Future Spaceborne Salinity Missions

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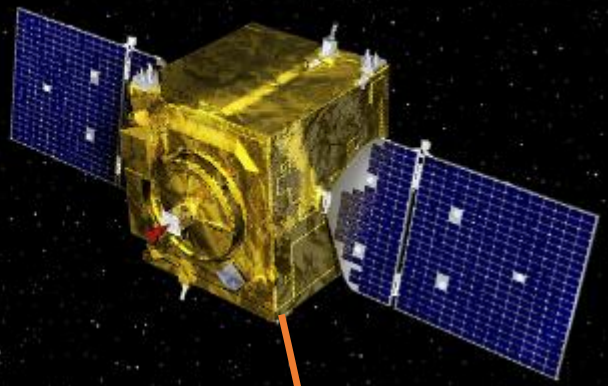


Salinity snakes in space

Targeted Observable	Science/Applications Summary	Candidate Measurement	Designated	Earth System Explorer	Incubation
	water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	of radiometry-based atmos. motion vectors (AMVs) tracking; or lidar**			
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			X
Surface Topography and Vegetation	**High-resolution global topography** including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			X

** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables

Other ESAS 2017 Targeted Observables, not Allocated to a Flight Program Element

Aquatic Biogeochemistry	**Radiance Intercalibration**
Magnetic Field Changes	**Sea Surface Salinity**
Ocean Ecosystem Structure	**Soil Moisture**

NOTE: Observations (Targeted Observables) identified by the committee as needed in the coming decade, beyond what is in the Program of Record, allocated as noted in the last three columns (and color-coded) to three new NASA flight program elements (*Designated*, *Earth System Explorer*, *Incubation*; as defined in the accompanying text). Within categories, the targeted observables are listed alphabetically. Targeted Observable included in the original priority consideration but not allocated to a program element are listed at the bottom of the table.

Ice Elevation	elevation change of land ice to assess sea level contributions and freeboard height of			X	

Now what?

- Future L-band mission in NASA not designated, falls into competed programs (e.g. Ventures continuity, instrument or mission)

- Small cost-cap (~$150M)

Paths forward

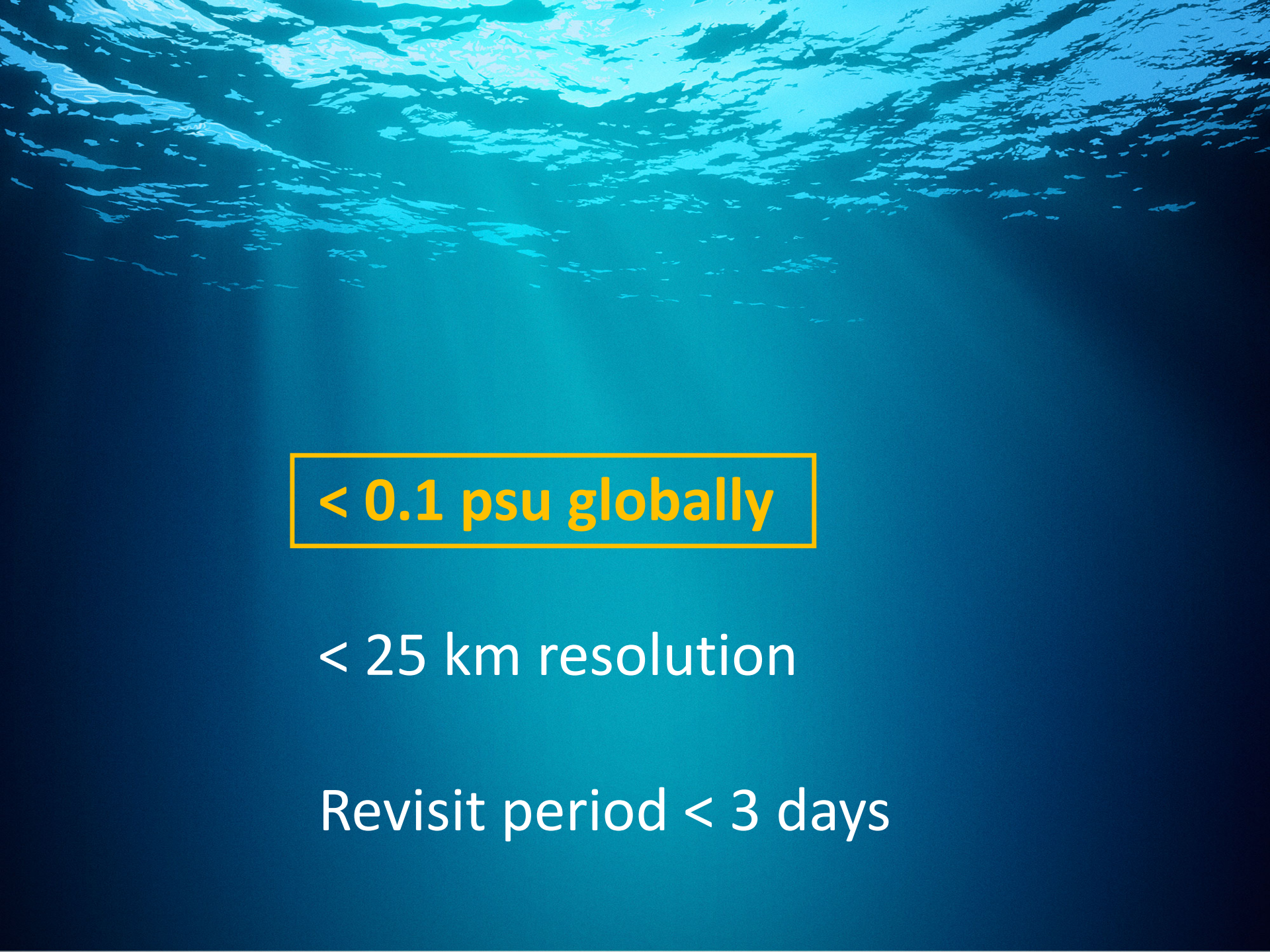
- Innovative mission design – science trades

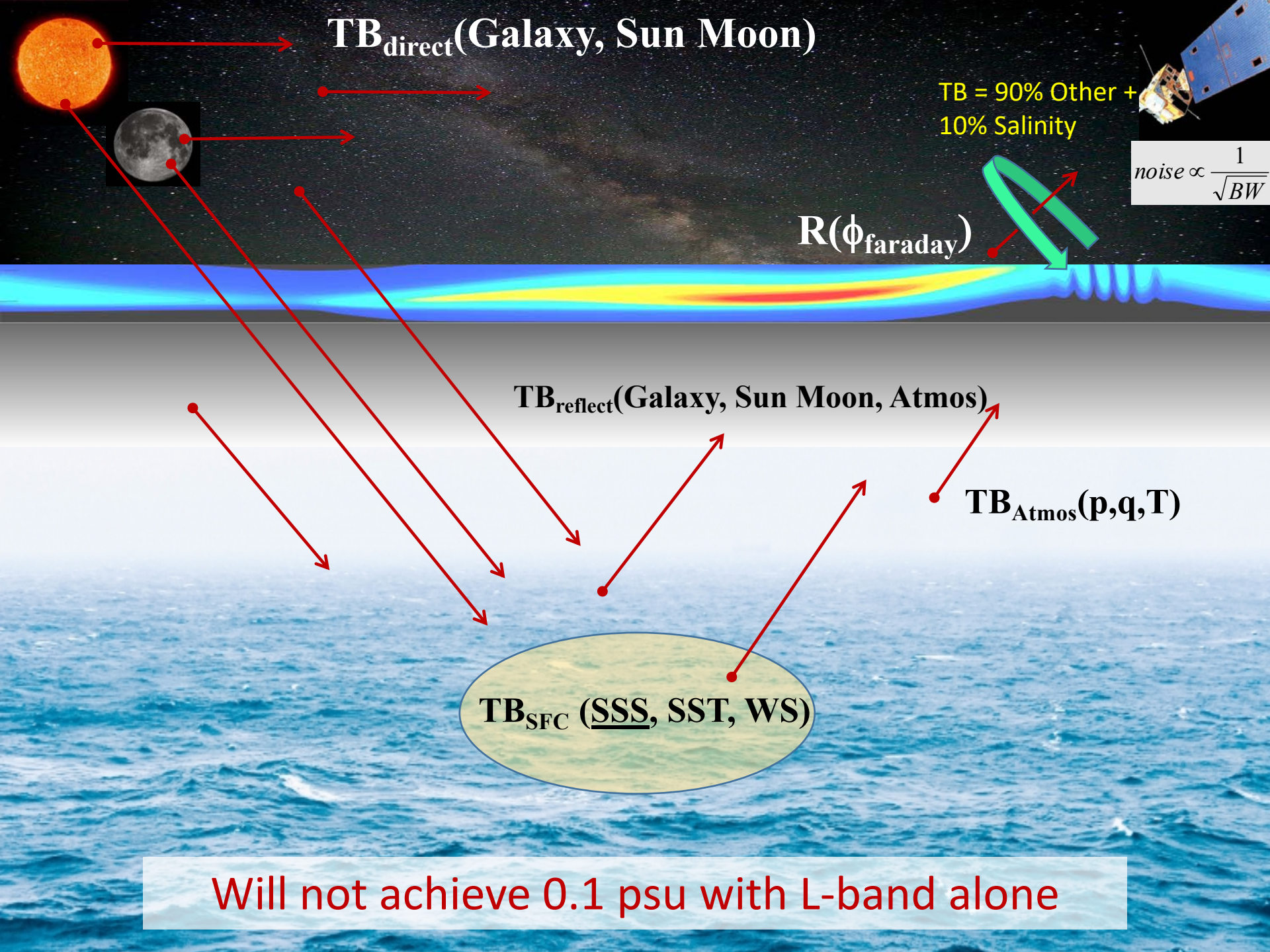
- International partnerships
  - CIMR, SMOS-HR

Future Missions

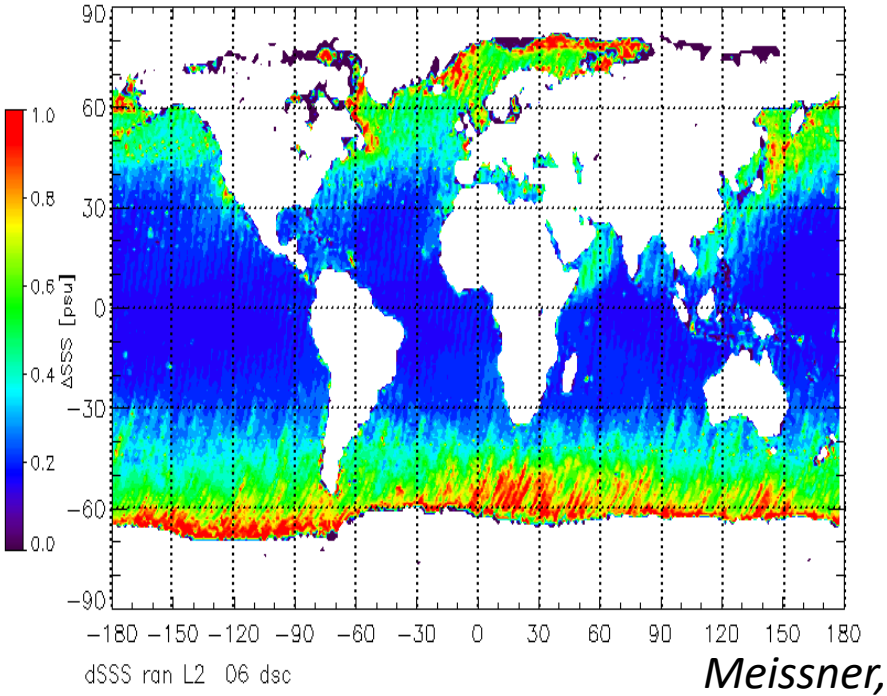
- Maintain continuity
  - 40-100 km resolution
  - 0.2-0.5 psu
  - Revisit period every 3-7 days

- Enhancements
  - < 25 km resolution
  - < 0.1 psu globally
  - Revisit period < 3 days


< 0.1 psu globally
< 25 km resolution
Revisit period < 3 days

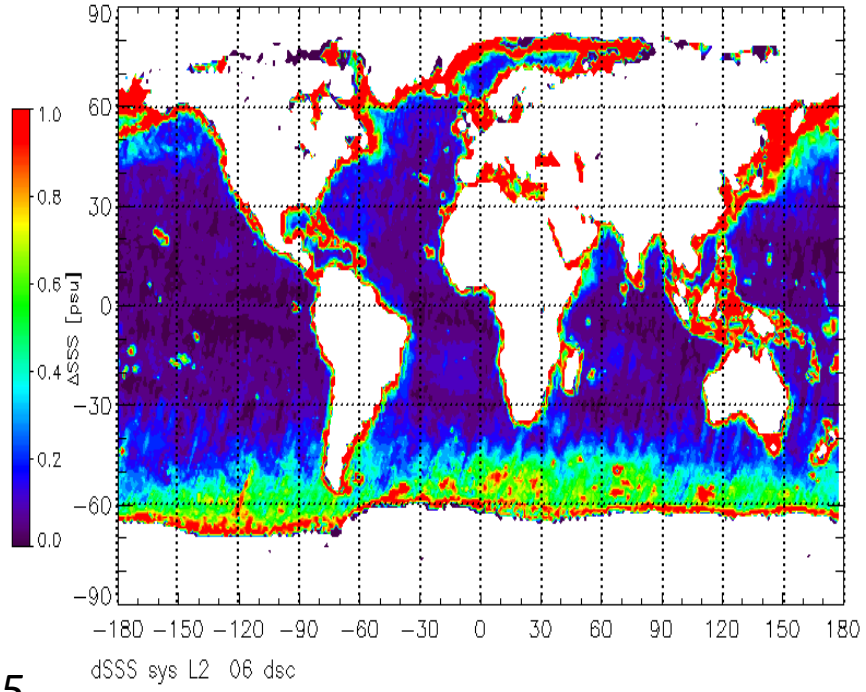

TB_{direct}(Galaxy, Sun Moon)
TB = 90% Other +
10% Salinity
$noise \propto \frac{1}{\sqrt{BW}}$
$R(\phi_{faraday})$
$TB_{reflect}$(Galaxy, Sun Moon, Atmos)
TB_{Atmos}(p,q,T)
TB_{SFC} (SSS, SST, WS)
Will not achieve 0.1 psu with L-band alone

Aquarius Uncertainties



Meissner, 2015

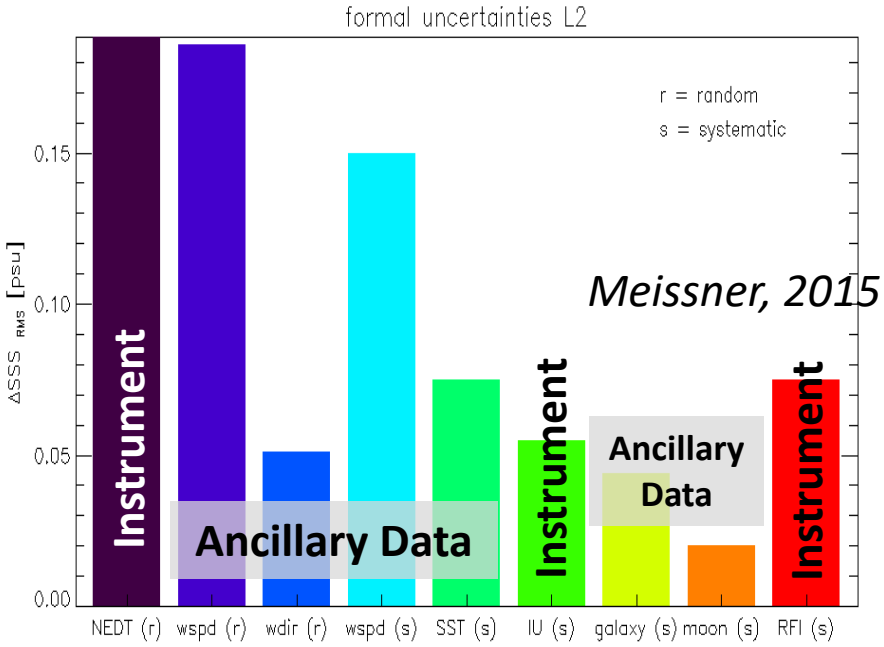
Random Error (psu)



Systematic Error (psu)

