Ultra Stable Microwave Radiometers for Future Sea Surface Salinity Missions

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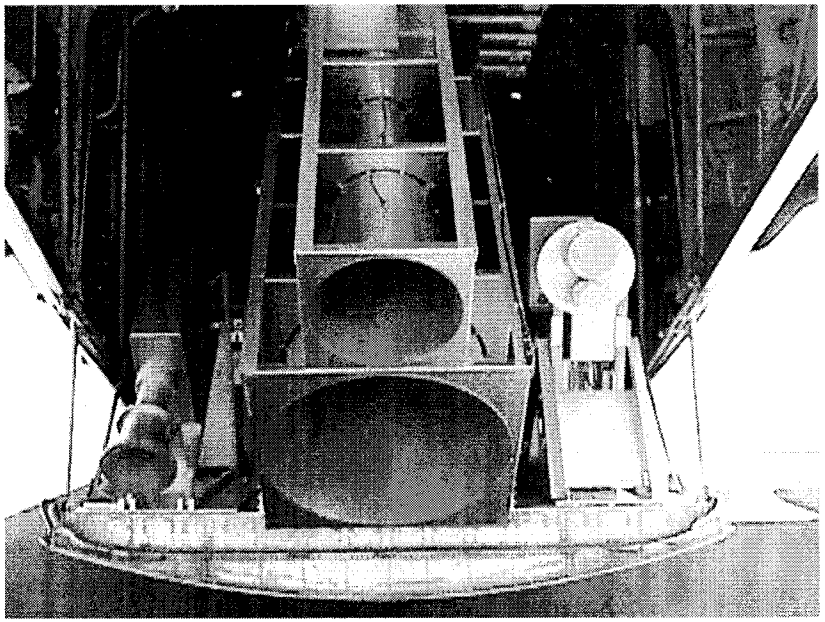
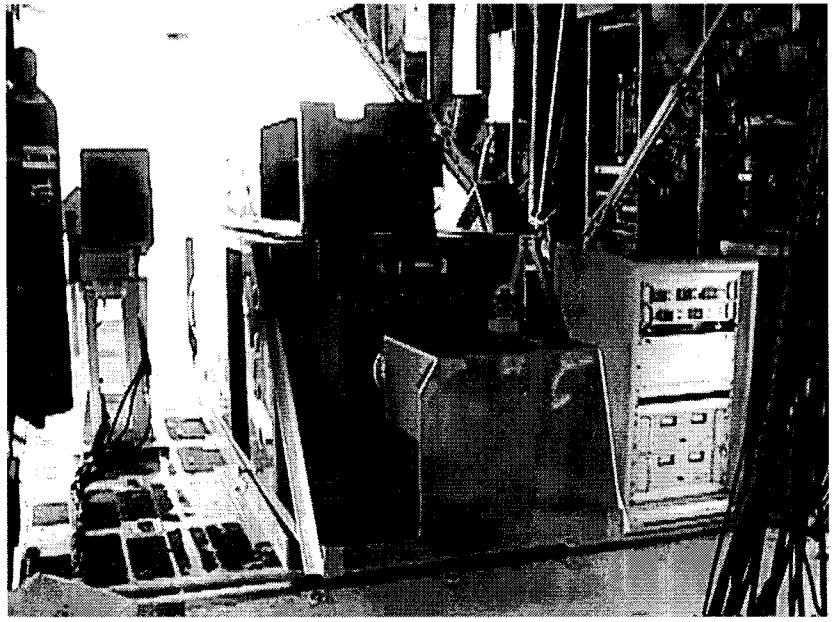
Overview

- Requirements for Salinity Measurements
- Passive Active L/S-band (PALS) Instrument
  - Latest design
  - Sky measurements
  - Ocean measurements
- AQUARIUS Salinity Mission

