Feasibility and Error Sources for Ocean Surface Salinity Measurements from Space

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Sea surface salinity (SSS) is a key parameter for studying ocean circulations and global hydrologic budgets. Recent studies have shown that assimilating SSS combined with other parameters has a positive impact on coupled forecasts. In addition, the ocean rainfall is reflected in the SSS variability, enabling estimates of ocean rainfall from SSS to balance surface freshwater flux in the climate prediction models. The ocean surface salinity has been viewed as a missing element in satellite ocean observations.

The principles of satellite SSS remote sensing are based on the sensitivity of sea surface brightness temperatures (Tb) to SSS. The sea surface Tb is a function of the water dielectric constant and surface temperature (SST). The water dielectric constant, influencing the emissivity of sea surfaces, is a function of salinity, temperature, and radio frequencies. The 1.4 GHz (L-band) frequency band set aside for radio astronomy use is considered to be adequate for SSS remote sensing. However, the L-band sea surface Tb is influenced by many other geophysical parameters, such as sea surface roughness, sea surface temperature, ionospheric Faraday rotation, solar radiation, and atmospheric gases. This paper will describe the effects of these parameters and potential techniques for corrections. We also describe space mission concepts for global SSS measurements.

To investigate the feasibility of SSS remote sensing with an accuracy of 0.2-0.3 psu required for weekly global mapping of open oceans, the aircraft Passive Active L/S (PALS) microwave instrument has been developed by the Jet Propulsion Laboratory (JPL). This instrument is a dual-frequency, dual-polarized combined radiometer and radar. This instrument has been flown on the NCAR C-130 with three flights off US east coast across the Gulf Stream and National Data Buoy Center (NDBC) buoys on July 17-19, 1999. The in-situ sea surface salinity was provided by the Cape Hatteras research vessel from Duke University. The PALS dataset has been analyzed to quantify the influence of surface roughness. The data indicate that the excess brightness temperatures due to sea surface roughness can be as high as 1 to 2 Kelvins, which will yield about 2-3 psu SSS errors if uncorrected. The PALS data suggest a linear relationship between the excess brightness temperatures and the radar measurements for the range of wind speed encountered wind (<7 m/s). A linear relationship is consistent with the Bragg scattering theory for sea surfaces, which predicts a linear dependence of the excess brightness temperatures and radar backscatter on the surface wave spectra. The proportional coefficients, estimated from the PALS data, vary with the polarization and frequency. We remove the excess brightness temperatures from the PALS radiometer data with this linear model. The standard deviation of the residual errors is estimated to be less than 0.2 Kelvin. By comparison with the Cape Hatteras SSS data, the SSS retrieval error approaches the accuracy required for open ocean conditions.
FEASIBILITY AND ERROR SOURCES FOR OCEAN SURFACE SALINITY MEASUREMENTS FROM SPACE

JPL

SIMON YUEH, E. NJOKU, W. J. WILSON AND FUK LI

JET PROPULSION LABORATORY
6-10 DECEMBER 1999
OUTLINE

- INTRODUCTION
- ANALYSIS OF ERROR SOURCES
- FEASIBILITY OF SATELLITE SSS RETRIEVAL
- AIRCRAFT SSS EXPERIMENT PROGRESS
- SUMMARY
OCEAN SURFACE SALINITY MISSION
SCIENCE MEASUREMENT AND APPLICATIONS
OBJECTIVES:

• SCIENCE THEMES
  • Climate Variation and Prediction
  • Global Water and Energy Cycle

• SCIENCE QUESTIONS
  • Exploration  What are the large scale salinity anomalies of the ocean?
  • Understanding  What is the role of salinity in the global water cycle?
  • Impact  What is the impact of salinity on seasonal to decadal climate change?

• DATA PRODUCTS
  • Sensor Data Records  (along track swath geometry, $T_B$)
  • Geophysical Data Records  (along track swath geometry, salinity)
  • Gridded maps (rectilinear coordinates, salinity)
OCEAN SALINITY MISSION
SCIENCE MEASUREMENT AND APPLICATIONS
OBJECTIVES (cont.)