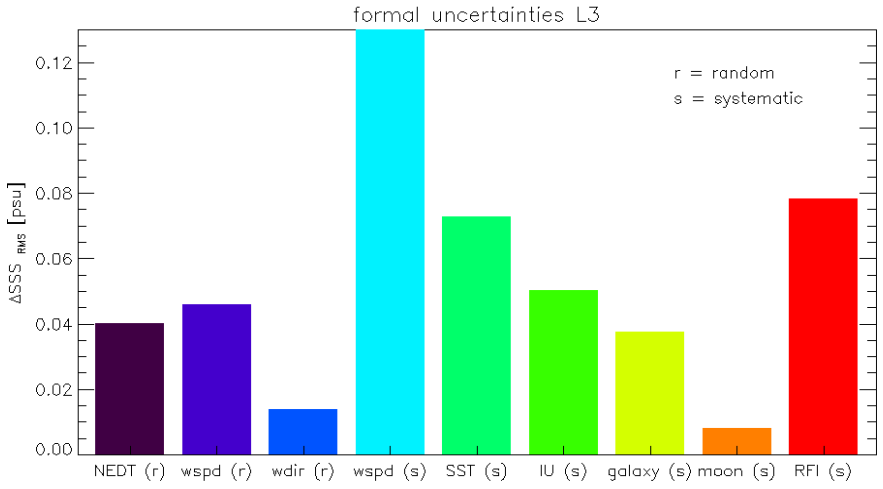
Aquarius Uncertainties

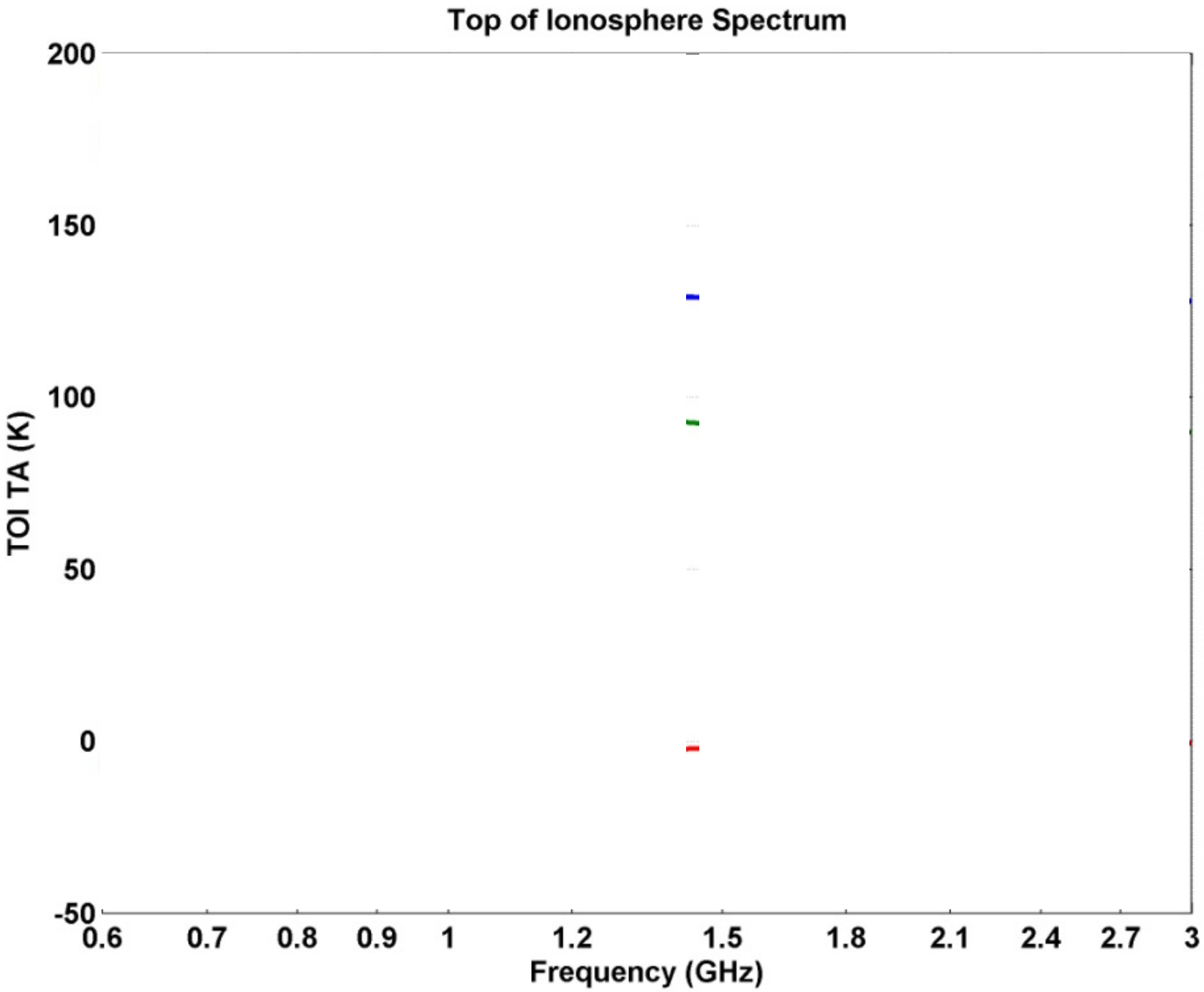
Single Sample (psu)



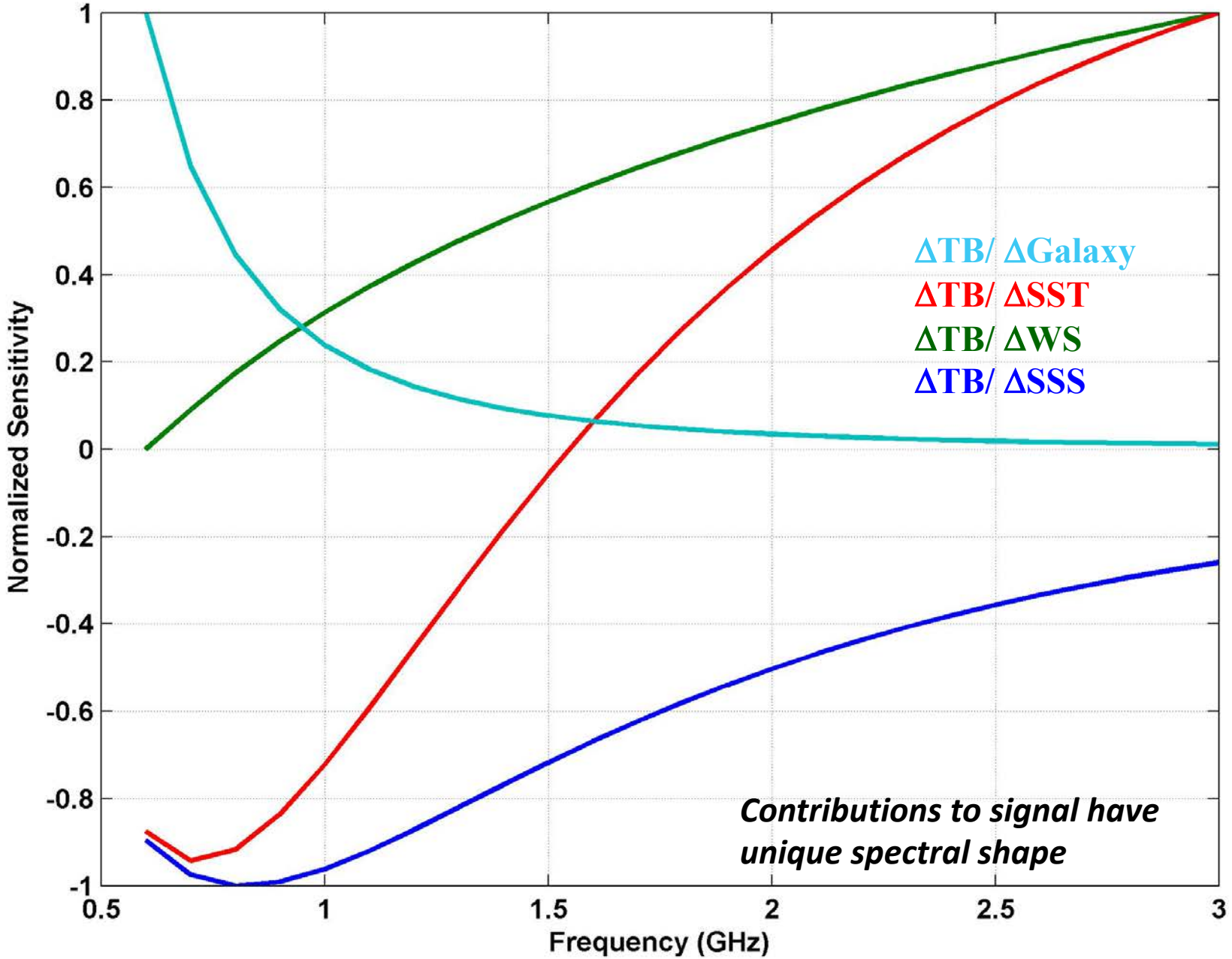
Meissner, 2015

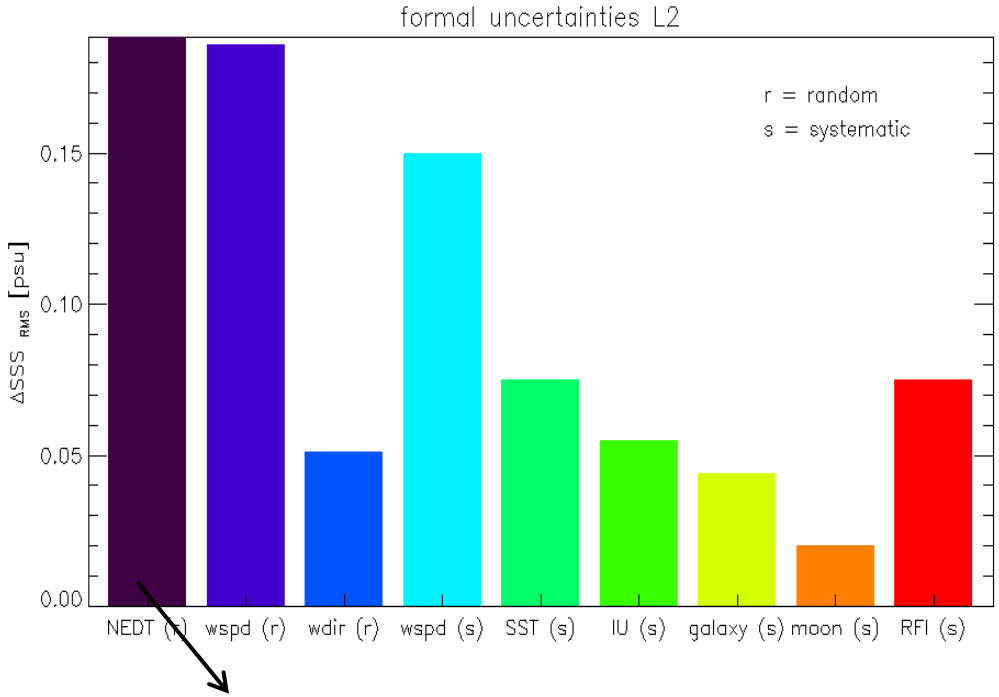
1º Monthly Grid (psu)



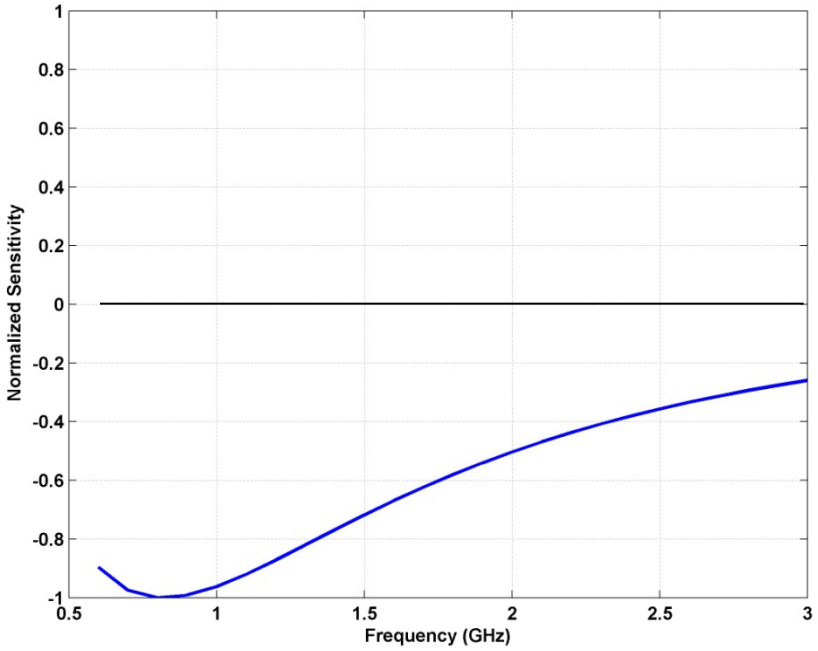

Top of Ionosphere Spectrum
200
150
100
50
0
-50
TOI TA (K)
0.6
0.7
0.8
0.9
1
1.2
1.5
1.8
2.1
2.4
2.7
3
Frequency (GHz)