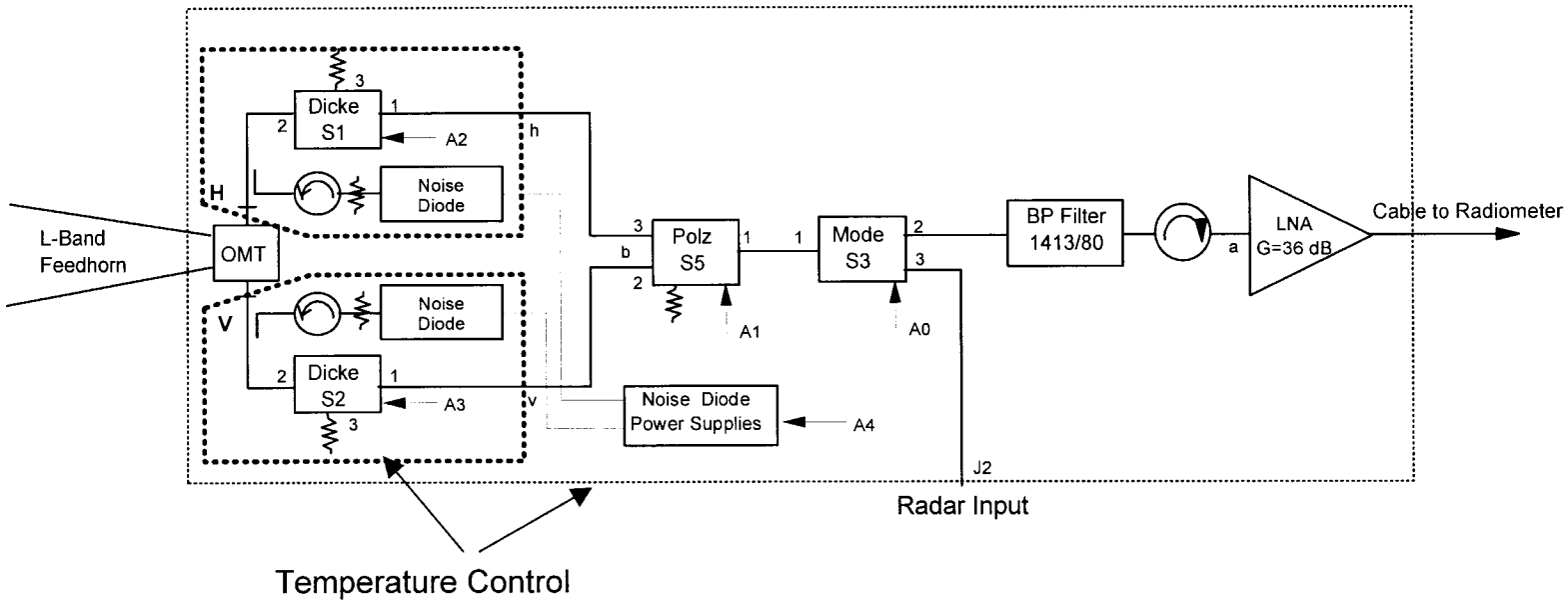
- **Goal: Develop L-band radiometers to have low NEDT and calibration stabilities of ≤ 0.05 K over 2 days**
- **Future Sea Surface Salinity (SSS) missions will require SSS measurements with accuracy of 0.1 psu and with spatial resolutions < 50 km**
- **System Constraints: At microwave frequencies, with large antenna feedhorns, it is not possible to calibrate with external thermal loads through the feedhorn because the loads would be large, and have temperature variations**
- **Radiometer calibration must be done following the feedhorn using noise diodes and reference switch, and corrections must be made for front-end components**