- SCIENCE MEASUREMENT REQUIREMENTS
  - Spatial resolution: <100 km footprint
  - Temporal sampling:
    - repeat global coverage every 2-3 days
    - weekly (or monthly) (gridded maps)
  - Precision / calibration stability:
    - 0.1 - 0.2 K (sensor record)
    - < 1 psu (geophysical record)
    - 0.2-0.3 psu (weekly gridded maps)
    - 0.1-0.2 psu (monthly gridded maps)

- POTENTIAL APPLICATIONS
  - Improving seasonal to interannual [ENSO] climate predictions
  - Improving ocean rainfall estimates and global hydrologic budgets
  - Monitoring large scale salinity events
STATUS OVERVIEW

- A OCEAN SURFACE SALINITY MISSION HAS BEEN INCLUDED IN THE NASA EARTH SCIENCE MISSION PLAN IN 2000+
- JPL IS BEING FUNDED BY THE NASA INSTRUMENT INCUBATOR PROGRAM TO STUDY THE LARGE MESH-DEPLOYABLE TECHNOLOGY
- JPL HAS A FUNDED R&D PROGRAM TO STUDY THE FEASIBILITY AND ALGORITHM WITH AIRCRAFT INSTRUMENTATION
- WILL SUBMIT AN ESSP PROPOSAL IN 2000
BASIS OF SSS MICROWAVE REMOTE SENSING

- THE SENSITIVITY OF L-BAND (1.4 GHZ) OCEAN SURFACE BRIGHTNESS TEMPERATURES TO THE SEA SURFACE SALINITY ENABLES SPACEBORNE REMOTE SENSING.
  - SSS SENSITIVITY REDUCES WITH INCREASING FREQUENCY
  - VERTICAL POLARIZATION IS MORE SENSITIVE TO SSS THAN HORIZONTAL POLARIZATION
  - BETTER SENSITIVITY FOR WARMER SURFACES
  - SST CAN BE OBTAINED FROM S- OR C-BAND RADIOMETERS

<table>
<thead>
<tr>
<th>SST (°C)</th>
<th>ΔTv/ΔSSS (K/psu)</th>
<th>ΔTh/ΔSSS (K/psu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.44</td>
<td>0.30</td>
</tr>
<tr>
<td>20</td>
<td>0.65</td>
<td>0.43</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Sensitivity of L-Band Brightness Temperatures to SSS at 45° Incidence Based on Klein and Swift’s Model
OCEAN SALINITY RETRIEVAL STUDY
OBJECTIVES

- TO DETERMINE THE ERROR SOURCES FOR SSS MEASUREMENTS
- TO ESTIMATE THE OCEAN SALINITY MEASUREMENT ACCURACY FOR SPACEBORNE SENSORS
  - TO DETERMINE THE CALIBRATION REQUIREMENTS
  - TO DETERMINE THE SCANNING GEOMETRY
    • CONICAL SCANNING VS. CROSS-TRACK SCANNING
- TO STUDY THE RETRIEVAL ALGORITHM
OCEAN SALINITY RETRIEVAL STUDY APPROACH

• ANALYSIS OF ERROR BUDGET
  – RADIOMETER SENSITIVITY
  – CALIBRATION ERROR
  – GEOPHYSICAL MODELING ERROR

• SALINITY RETRIEVAL SIMULATION
  – CONFIGURATION PARAMETERS: POLARIZATION, FREQUENCIES, INCIDENCE ANGLES
  – CALIBRATION REQUIREMENT
GEOPHYSICAL CONTRIBUTIONS TO SATELLITE MICROWAVE MEASUREMENT

- Microwave ocean radiation is influenced by

  Galactic radiation and etc.
  | Ionosphere                      | Faraday Rotation               |
  | Atmospheric gases               |                               |
  | water vapor                     |                               |
  | liquid water                    |                               |
  | temperature                     |                               |
  | Salinity                        |                               |
  | Temperature                     |                               |
  | Surface Roughness               |                               |
NMC EFFECTIVE ATMOSPHERIC PARAMETERS

f=1.4 GHz, Day 127, 1995

Surface Air Temperature (°C)
NMC EFFECTIVE ATMOSPHERIC PARAMETERS

f=2.69 GHz, Day 127, 1995

1-β

0.0110
0.0100
0.0090

0.0
10.0
20.0
30.0
40.0

T_μ (K)

2.90
2.80
2.70
2.60

0.0
10.0
20.0
30.0
40.0

T_j,h(μ)

2.90
2.80
2.70
2.60

0.0
10.0
20.0
30.0
40.0

Surface Air Temperature (°C)
CLOUD LIQUID WATER RADIATION AND ATTENUATION

40° Inc. Angle

- 1.4 GHz
- 2.69 GHz

TB (KELVIN)