Normalized TB (h-pol, 40°) sensitivity vs frequency

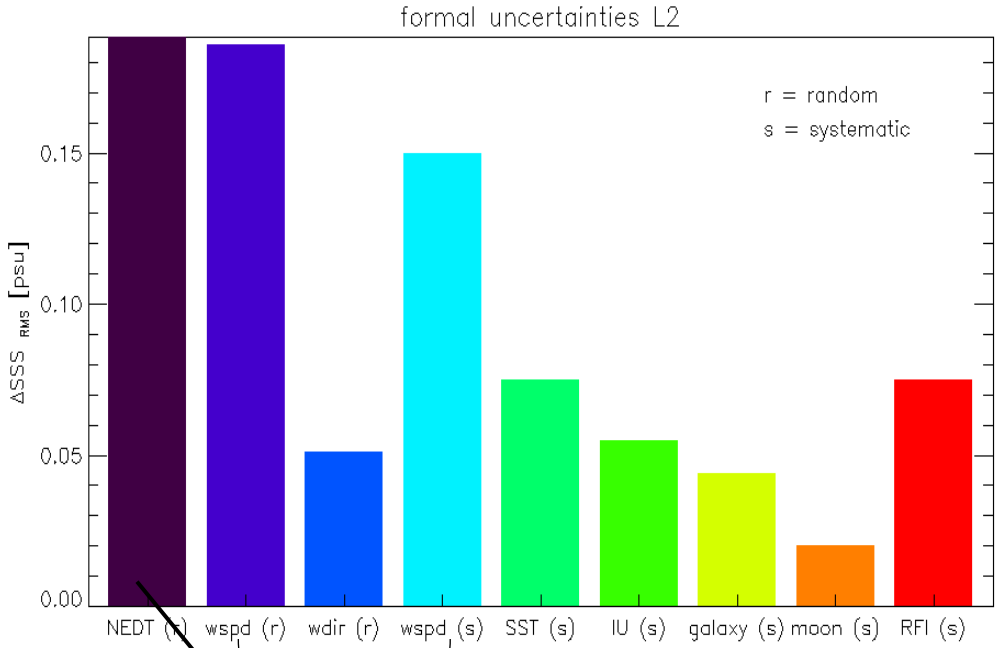


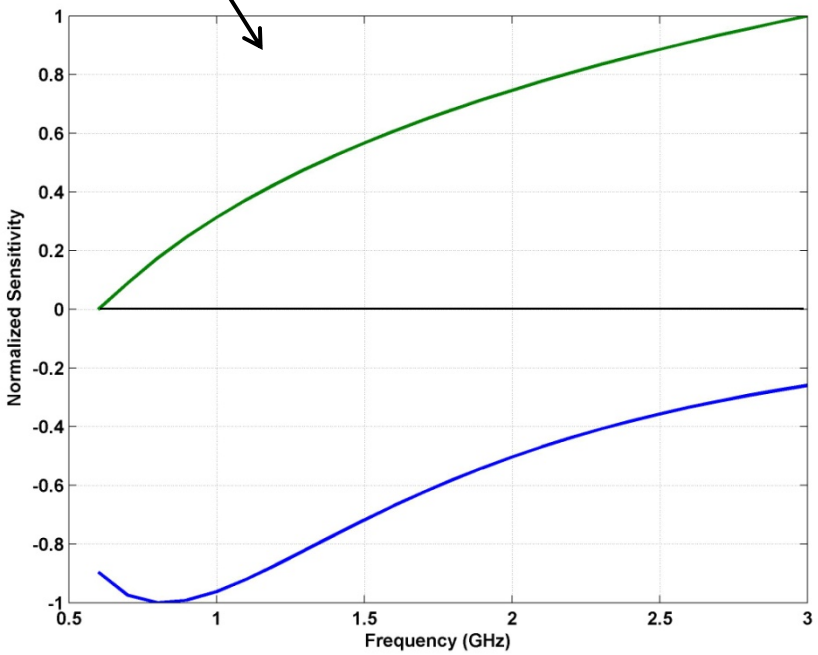


Normalized TB (h-pol, 40°) sensitivity vs frequency



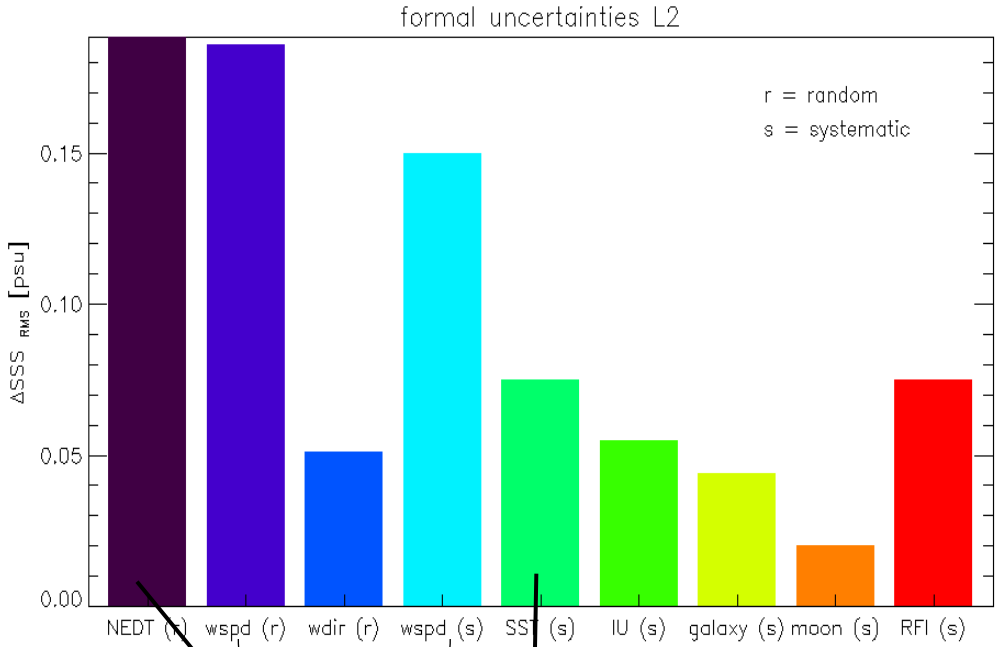
ΔTB/ ΔSSS

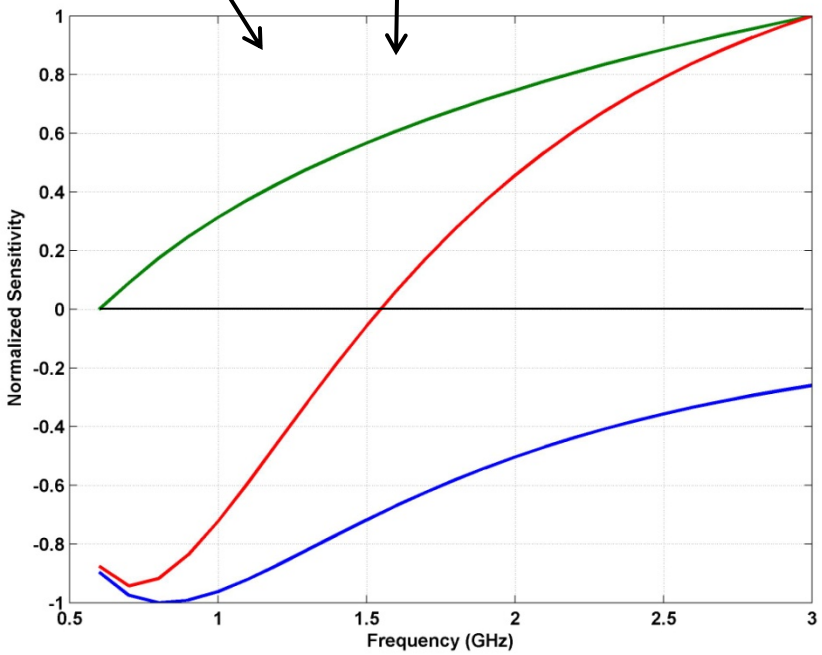




Normalized TB (h-pol, 40°) sensitivity vs frequency

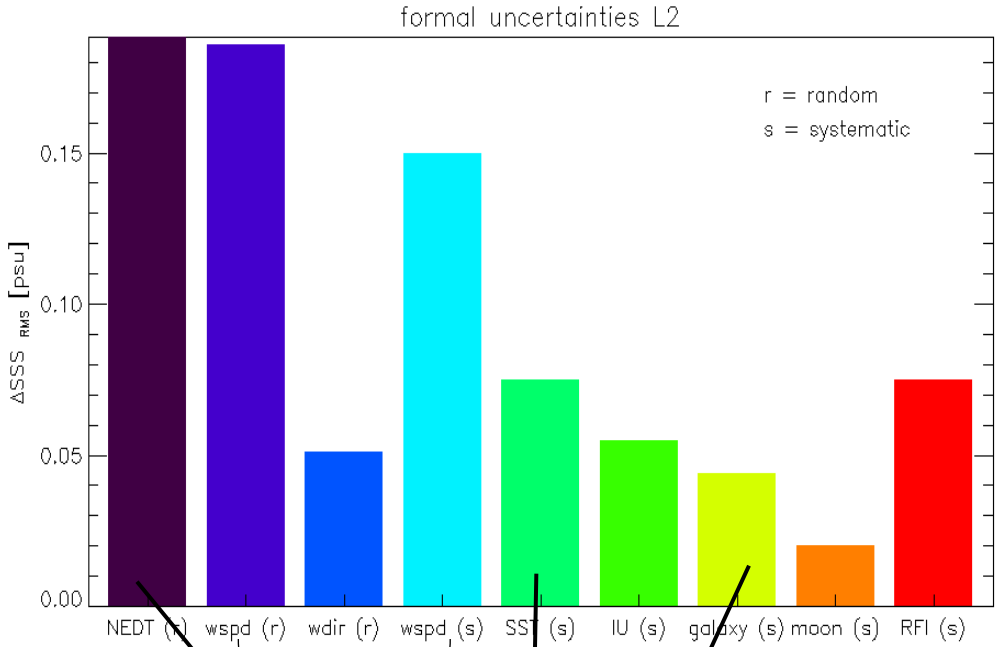
ΔTB/ ΔWS
ΔTB/ ΔSSS

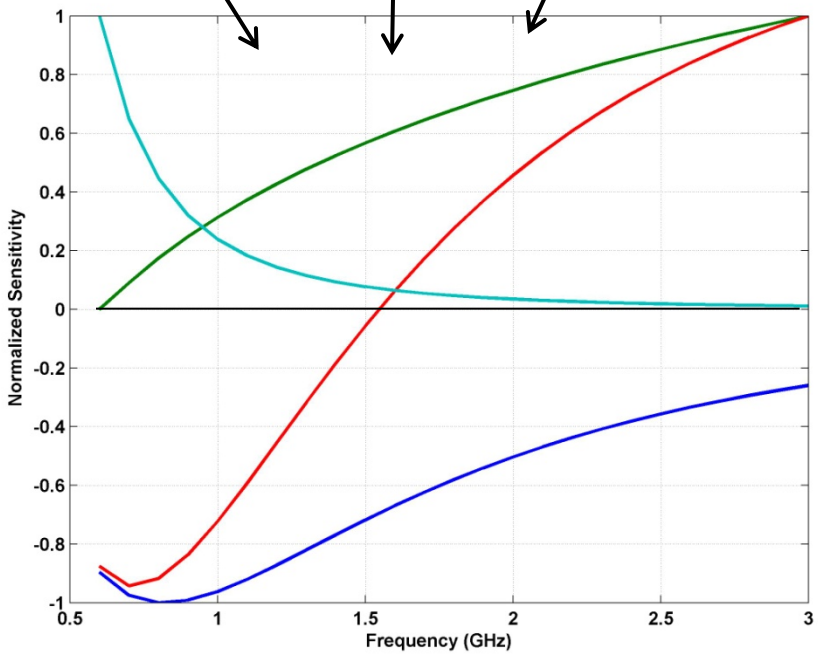




Normalized TB (h-pol, 40º) sensitivity vs frequency

ΔTB/ ΔSST
ΔTB/ ΔWS
ΔTB/ ΔSSS

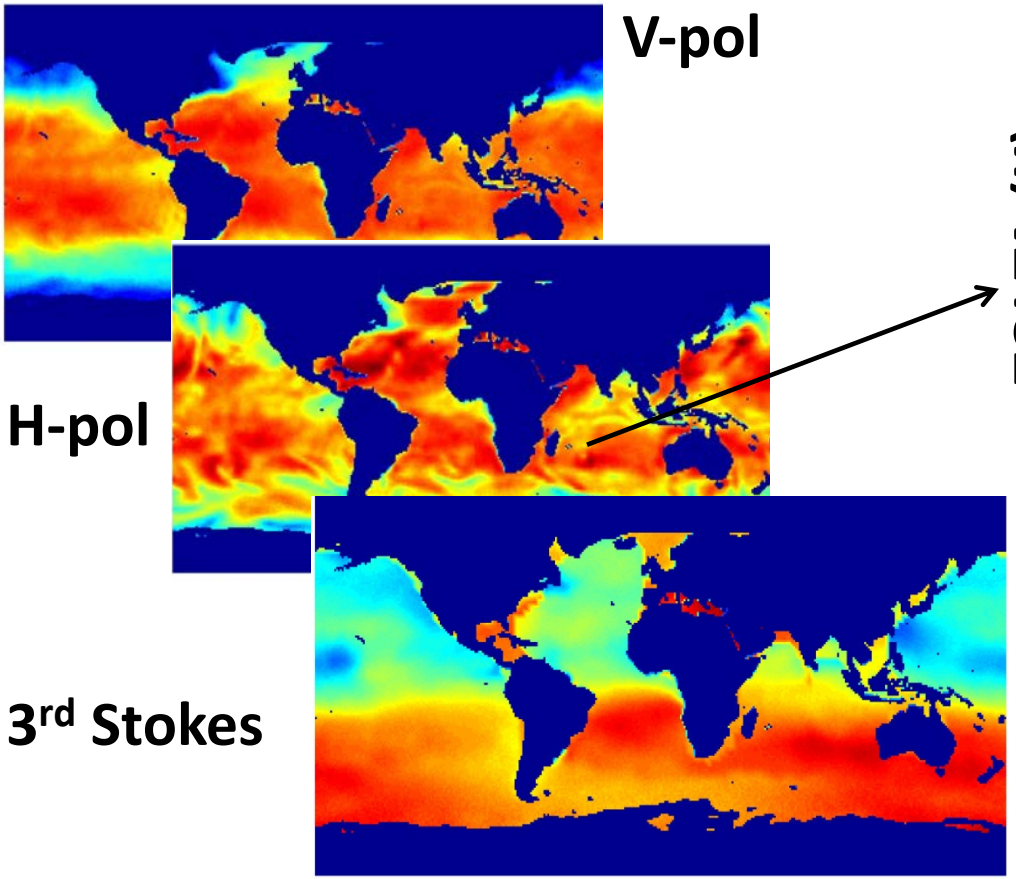


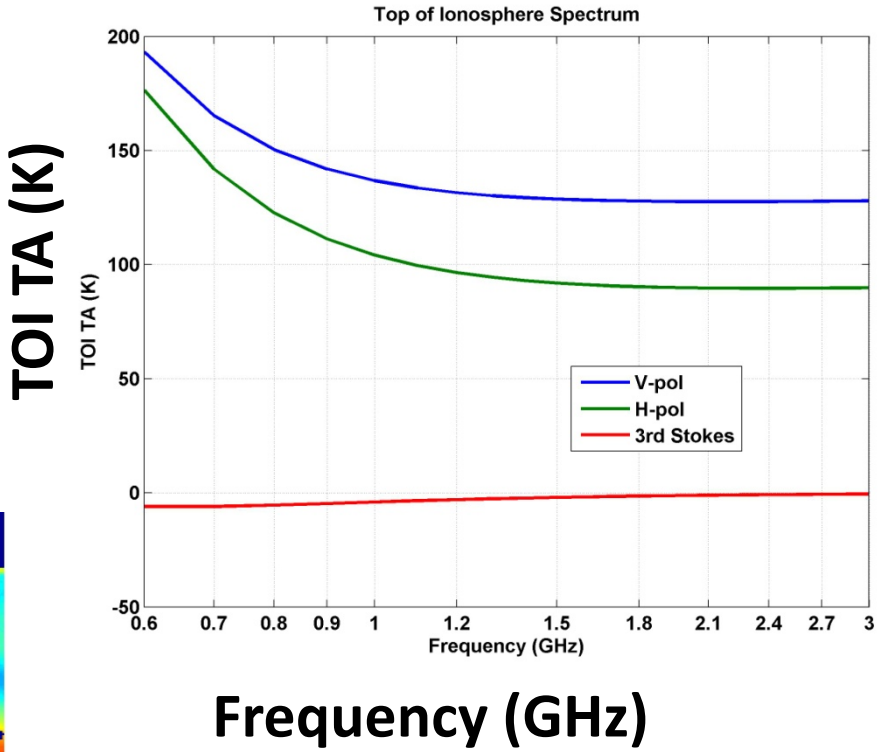


Normalized TB (h-pol, 40°) sensitivity vs frequency

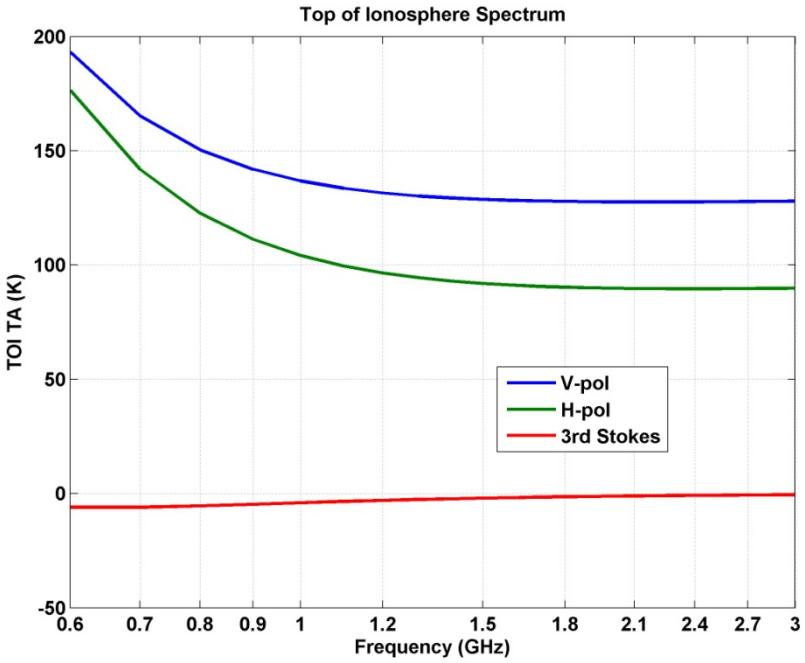
ΔTB/ ΔGalaxy
ΔTB/ ΔSST
ΔTB/ ΔWS
ΔTB/ ΔSSS

Proof of Concept Error Simulations





- Unconstrained simultaneous retrieval of SST, SSS and WS
- Also extract galaxy contribution and ionosphere electron content