PALS on C-130 Aircraft

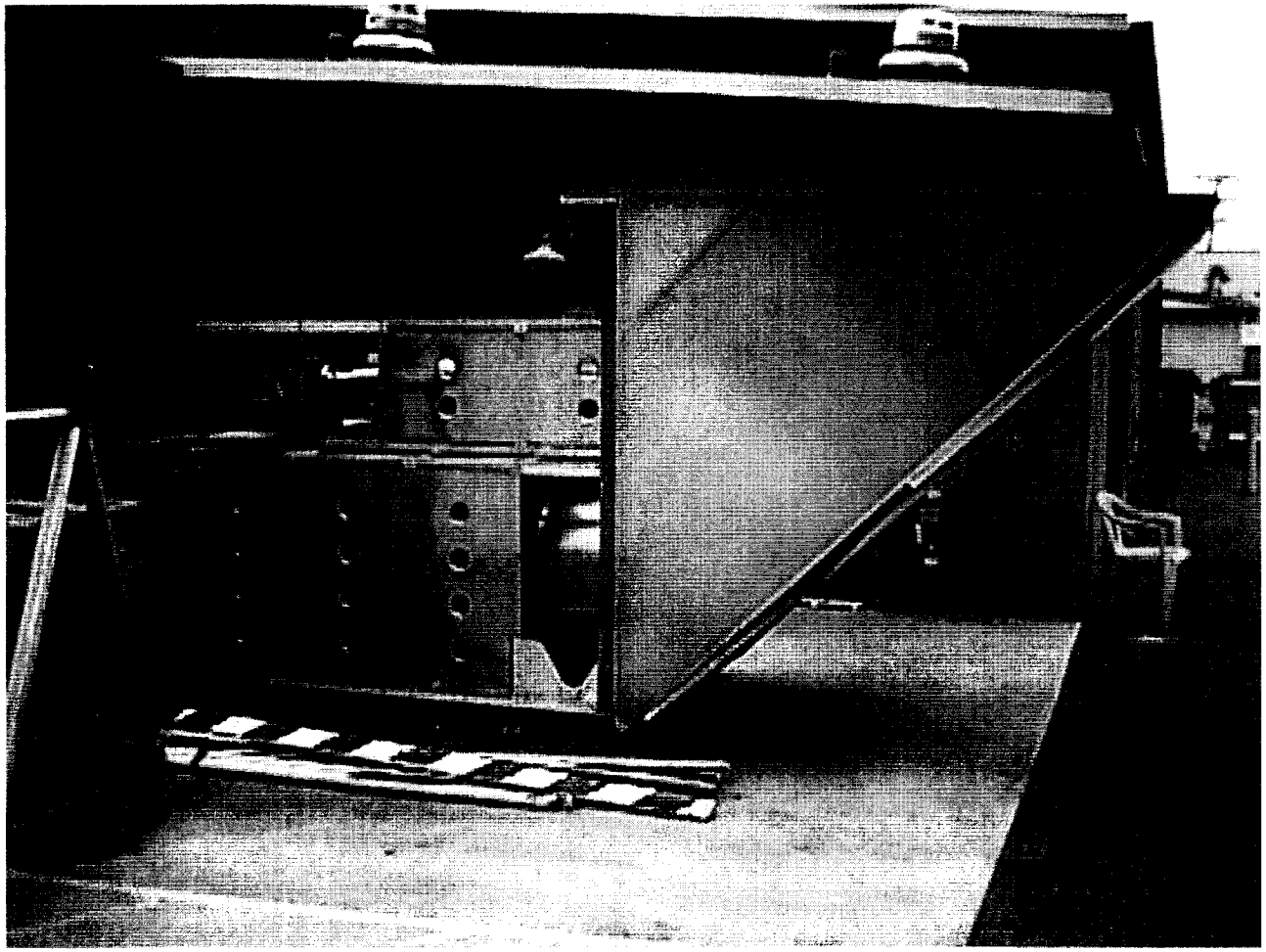




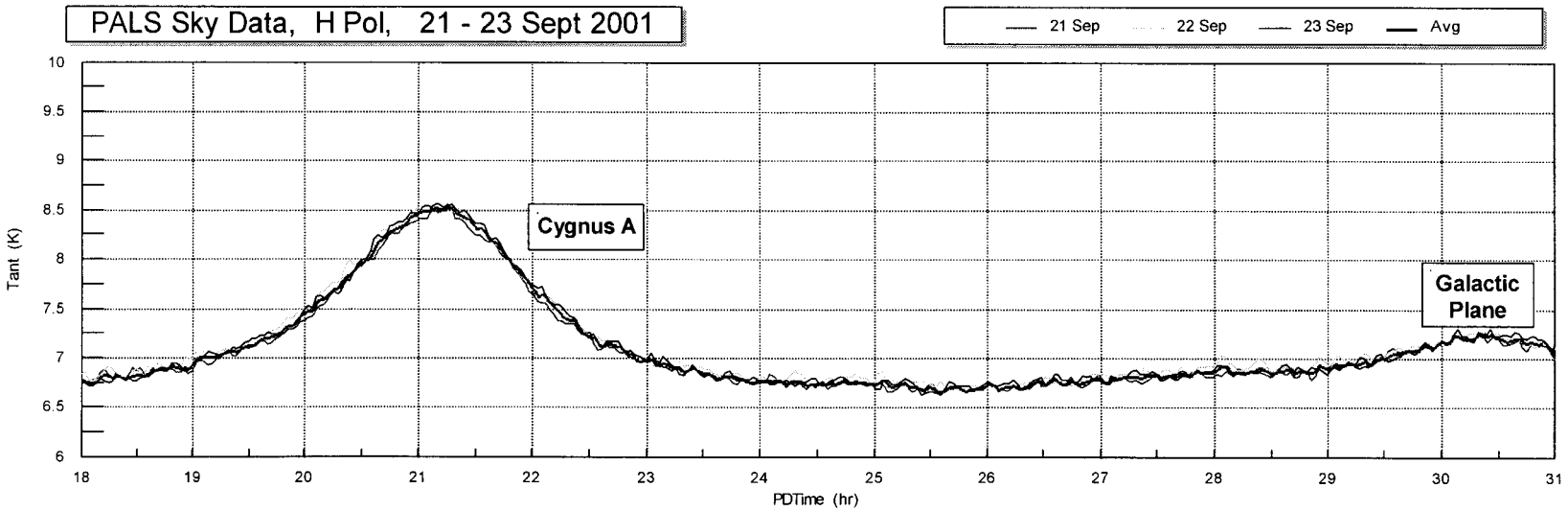
PALS L-band Front End



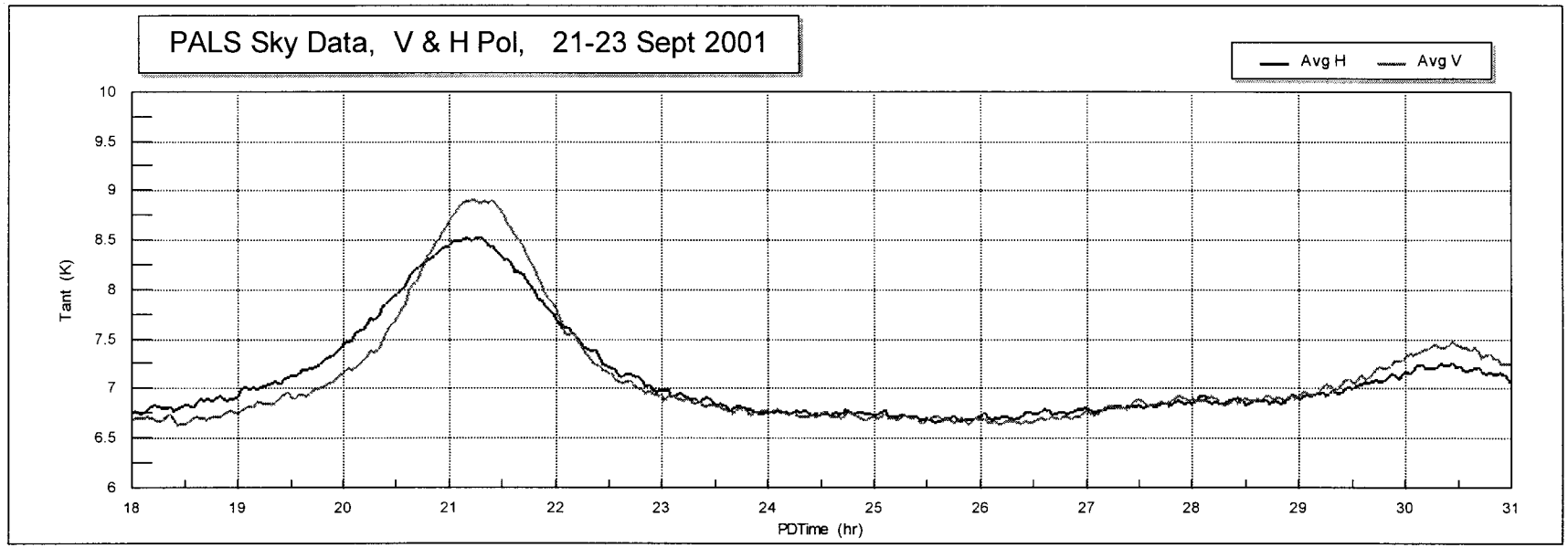
PALS instrument in sky measurement



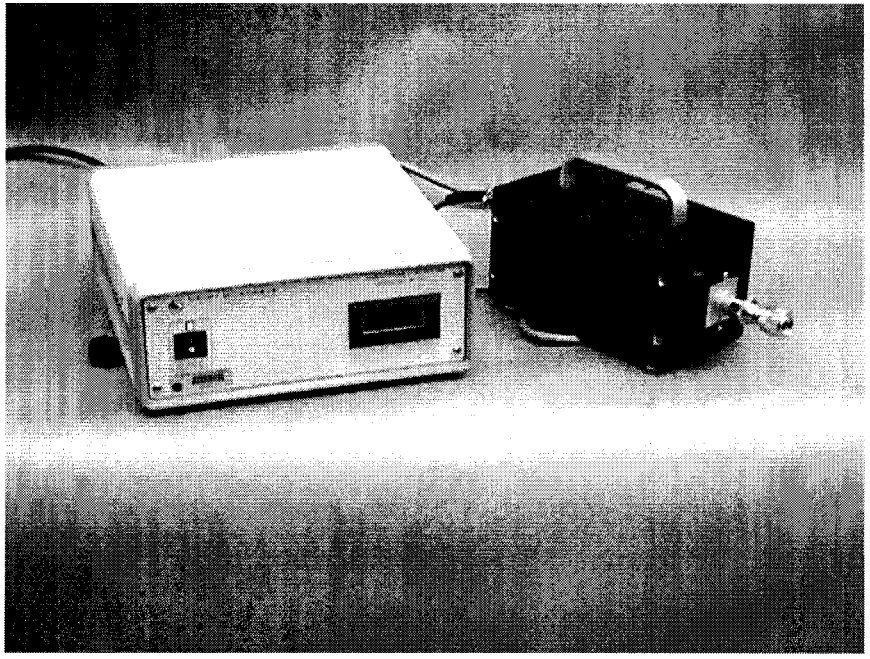