Attenuation (dB)

Cloud Liquid Water (mm)
ATMOSPHERIC MODELING NOISE

- USE LIEBE'S MPM TO STUDY THE ATMOSPHERIC TRANSMITTANCE AND RADIATION AT L (1.28&1.4 GHz) AND S (2.69&3.1GHz)
  - 3 NMC ANALYSIS IN MAY 1995
    - GLOBAL HUMIDITY, TEMPERATURE, AND PRESSURE PROFILES
  - SSM/I MONTHLY AVERAGED WATER VAPOR, CLOUD LIQUID WATER, AND CLOUD FRACTION FOR MAY 1995

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DTm (L)</th>
<th>DTm (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWP (mm)</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>VAPOR &amp; GASES</td>
<td>0.040</td>
<td>0.040</td>
</tr>
<tr>
<td>CLOUD (K)</td>
<td>0.000</td>
<td>0.020</td>
</tr>
<tr>
<td>RSS (K)</td>
<td>0.040</td>
<td>0.045</td>
</tr>
</tbody>
</table>
IONOSPHERE TEC MODELING NOISE

- **USE OF GPS NETWORK GLOBAL TEC MEASUREMENTS BEING EVALUATED**
  - MAYBE INADEQUATE FOR SOUTHERN OCEANS DUE TO LESS GPS COVERAGE
  - HOW WELL CAN THE TEC BETWEEN THE SURFACE AND SATELLITE AT 600 KM ALTITUDE BE ESTIMATED FROM GPS TEC?

- **ACCURACY OF L-BAND POLARIMETRIC U CHANNEL MEASUREMENTS FOR THE DETERMINATION OF FARADAY ROTATION**
  - $T_v$ and $Th$ ERRORS CAN BE REDUCED TO LESS THAN 0.08 K.

\[
\begin{array}{ccc}
\Delta U(K) & \Delta \chi \text{ (deg)} & \Delta T_v, \Delta Th \text{ (K)} \\
0.2 & <0.15 & <0.08 \\
\end{array}
\]
GEOPHYSICAL MODELING
ERROR ALLOCATION AT 1.4 GHZ

- KNOWLEDGE ACCURACY
- DATA FLAG IF THE NOISE IS LARGER THAN THE ALLOCATION
- *ASSUME L-BAND POLARIMETRIC RADIOMETER MEASUREMENTS FOR IONOSPHERIC CORRECTION

ERROR ALLOCATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dTm (K) 1 sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>0.05</td>
</tr>
<tr>
<td>Faraday Rotation*</td>
<td>0.08</td>
</tr>
<tr>
<td>Solar</td>
<td>0.15</td>
</tr>
<tr>
<td>Lunar</td>
<td>0.03</td>
</tr>
<tr>
<td>Galactic</td>
<td>0.05</td>
</tr>
<tr>
<td>HI</td>
<td>0.02</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>0.1</td>
</tr>
<tr>
<td>RSS</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Sea surface salinity mission simulated with realistic ocean fields for a conical scanning microwave radiometer and radar

The difference between the input and retrieved SSS fields depends on the instrument calibration errors, instrument sensitivity, and geophysical modeling uncertainty

Predicted accuracy of 0.2-0.3 psu weekly and 0.1-0.2 psu monthly meets the post 2002 EX-4 sss mission requirements for 0.2 K radiometer and 0.2 dB radar calibration stability.
OCEAN SALINITY RETRIEVAL SIMULATION

SSMI WVP AND CLOUD

Frequency
WVP
LQW
Surface Temperature

ATM MODEL

β, Tau, Tad

POCM SSS
SST
Surface Roughness

SEA SURFACE SCATTERING MODEL

(sea foam has not yet been modelled)

PIERSON MOSKOWITZ DURDEN Spectrum

RADIATIVE TRANSFER

e Ts

Tv and Th at 1.4 and 2.69 GHz
σ0 at 1.28 and 3.1 GHz

Salinity Retrieval (LSE)

DT: Sensitivity
dTr: Calibration noise
dTm: Modelling noise

Radar noise: Kpr and Kpc
OCEAN SALINITY RETRIEVAL ALGORITHM

T_v, T_h, U

FARADAY ROTATION CORRECTION

CORRECTED
T_v, T_h (L)
T_v, T_h (S)
\sigma_0 (OPTION)