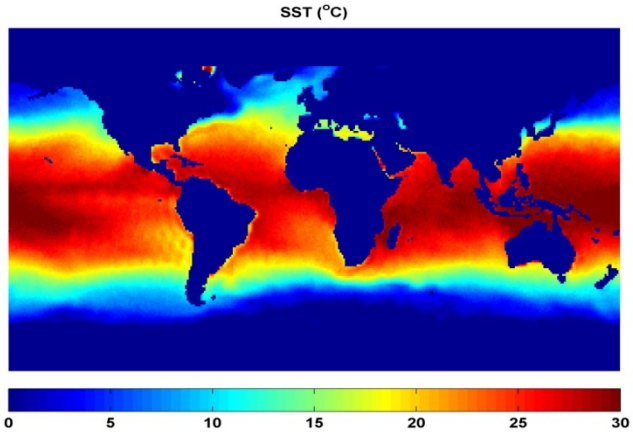


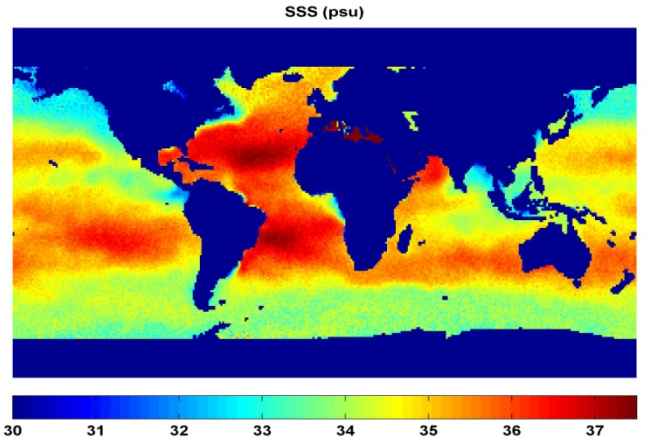
SST

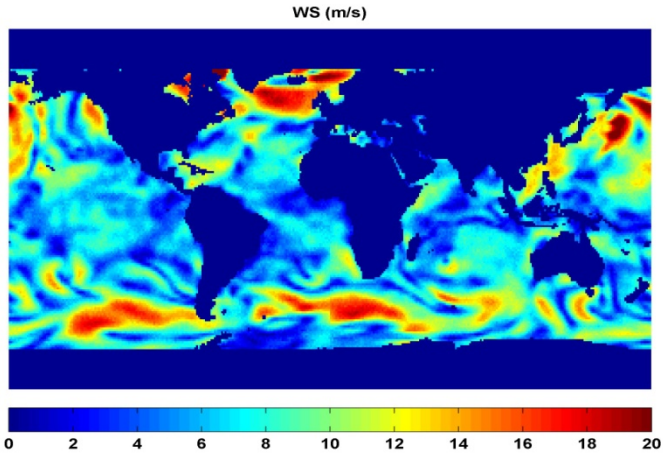
SSS

WS

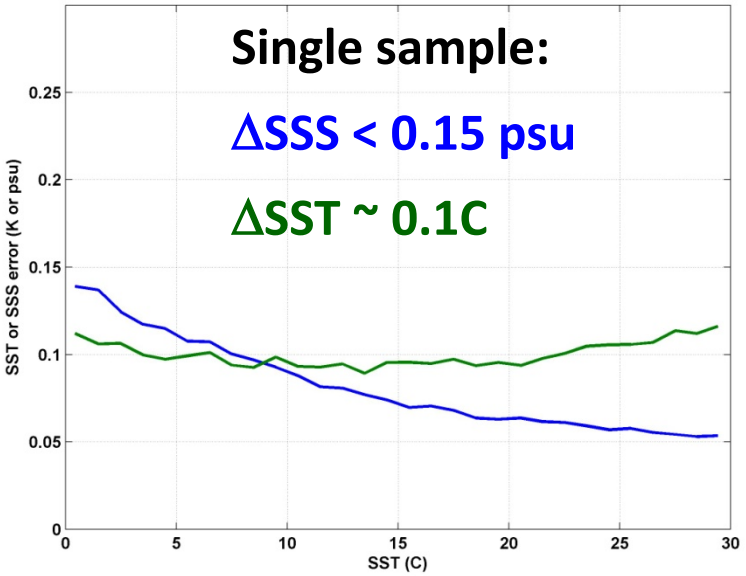
retrievals

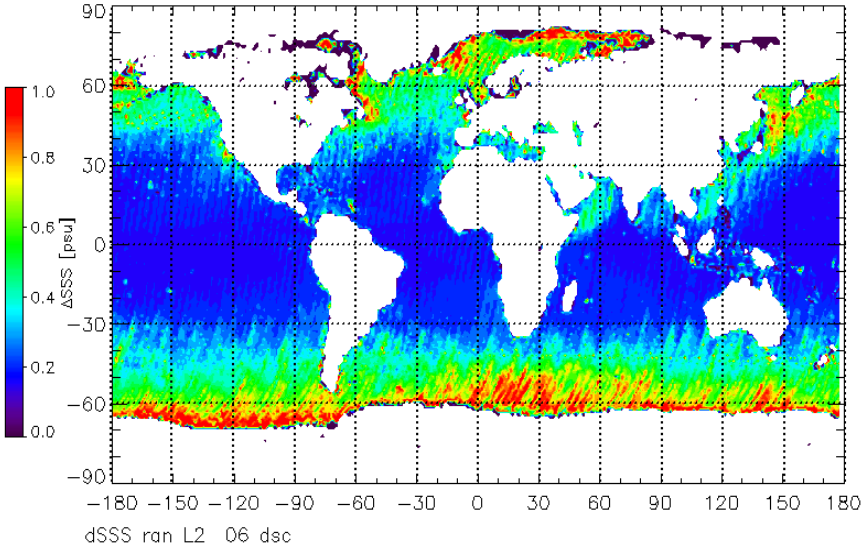




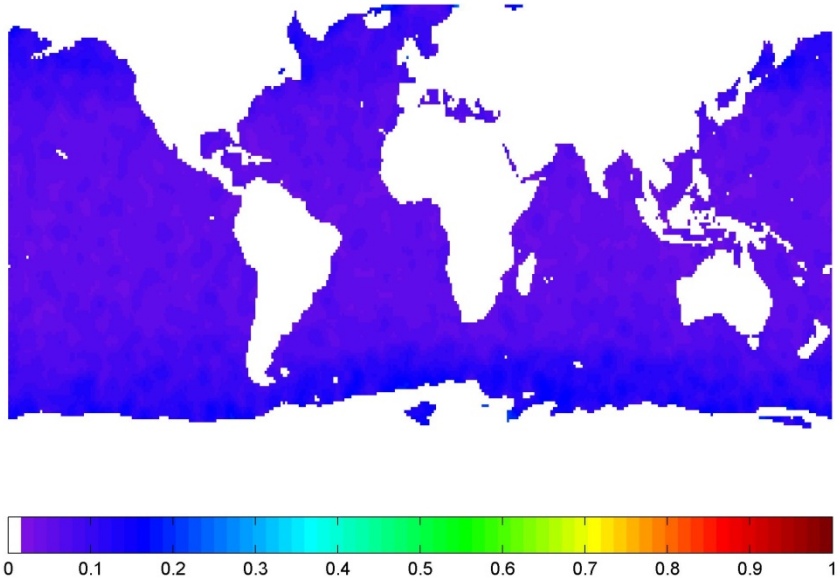


If the spectrometer is as well-calibrated as Aquarius…

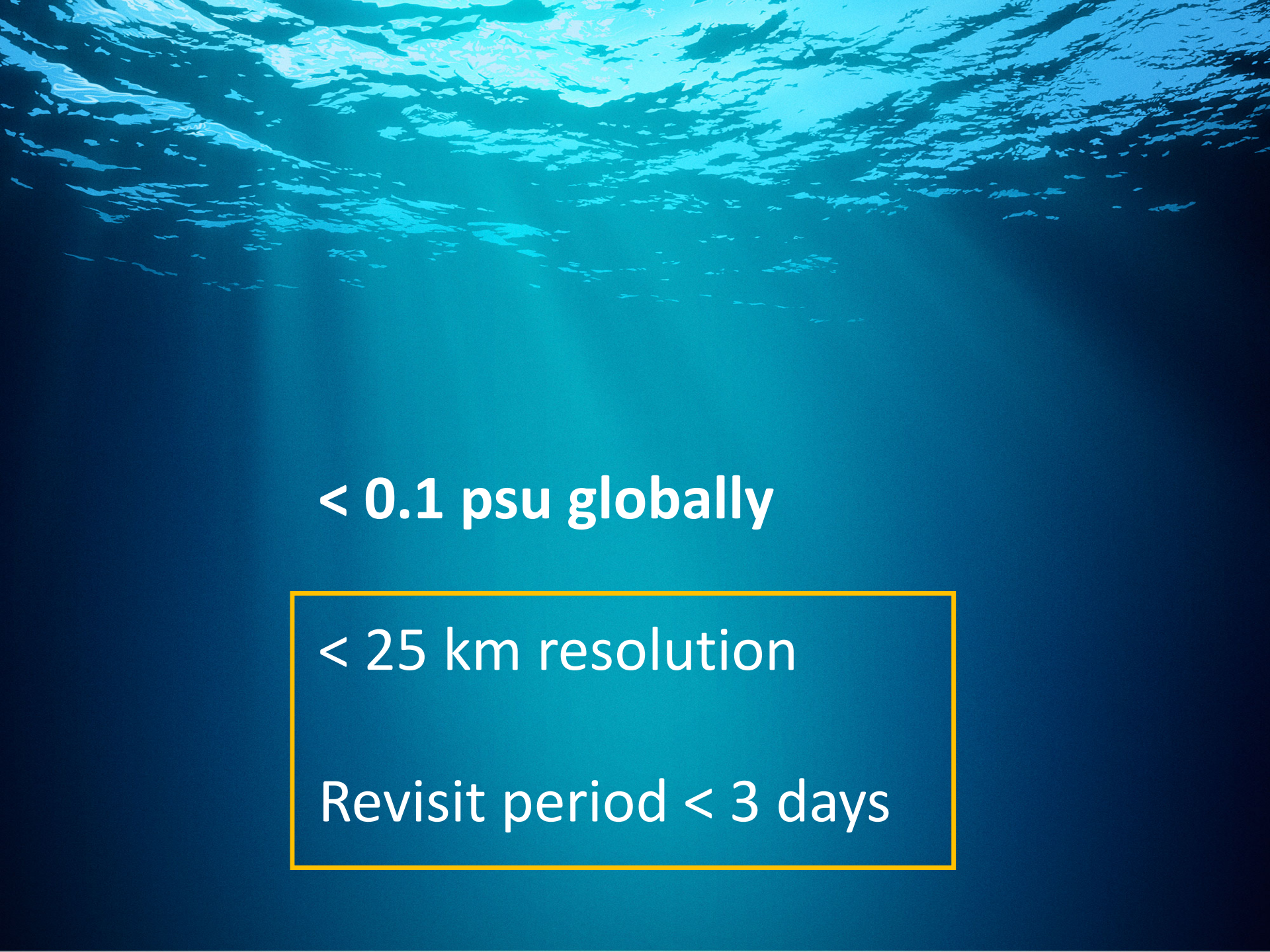




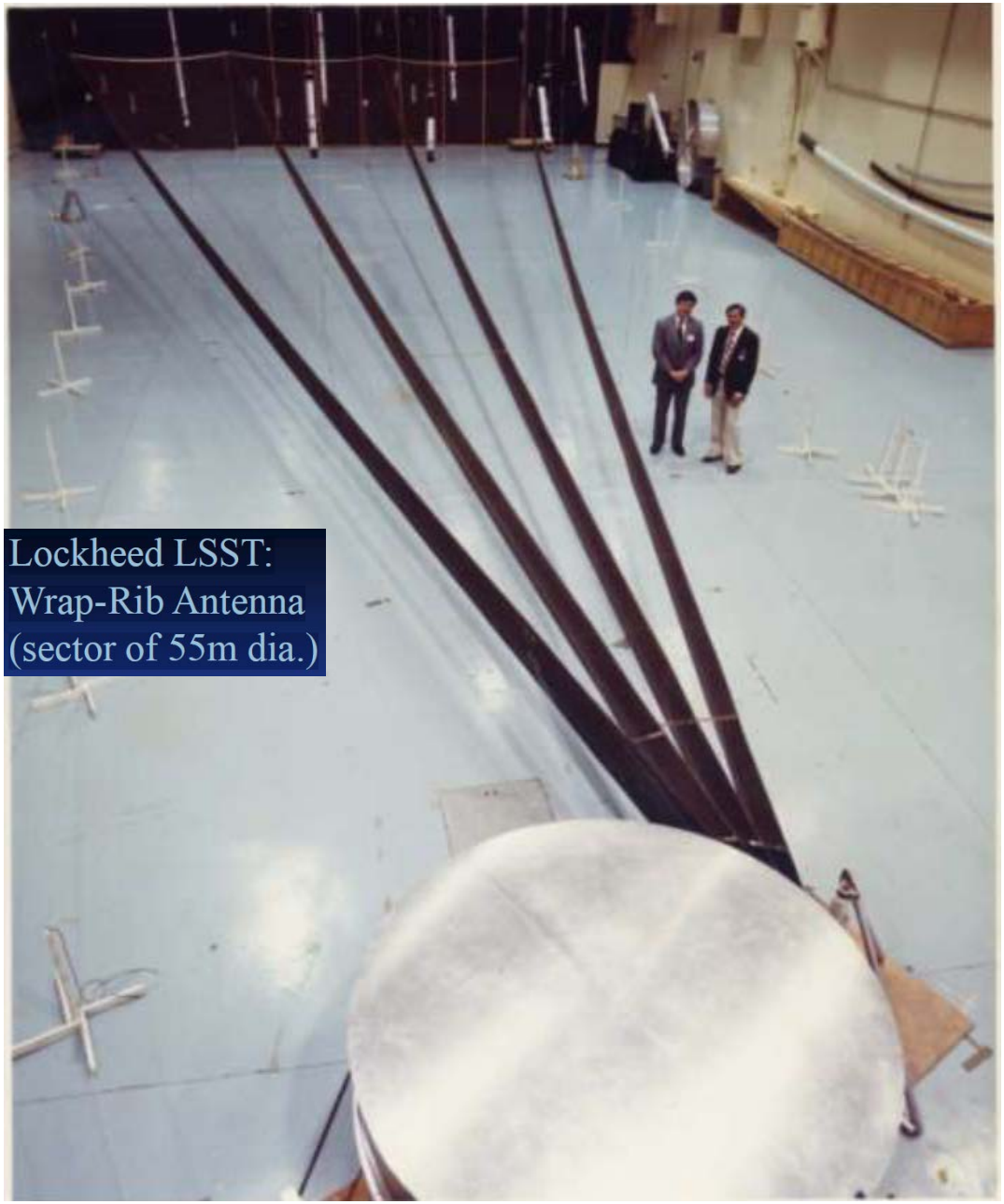
Aquarius Single Sample Random Error (psu)



0.6-3.0 GHz Spectrometer Single Sample Error (psu)


< 0.1 psu globally
< 25 km resolution
Revisit period < 3 days

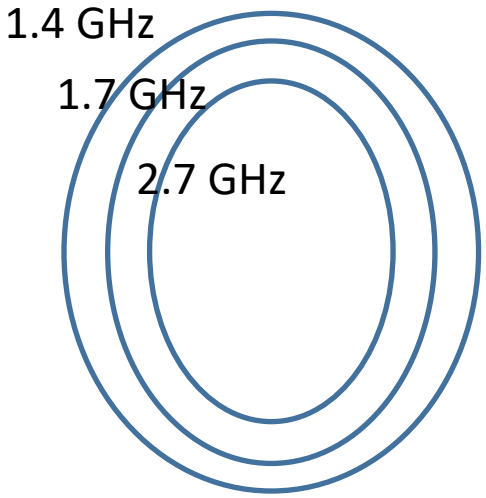
Spatial resolution proportional to λ/D – low-frequency-> large antenna

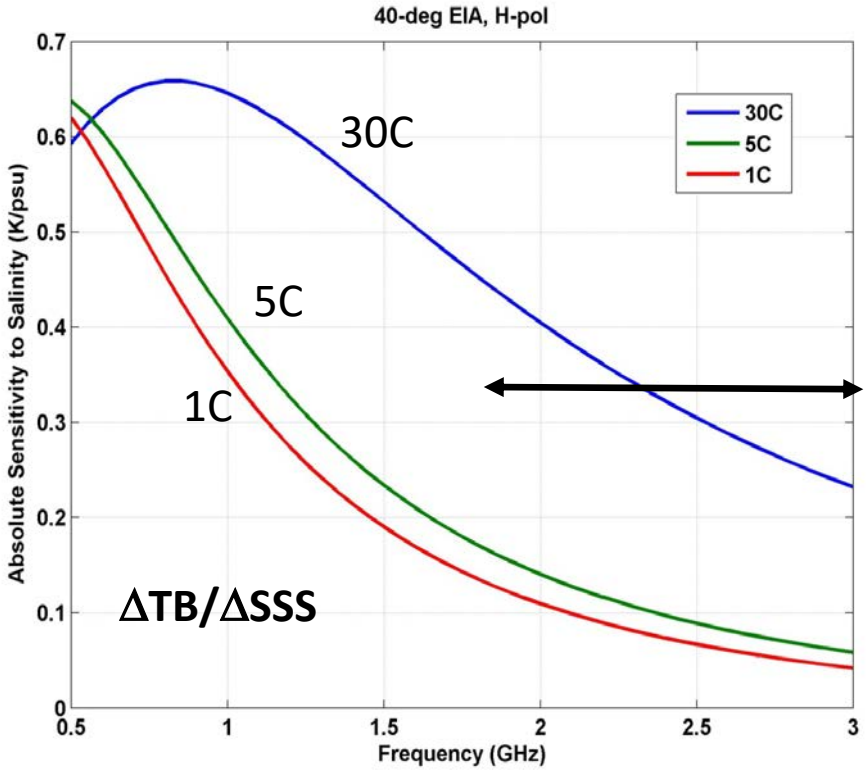


- Can trade resolution and revisit time
  - <25km resolution with 560km swath flying at 425km altitude with 6m antenna

SMAP 6m reflector

- **With spectrometer, can also optimize ground processing to maximize resolution for given reflector size preserving signal to noise**
  - 1.4 GHz: 25km
  - 1.7 GHz : 22km
  - 2.7 GHz: 13km





Use only higher portion of spectrum in warm water or when signal is large (e.g. fresh water outflow)

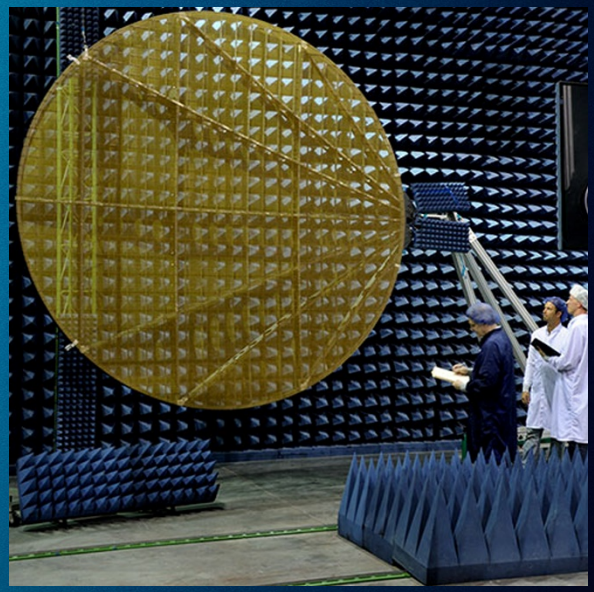
Spectral Radiometry for Ocean Surface State

