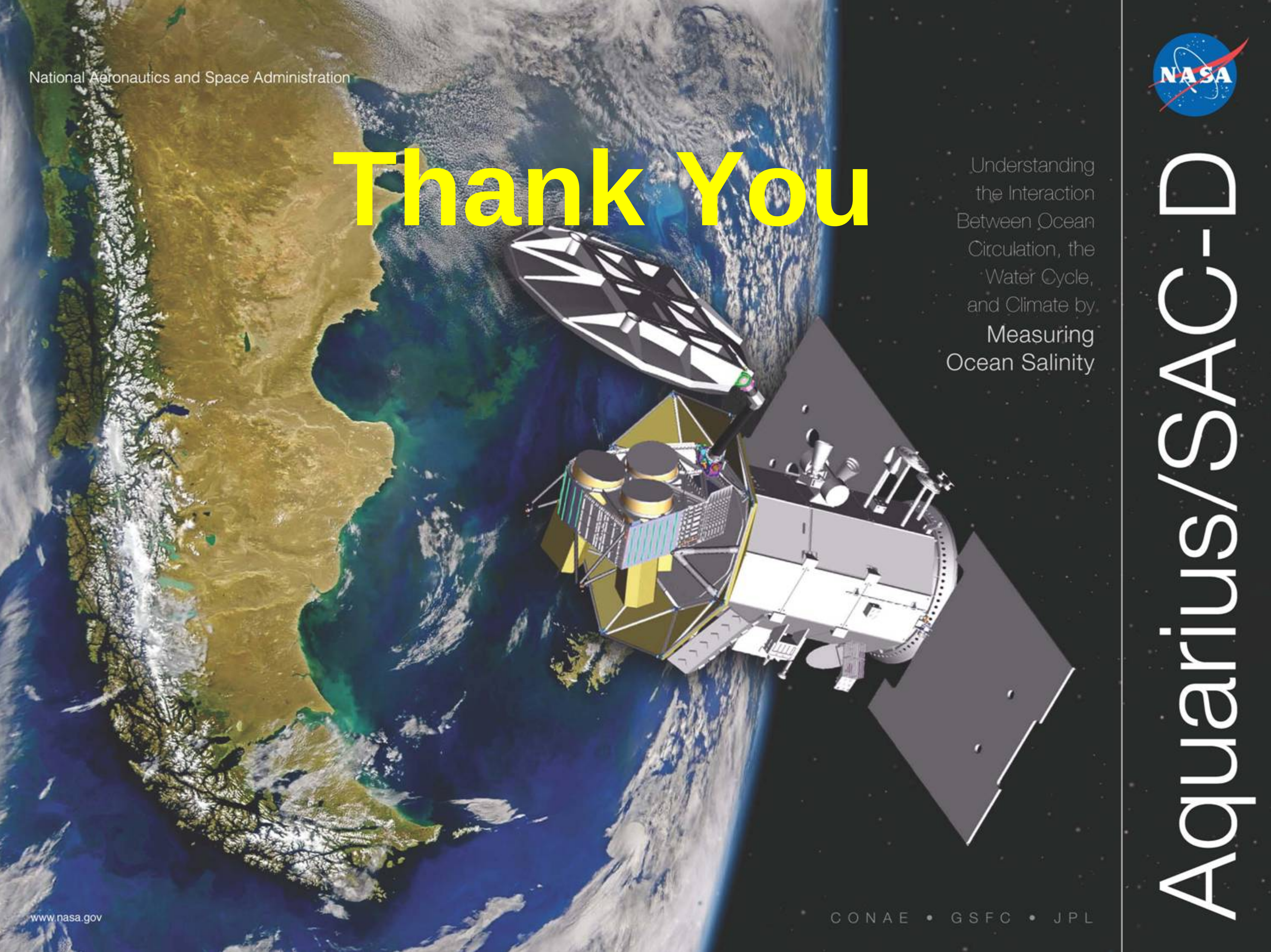


Aquarius/SAC-D Science Team



- Ocean Salinity Science Team (OSST) will be one element of the broader Aquarius/SAC-D Science Team.
- Competed in "Research Opportunities in Space and Earth Science 2008." Ocean Salinity Science Team Proposals due March 18 2009.
- Proposals required only for those requesting NASA funding.
- <u>Access to Aquarius data and science meetings will be open to the full science community</u>

Thank You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