IONOSPHERIC TEC

INITIALIZE
SSS, SST,
ROUGHNESS
(WIND SPD/DIR)

MODEL
T_v, T_h (L)
T_v, T_h (S)
\sigma_0 (OPTION)

FORWARD MODEL

DISTANCE MEASURE:
WEIGHTED LEAST SQUARE

SSS, SST

CONJUGATE
GRADIENT
ITERATION

SSS, SST
AND ETC.
ERROR BUDGET

- **RADIOMETER NEDT**
  - Modeled by white Gaussian noise

- **CALIBRATION STABILITY $\Delta T_r$**
  - Modeled by temporally correlated Gaussian noise (4 min correlation time)

- **GEOPHYSICAL MODELING NOISE $\Delta T_m$**
  - Spatially correlated (50 km correlation length)

<table>
<thead>
<tr>
<th></th>
<th>50km</th>
<th>100km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$ (K)</td>
<td>0.07</td>
<td>0.035</td>
</tr>
<tr>
<td>$\Delta T_m$ (K)</td>
<td>0.20</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Delta T_r$ (K)</td>
<td>0.20</td>
<td>0.2</td>
</tr>
<tr>
<td>RSS (K)</td>
<td>0.29</td>
<td>0.23</td>
</tr>
</tbody>
</table>

ANTENNA FOOTPRINT
GLOBAL SSS MISSION SIMULATION

- SSS Anomaly of Various Spatial Scales Well Retrieved
Salinity Retrieval Simulation (7 Days of Data)
19960915–19960921

Conical-Scan L/S-Band Dual-Pol Radiometer

Conical-Scan L/S-Band Dual-Pol Radiometer + L-Band Radar
Salinity Retrieval Simulation (4 Week Average)
19960915–19961012

Salinity Error (psu)

Conical-Scan L/S-Band Dual-Pol Radiometer
Conical-Scan L/S-Band Dual-Pol Radiometer + L-Band Radar

Latitude (deg)
In collaboration with GSFC, three successful PALS radiometer and radar flights across the Gulf Stream performed in July 17-19, 1999

- 3 Kelvin L-band brightness temperature change consistent with 5 psu salinity change measured by Cape Hatteras
- Surface roughness change detected by radar

Ready for ocean field campaign in 2000
• Flight on July 18 observed repeatable SSS signal in L-band Tb data across the Gulf Stream
• The surface appeared to be more uniform than that on July 17. Radiometer, radar, and ship data do not show a large change of surface roughness.
The change of surface roughness is noticeable in the radiometer and radar data between 74.7W-74.8W longitude - about 1 Kelvin in L-band Tv and 2 Kelvin in L-band Th.

The excess brightness temperatures due to the surface roughness are successfully removed by using the radar data with an empirical linear correction (ΔTb=A σh). A=300 for Tv and 600 for Th. The values of A agree with the theoretical expectations that h-polarization is more sensitive to the surface roughness than v-polarization. The corrected brightness temperatures (Tv' and Th') vary around their mean values by a standard deviation of about 0.2 K.
L-band Tv data from the flight adjacent to the Oleander track show a drift of about 0.5-0.6 Kelvin from the beginning to the end of the flight line (west to east). This change appears to correspond to the SSS change of about 0.8 psu. Note that 0.8 psu x 0.6 K/psu = 0.48 Kelvin.
SUMMARY

- PROJECTED SALINITY MEASUREMENT ACCURACY MEETS THE SCIENCE REQUIREMENT FOR CONICAL SCANNER
  - CONICAL SCAN SUPERIOR TO CROSS-TRACK SCAN
- EXCELLENT CALIBRATION STABILITY REQUIRED
- EXCELLENT ANTENNA CHARACTERISTICS REQUIRED TO REDUCE THE IMPACT OF SOLAR RADIATION
- ACCURATE CORRECTION OF FARADAY ROTATION, SURFACE ROUGHNESS AND GALACTIC RADIATION SOURCES REQUIRED
- AIRCRAFT PALS RADIOMETER/RADAR MEASUREMENTS IN JULY 1999 DEMONSTRATE FEASIBILITY
FEASIBILITY AND ERROR SOURCES FOR OCEAN SURFACE SALINITY MEASUREMENTS FROM SPACE