- Multi-frequency radiometric observation in the range of 0.6-3.0 GHz has multiple benefits
  - Enables simultaneous retrieval of SST, SSS, WS
  - Improved SSS retrievals overall, less ancillary corrections
  - Dramatic improvement in cold water SSS
  - Dynamic spatial resolution
  - Sea ice thickness 0 – 1m
  - Soil moisture

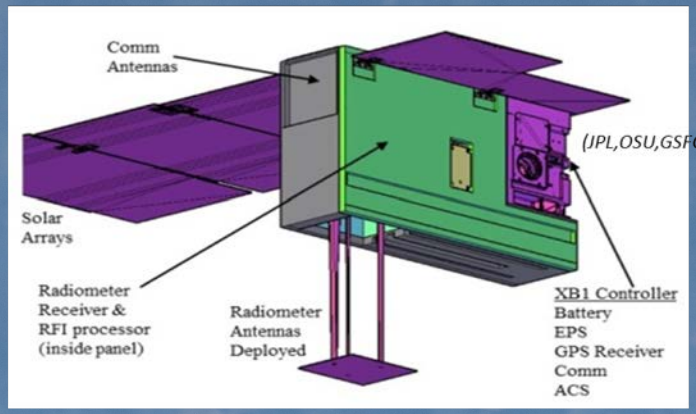
Technology

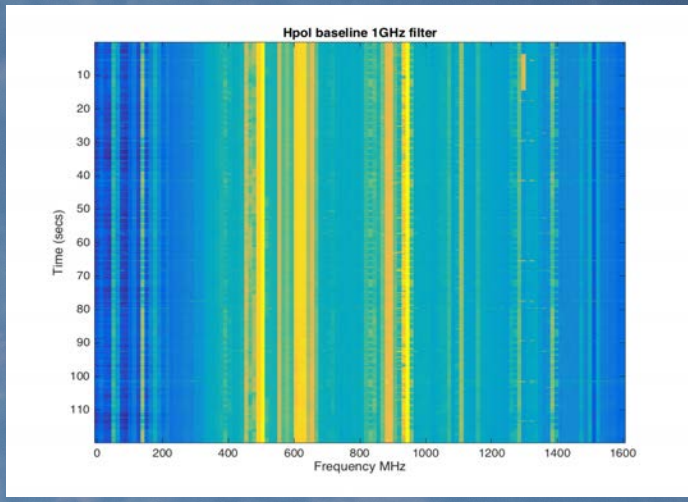
- RFI tolerance
  - Broadband digital spectrometers with signal processing to detect/remove RFI demonstrated in space

- Large reflectors
  - Commercial deployable reflectors available up to 25m
  - SMAP demonstrated a 6m spun reflector
  - Lightweight fixed reflectors available to 3.5 m

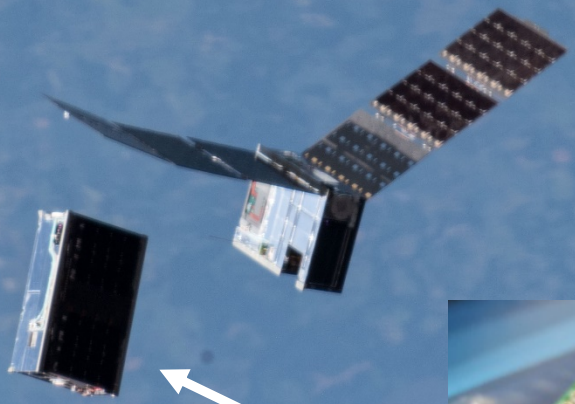


ESTO InVEST program – CubeSat Radiometer RFI Technology Demonstrator (CubeRRT)





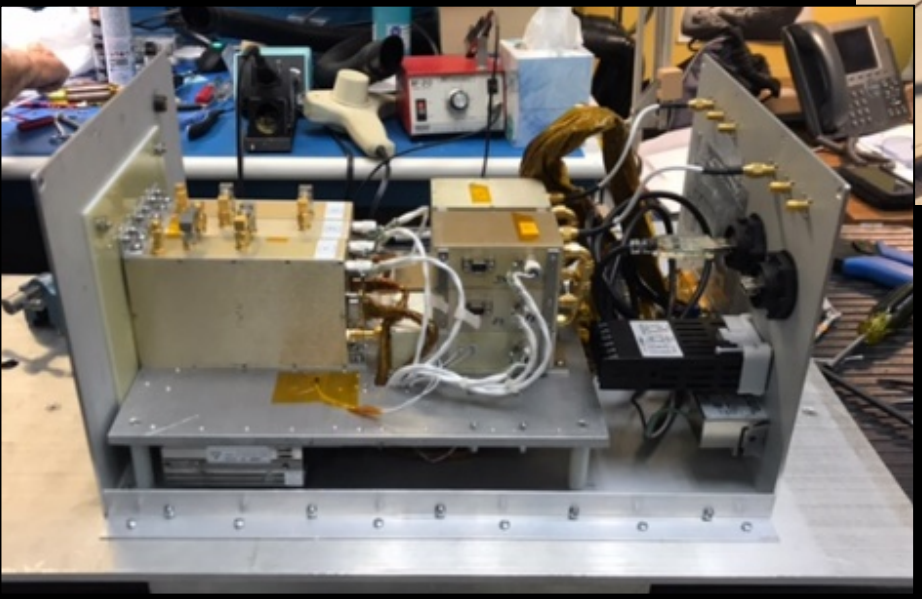
NASA CubeRRT Technology Demonstration CubeSat



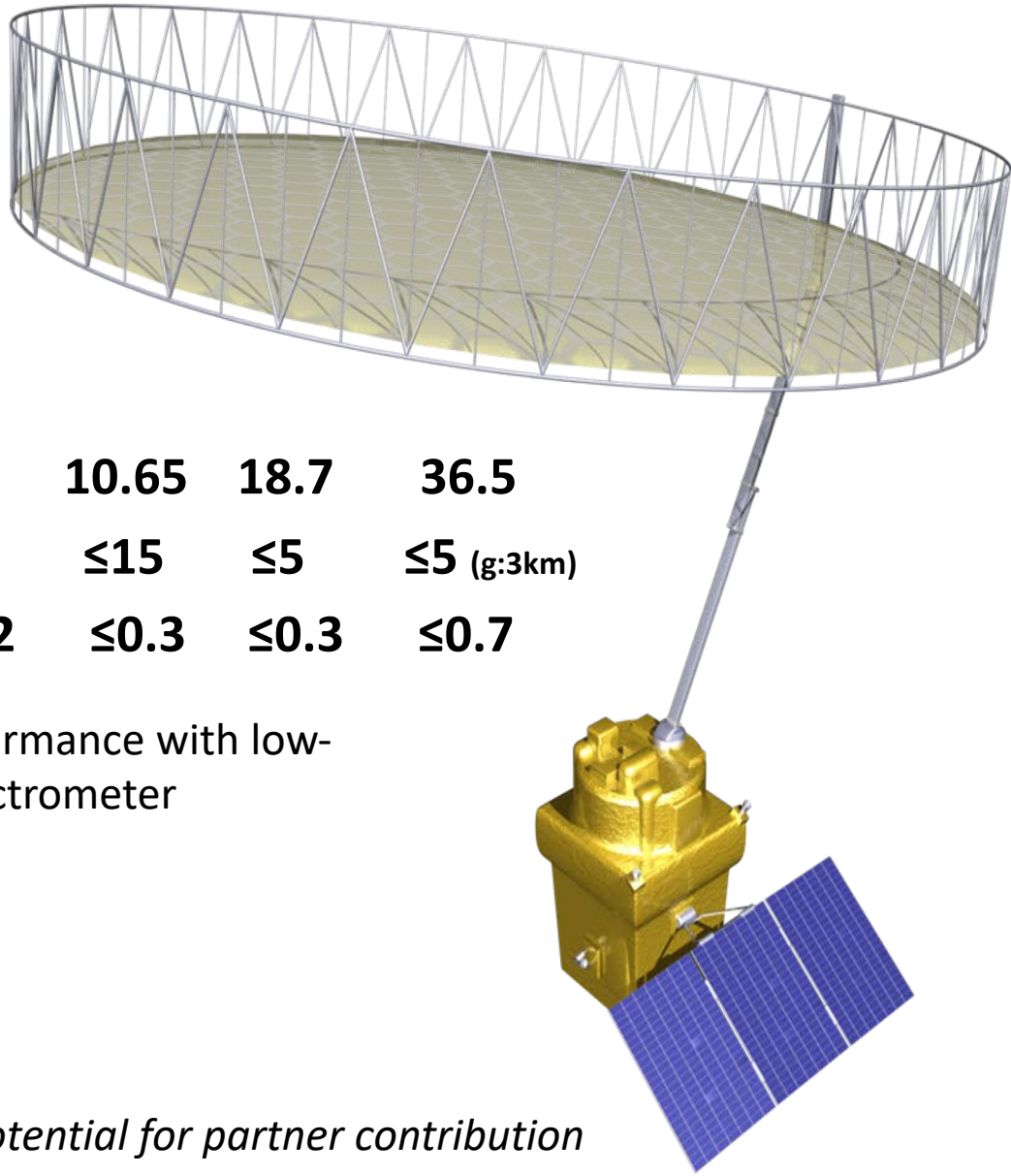
Wideband RFI tolerant software defined spectrometer demonstrated in space (Jul 2018 - present) – TRL7

JPL Spectrometer Demonstration Instrument (by Land, Air and Sea)

	PALS 2.0
RF coverage	0.5 GHz to 1.5 GHz
Bandwidth	1 GHz
No. of channels	4192 channels
Polarimetric	Digital Polarimetry
RFI mitigation	Detection + On-board Mitigation (Synced)
Variable	Gain variable (from 0-90dB at 3dB levels)

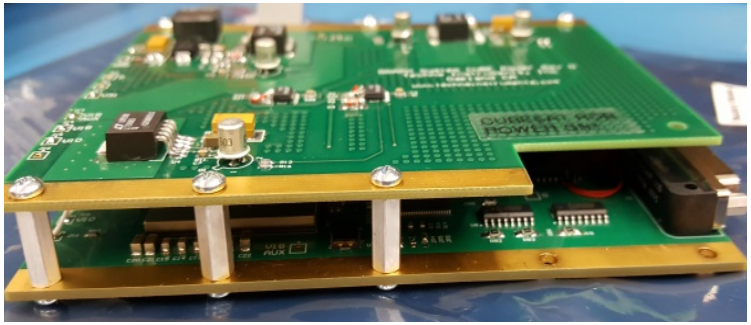


Copernicus Imaging Microwave Radiometer (CIMR)



	0.6-3	6.9	10.65	18.7	36.5
• Channels (GHz, all H&V):					
• Resolution (km):	≤55	**≤15**	**≤15**	**≤5**	**≤5** (g:3km)
• NEΔT (K @150K):	≤0.3	**≤0.2**	**≤0.3**	**≤0.3**	**≤0.7**

Optimize performance with low-frequency spectrometer



Potential for partner contribution

Summary

- Salinity mission enhancements realizable with recent technology advancements
  - Spectral measurements instead of single L-band channel
  - Simultaneous, accurate SST, SSS, Winds
  - 0.1C SST, < 0.15psu polar, < 0.1psu tropics
- Infusion paths and trades
  - Trade studies planned to evaluate concepts within program constraints
  - Partnerships likely required
  - Consider incorporation of spectrometer instrument into CIMR observatory
- Mission will also benefit cryosphere and land communities
  - Sea ice thickness can be measured in 0 – 1m range – complements other techniques
  - Deeper penetration into soil/vegetation for soil moisture measurement

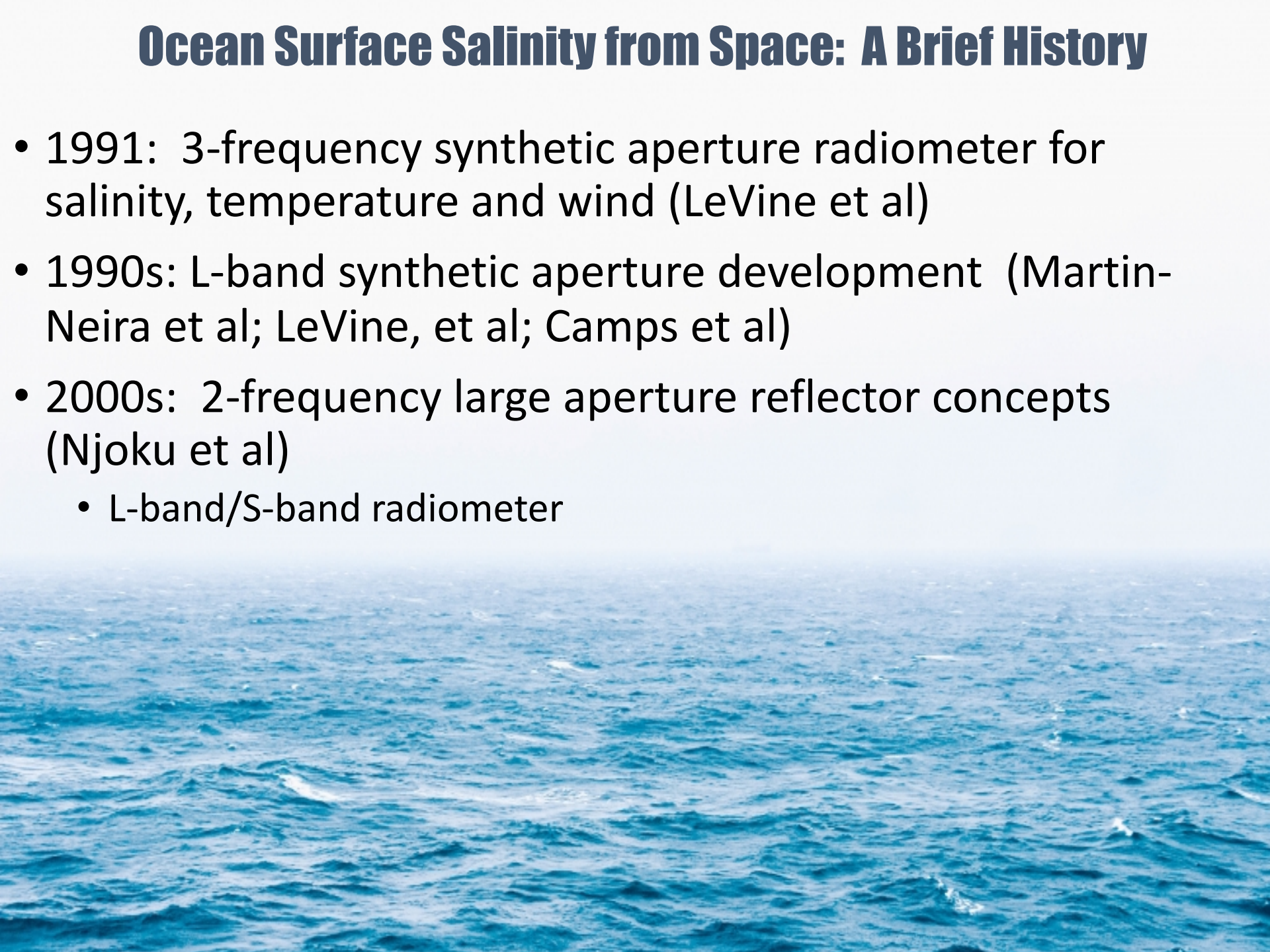
Backup

Ocean Surface Salinity from Space: A Brief History

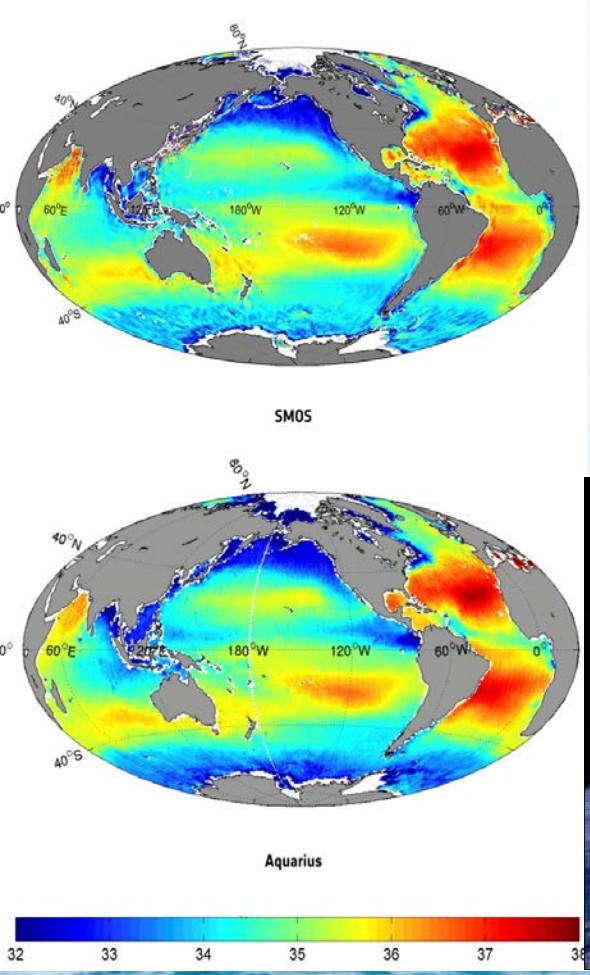
- 1973: L-band Airborne salinity measurements in estuary (Thomann)
- 1975: Remote sensing of salinity theoretical study (Wood et al)
  - Suggested 200-400 MHz radiometer
- 1978: Airborne measurement of sea surface temperature and salinity with a 1.4 and 2.6 GHz radiometer (Blume et al)
- 1983: Salinity mission concept study (Swift and McIntosh)
  - Proposed radiometer operating at 800 MHz as optimal frequency
- 1985: Airborne measurements with a 500 – 710 MHz spectrometer
  - Measurements so corrupted by RFI that no retrievals possible
  - Radiometer fixed to narrow 611 GHz protected band, but noise too high for retrieval

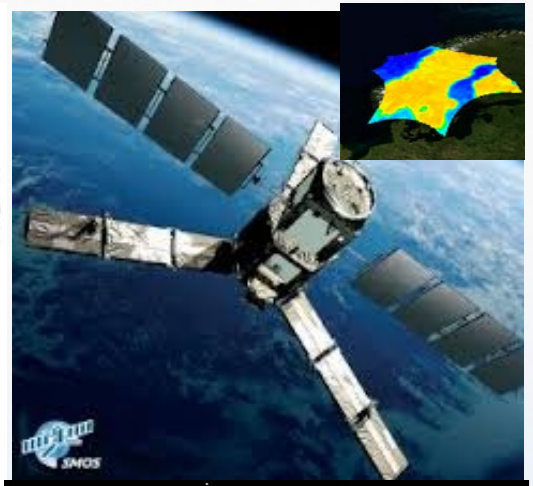
Ocean Surface Salinity from Space: A Brief History

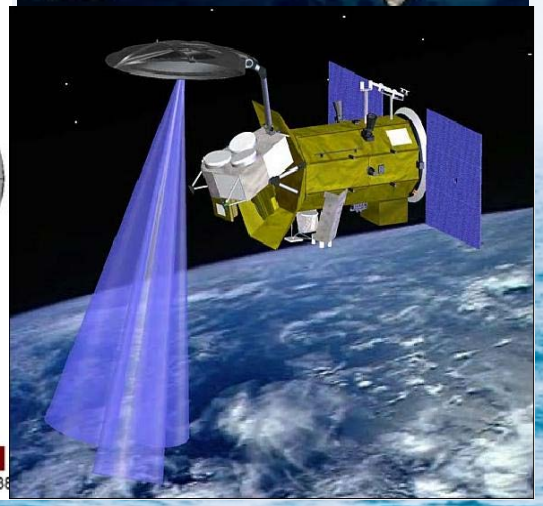
- 1991: 3-frequency synthetic aperture radiometer for salinity, temperature and wind (LeVine et al)
- 1990s: L-band synthetic aperture development (Martin-Neira et al; LeVine, et al; Camps et al)
- 2000s: 2-frequency large aperture reflector concepts (Njoku et al)
  - L-band/S-band radiometer



Ocean Surface Salinity from Space

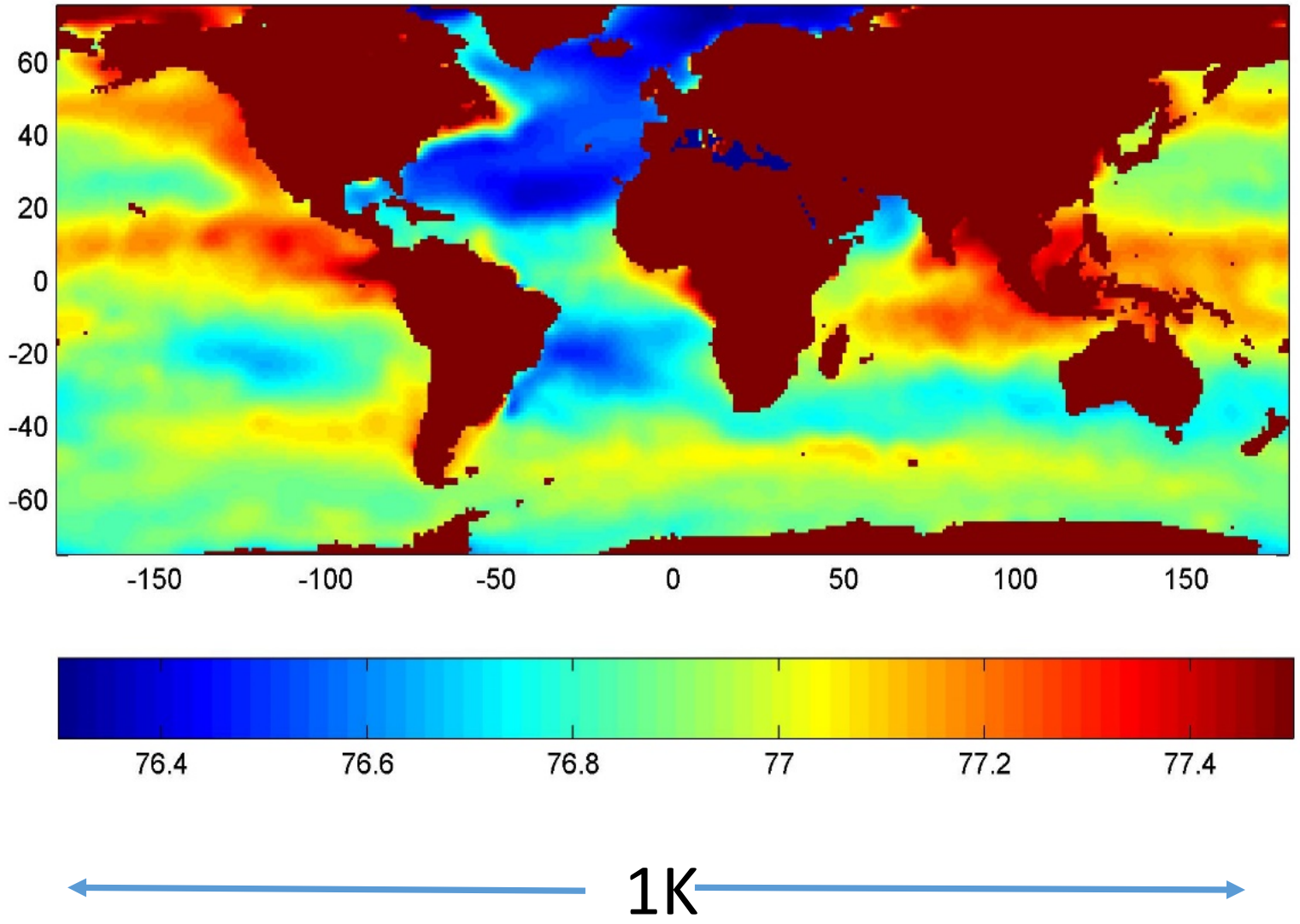




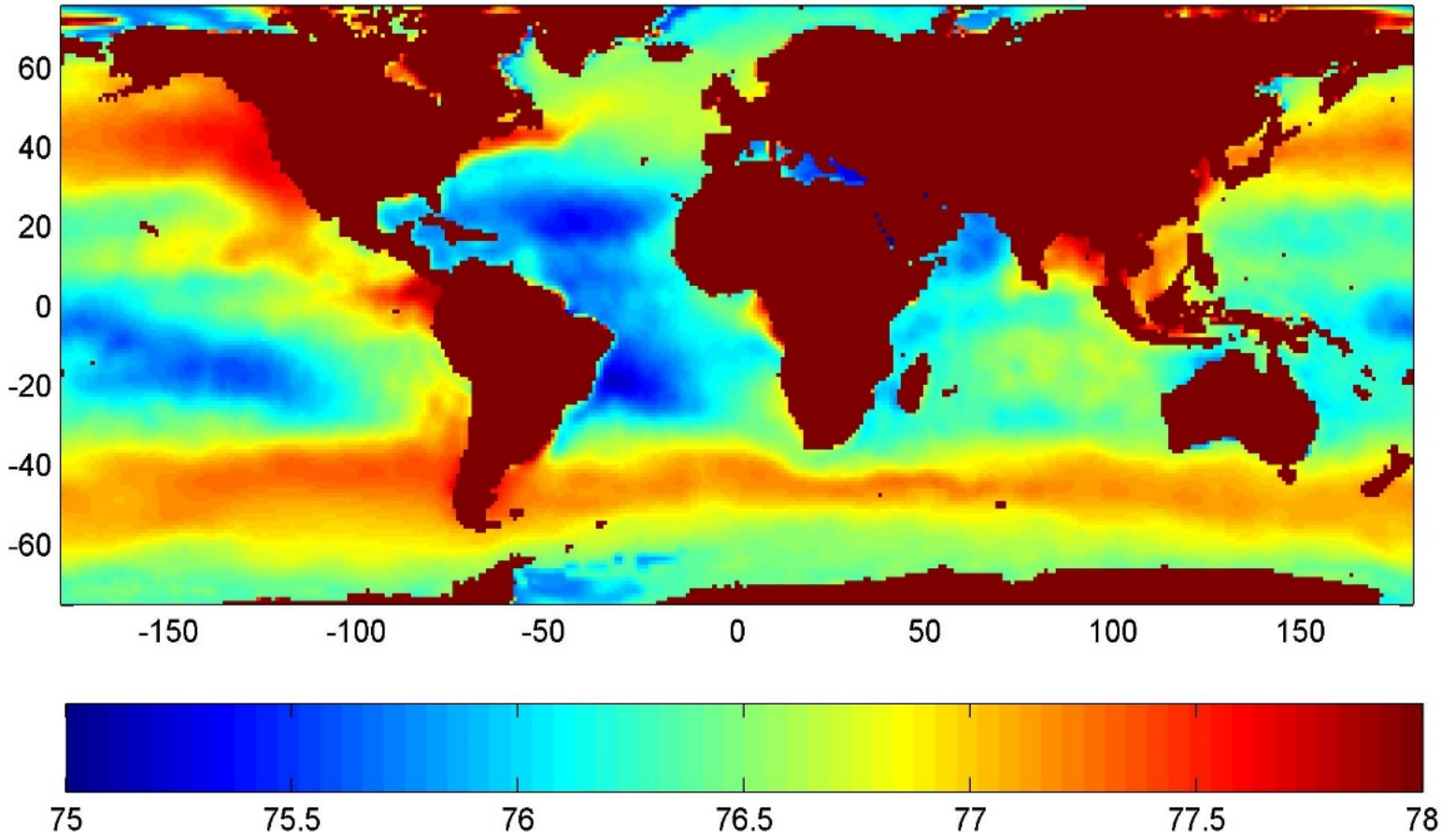


- SMOS, Aquarius and SMAP have unequivocally demonstrated ability to measure SSS from space
- These missions were limited to operate in narrow 1.4 GHz protected band to avoid RFI and fit within program costs
- Single frequency without UHF or S-band channels limits potential
  - Limited ability to measure SSS below 5C
  - Require significant ancillary corrections

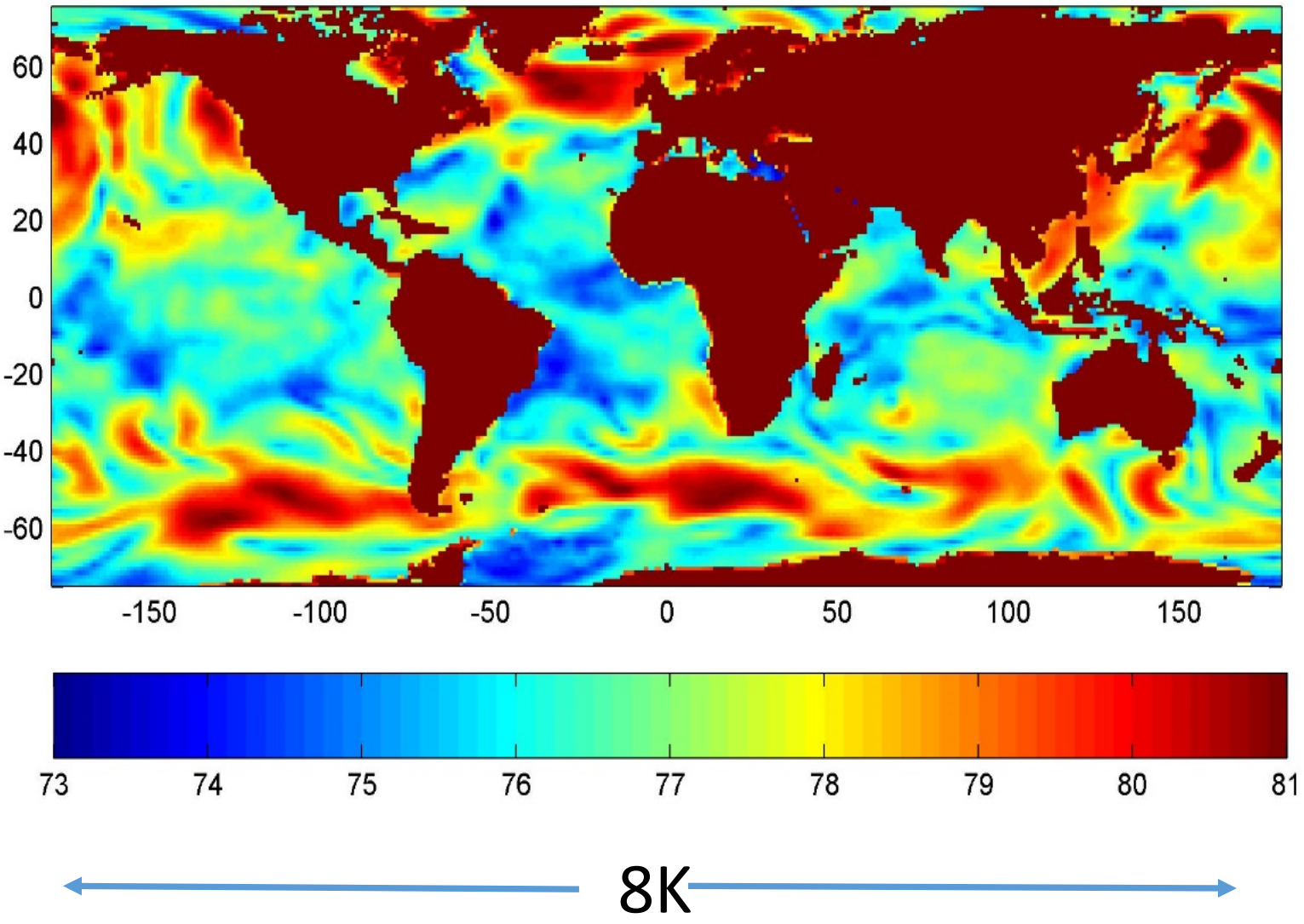
1.4 GHz TB(SSS)