APPENDIX

L-BAND RADIO CLUTTER STUDY

KYOTO
6-10 DECEMBER 1999
GALACTIC RADIATION

• GALACTIC RADIATION AT 1.4 GHZ

<table>
<thead>
<tr>
<th>SOURCES</th>
<th>BRIGHTNESS</th>
<th>KNOWLEDGE (1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GALACTIC CENTER</td>
<td>16 K</td>
<td>0.16K</td>
</tr>
<tr>
<td>GALACTIC POLE</td>
<td>1 K</td>
<td>0.01K</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>2.7 K</td>
<td>0.027K</td>
</tr>
</tbody>
</table>

• DATA LOSS VERSUS THE ANGULAR EXTENT OF DATA FLAG

<table>
<thead>
<tr>
<th>CASE</th>
<th>ANGULAR EXTENT</th>
<th>#BEAM WIDTH (3 DEG)</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20 DEG X 10 DEG NEAR THE GALACTIC CENTER</td>
<td>6 X 3</td>
<td>2X20/360X10/360&lt; 0.3%</td>
</tr>
<tr>
<td>2</td>
<td>10 DEG</td>
<td>+/- 1.5</td>
<td>10/360 &lt; 3%</td>
</tr>
</tbody>
</table>

CASE 1: GALACTIC CENTER IS ON THE ORBIT PLANE
CASE 2: GALACTIC CENTER IS ON THE ORBITAL AXIS
SOLAR RADIATION AND GEOMETRY

- 6AM-6PM ORBIT
  - ORBIT AXIS FACES THE SUN
- WHEN THE ANTENNA BEAM IS LOOKING TOWARD THE SUN IN AZIMUTH
  - SUN IS 86.2° FROM THE BORESIGHT OF FEEDHORN
  - DIFFUSE SURFACE SCATTERING INTO THE MAIN BEAM
  - SPECULAR REFLECTION BY THE SURFACE INTO THE SIDELOBE AT 26° FROM THE BORESIGHT
Apparent Antenna Temperature of Solar Radiation

Sun $T_s=100,000$ K, $D_{ant}=37.5$ dB, $D_{feed}=15$ dB

- Max. Specular/sidelobe
- Feedhorn
- Max. Diffused/Main Beam

Antenna and Feed Gain Pattern (dB)
LUNAR RADIATION

• LUNAR RADIATION

<table>
<thead>
<tr>
<th>WAVELENGTH</th>
<th>BRIGHTNESS ($T_B$)</th>
<th>SIZE OF LUNAR DISK ($\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.15 cm</td>
<td>180-200 K</td>
<td>0.215 DEG²</td>
</tr>
<tr>
<td>1.25 cm</td>
<td>200-300 K</td>
<td></td>
</tr>
</tbody>
</table>

• APPARENT ANTENNA TEMPERATURE = $T_B \Omega P_n / \Omega_A$

<table>
<thead>
<tr>
<th>$P_n$</th>
<th>ANT. TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>&lt; 30K</td>
</tr>
<tr>
<td>-30 dB</td>
<td>&lt; 0.03K</td>
</tr>
</tbody>
</table>

• DATA LOSS VERSUS THE ANGULAR EXTENT OF DATA FLAG

<table>
<thead>
<tr>
<th>CASE</th>
<th>ANGULAR EXTENT</th>
<th>#BEAM WIDTH (3 DEG)</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 DEG X 5 DEG</td>
<td>3 X 1.5</td>
<td>2X10/360X5/360 &lt; 0.1%</td>
</tr>
<tr>
<td></td>
<td>NEAR THE MOON</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10 DEG</td>
<td>+/- 1.5</td>
<td>10/360 &lt; 3%</td>
</tr>
</tbody>
</table>

CASE 1: MOON IS ON THE ORBIT PLANE
CASE 2: MOON IS ON THE ORBITAL AXIS
HYDROGEN LINE

- HYDROGEN LINE AT 1.4 GHZ
  - BANDWIDTH: ~ 1 MHz
  - AVG. BRIGHTNESS: 50 K

- APPARENT ANTENNA TEMPERATURE

<table>
<thead>
<tr>
<th>RECEIVER BANDWIDTH</th>
<th>TA</th>
<th>KNOWLEDGE (2%* TA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 MHZ</td>
<td>2K</td>
<td>0.04K</td>
</tr>
<tr>
<td>100 MHZ</td>
<td>0.5K</td>
<td>0.01K</td>
</tr>
</tbody>
</table>