1.4 GHz TB(SSS, SST)

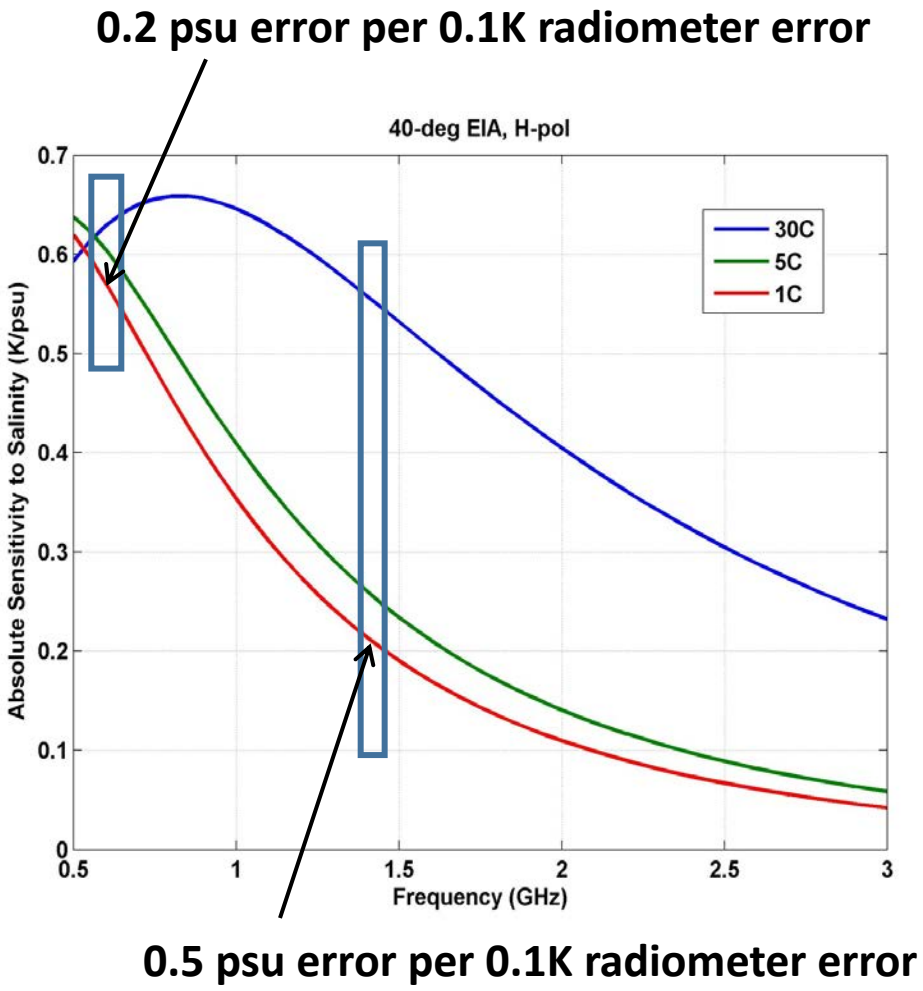


1.4 GHz TB(SSS, SST, WS)

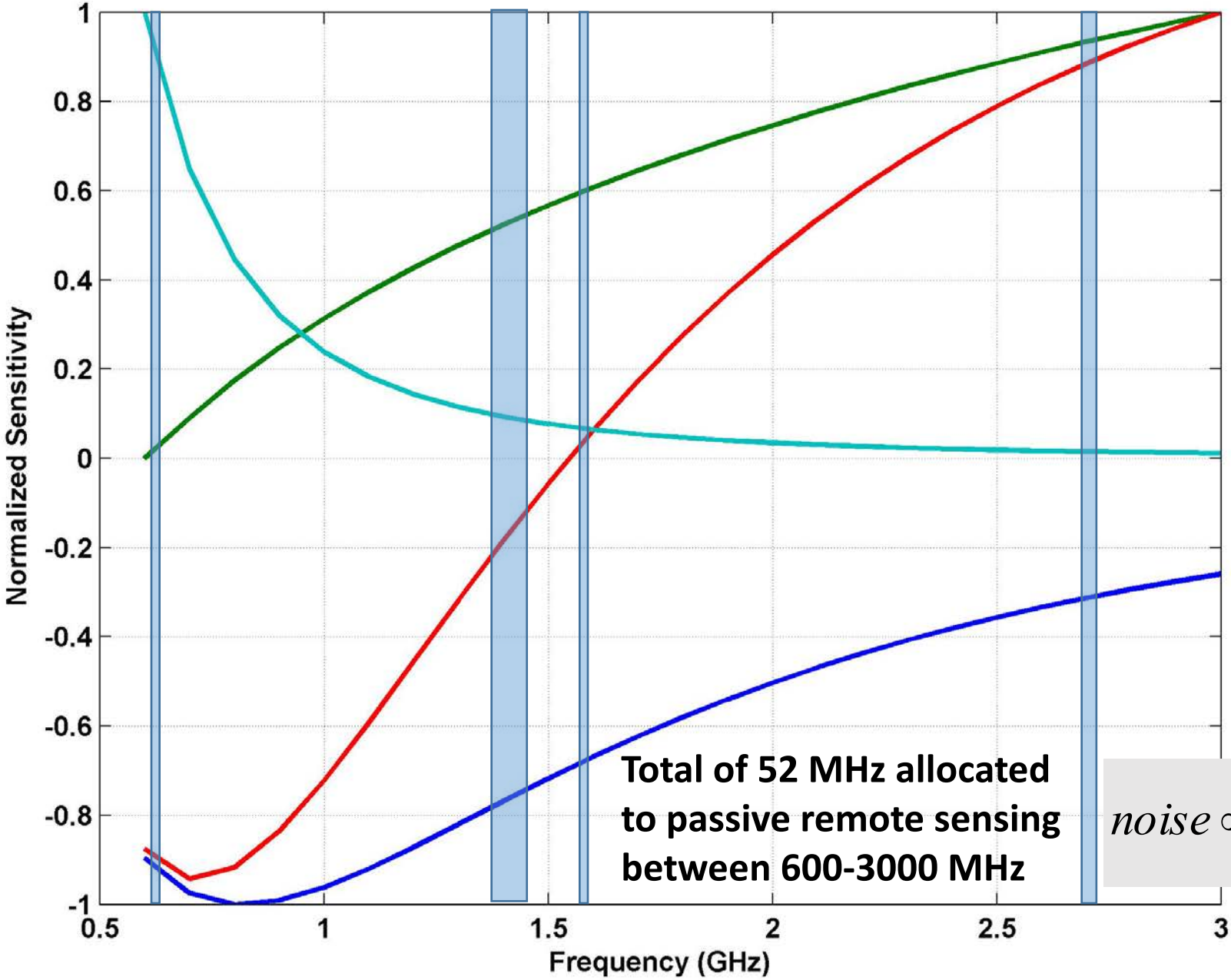


SSS Sensitivity in Cold Water

- L-band (1.4 GHz) has very low sensitivity to SSS below about 5C
- 600 MHz has 2.6x better sensitivity for all water temperatures



608-614 MHz 1.4-1.427 GHz 1.660.5-1.668 GHz 2.69-2.70 GHz



Total of 52 MHz allocated to passive remote sensing between 600-3000 MHz

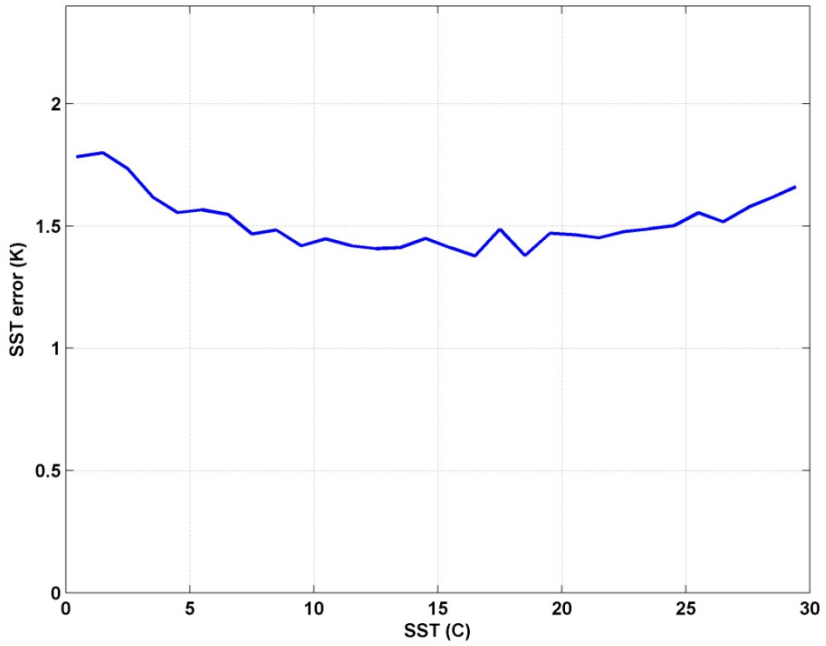
$$noise \propto \frac{1}{\sqrt{BW}}$$

Solution: Wideband digital spectrometer

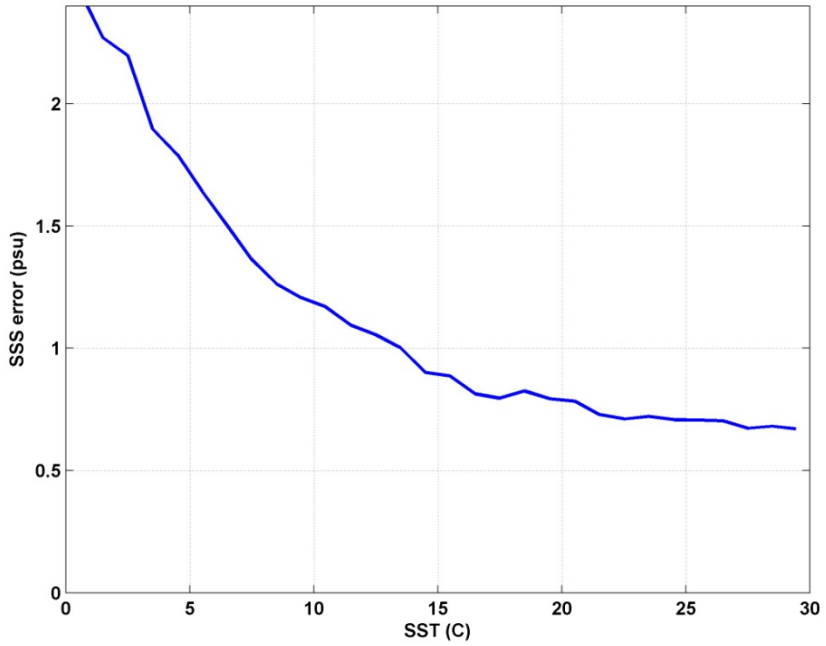
Simulated Retrieval Error (SST/SSS)

Scanning Narrow Band

SST Error vs SST



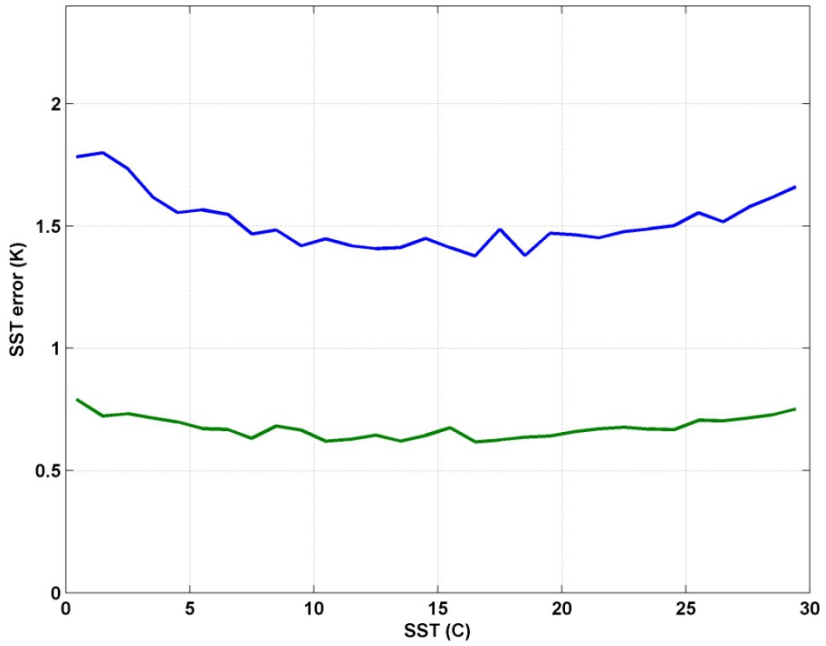
SSS Error vs SST



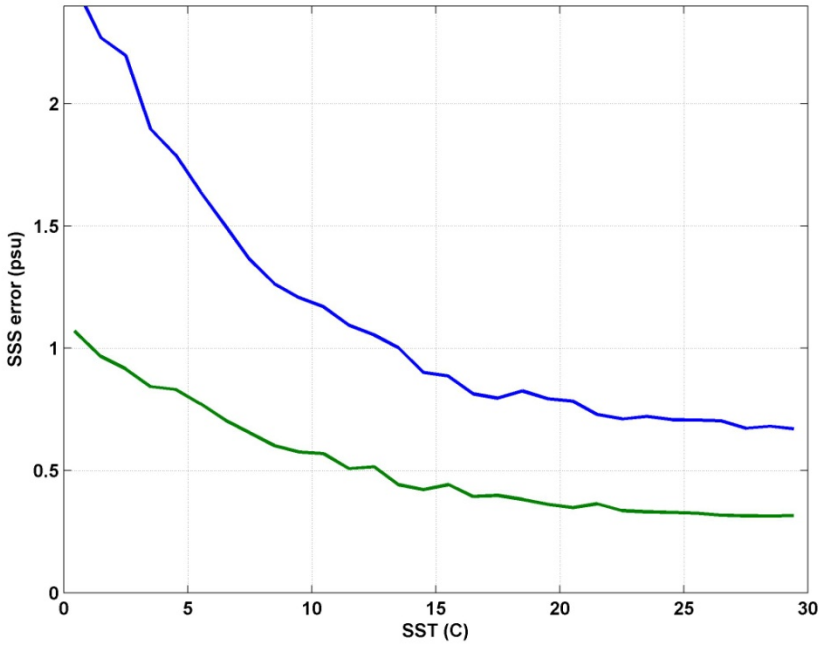
Simulated Retrieval Error (SST/SSS)

Fixed Beam Narrow Band
Scanning Narrow Band

SST Error vs SST



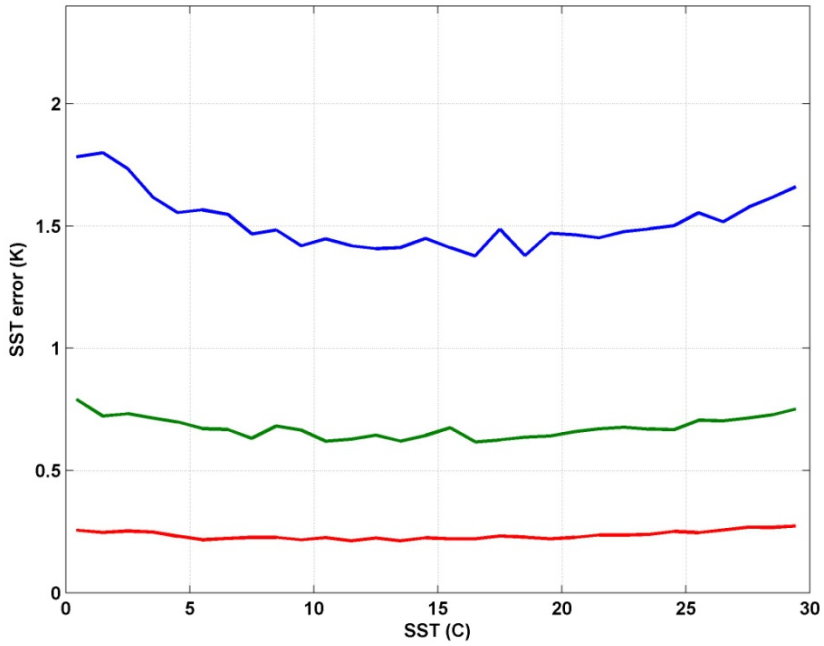
SSS Error vs SST



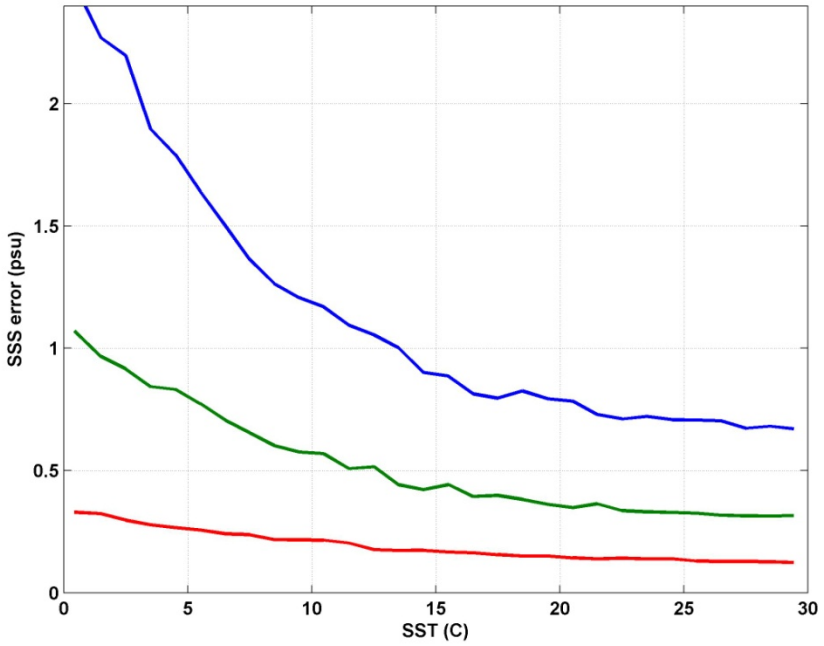
Simulated Retrieval Error (SST/SSS)

Scanning Wide Band
Fixed Beam Narrow Band
Scanning Narrow Band

SST Error vs SST



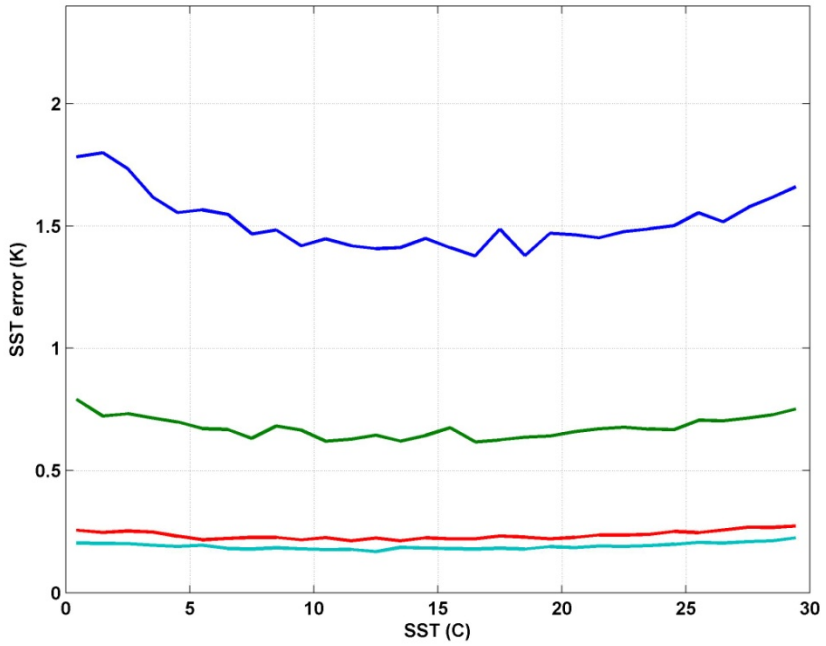
SSS Error vs SST



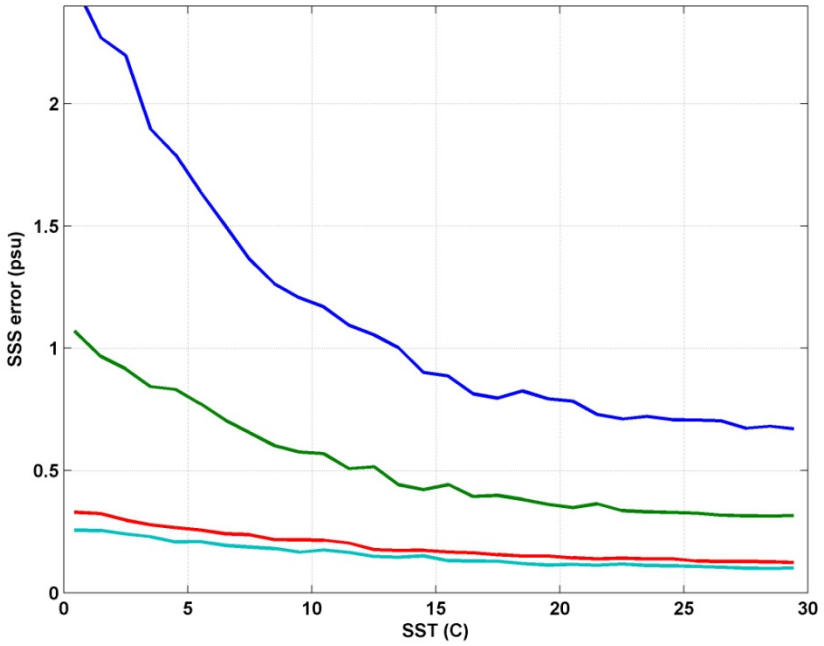
Simulated Retrieval Error (SST/SSS)

Fixed Beam Wide Band
Scanning Wide Band
Fixed Beam Narrow Band
Scanning Narrow Band

SST Error vs SST



SSS Error vs SST



Ocean State Mission

- Technology is rapidly maturing to where we can now consider measuring the ocean microwave spectrum from 0.6-3 GHz

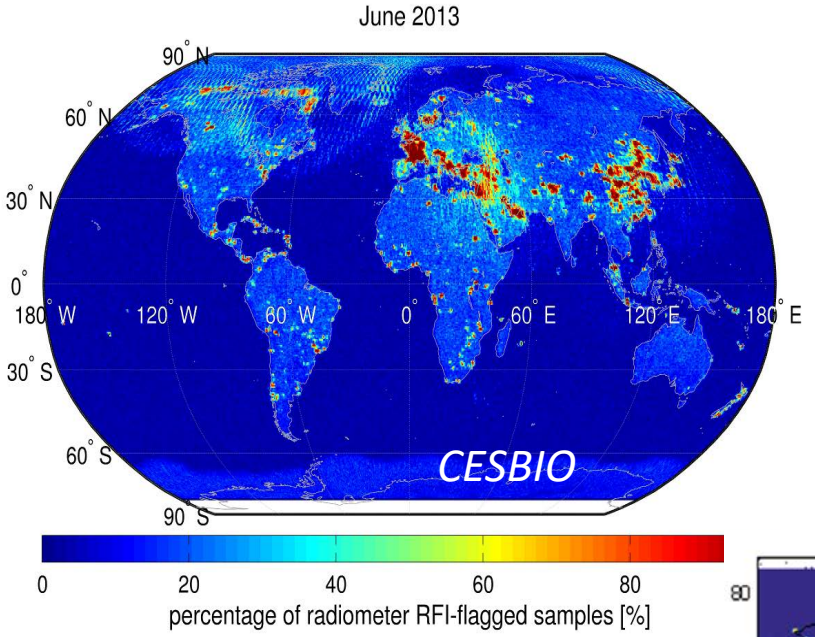
  Today --------

  - RFI filtering algorithms have been demonstrated
  - Wideband digital processing demonstrated in airborne and soon to be demonstrated in space
  - Broadband antennas deployed in radio astronomy community

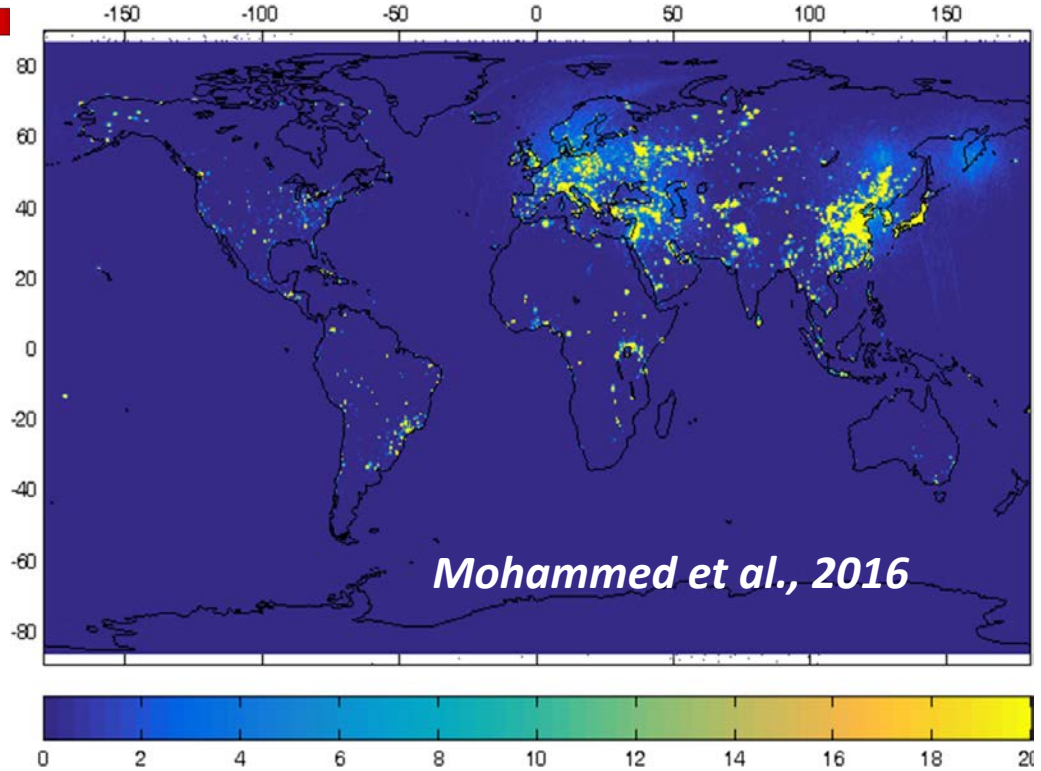
  Within 5 years -------

  - Digital focal plane arrays within reach that enable multi-mission capability and digitally defined antenna patterns (e.g. adaptive nulling, variable spatial resolution, beam matching)

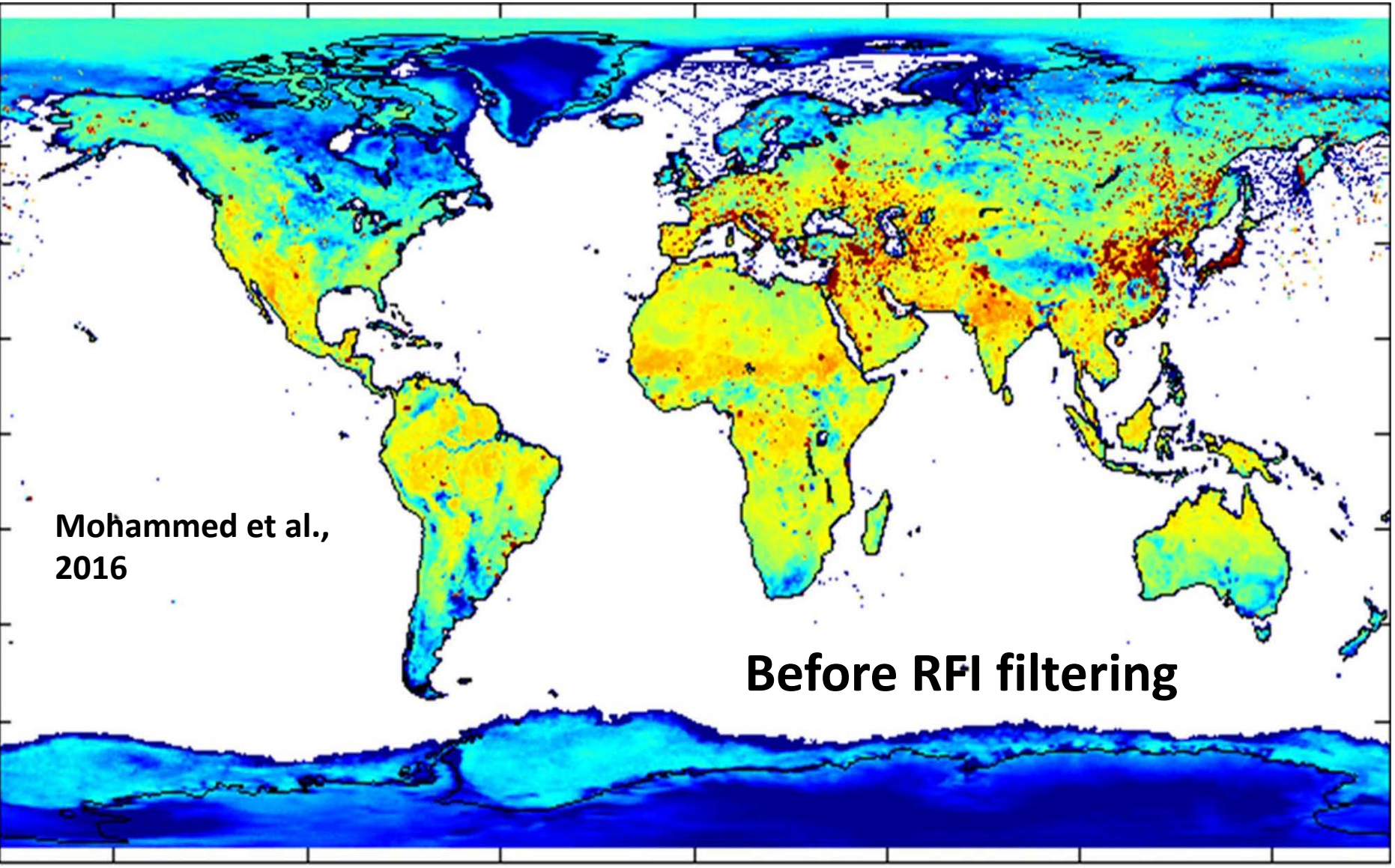
Radio Frequency Interference



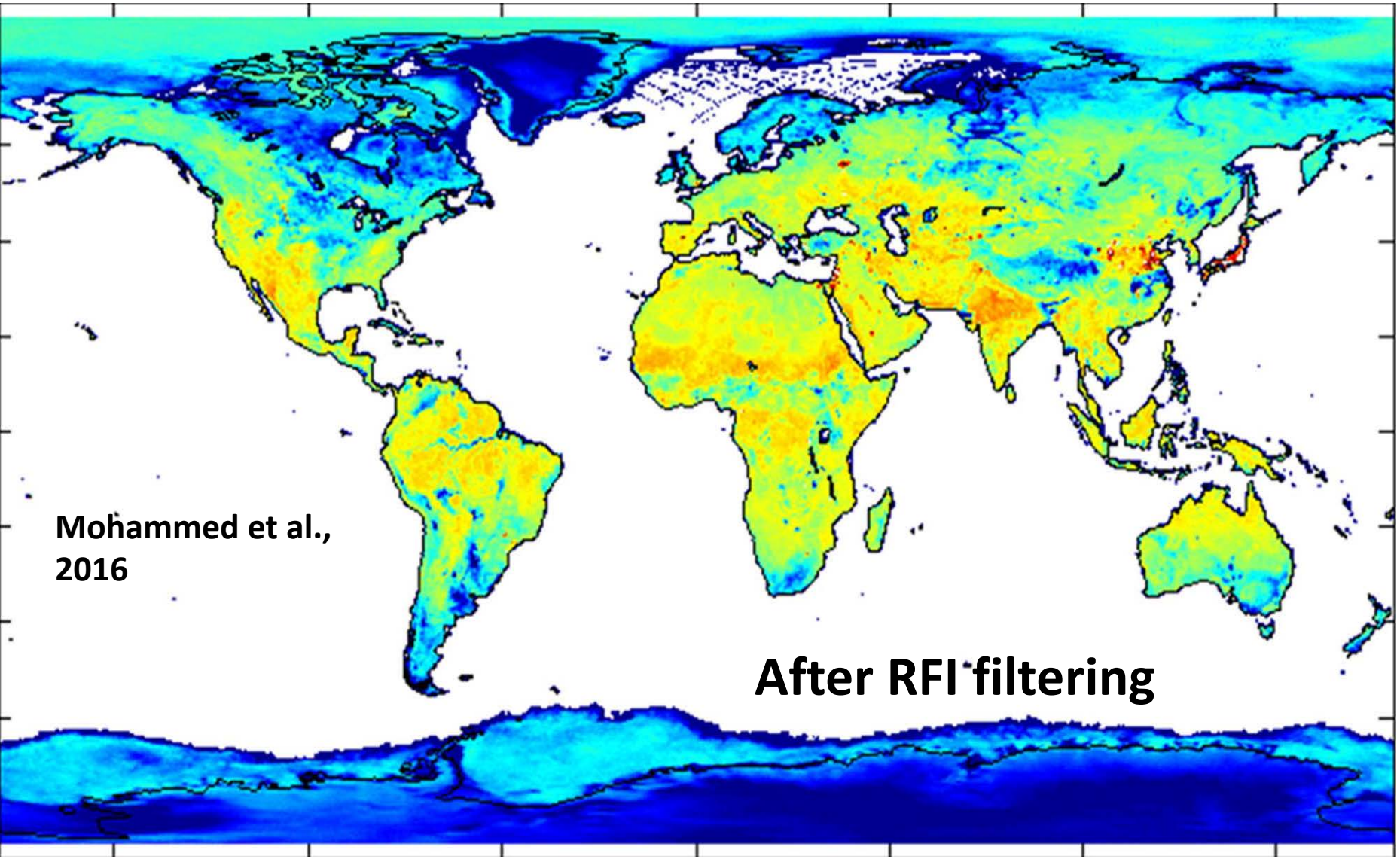
- Even in protected band, SMOS and Aquarius are significantly impacted by RFI
- Drove technology development in digital RFI tolerant radiometer backends



SMAP RFI Filtering



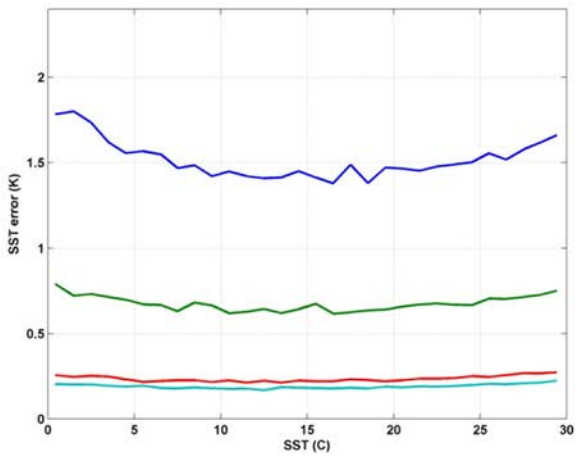
SMAP RFI Filtering



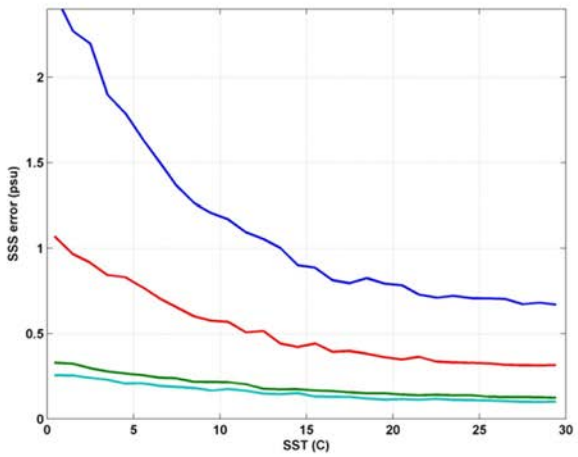
Mission Concepts

	Aquarius-like 2.5m Fixed Beam Reflector	SMAP-like 6m Reflector	SMAP-like 9m Reflector
SST and WS resolution	100 km	25 km	17 km
SSS (>5C) Resolution	125 km	30 km	20 km
SSS (<5C) Resolution	300 km	70 km	45 km
Swath width	150 km	700 km	700 km
Cost class	$200M	$400M	$800M

SST Error vs SST



SSS Error vs SST



Fixed Beam Wide Band
Scanning Wide Band
Fixed Beam Narrow Band
Scanning Narrow Band