Zenith sky data taken during the PALS sky calibration experiment on 21 - 23 September 2001



Vertical and Horizontal Polarization Zenith Sky Data



Precision Thermal Hot Load (100° C)



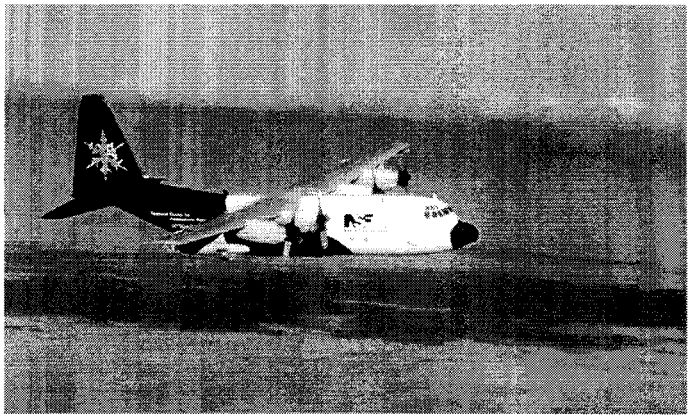
Maury Calibration Hot Load

(MT 7108B22)

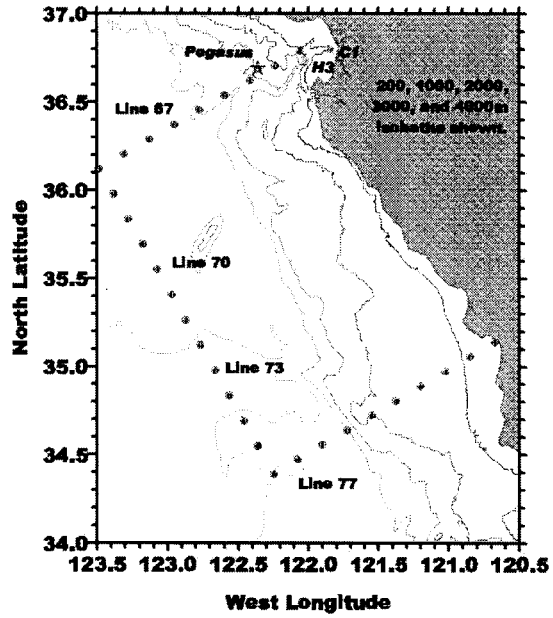
Calibration tests with the precision hot load showed repeatability within 0.1 K RMS over the two month period from May through July 2002

PALS RADIOMETER MEASUREMENTS FOR REMOTE SENSING OF OCEAN SALINITY

NCAR C-130 aircraft used for PALS Mission

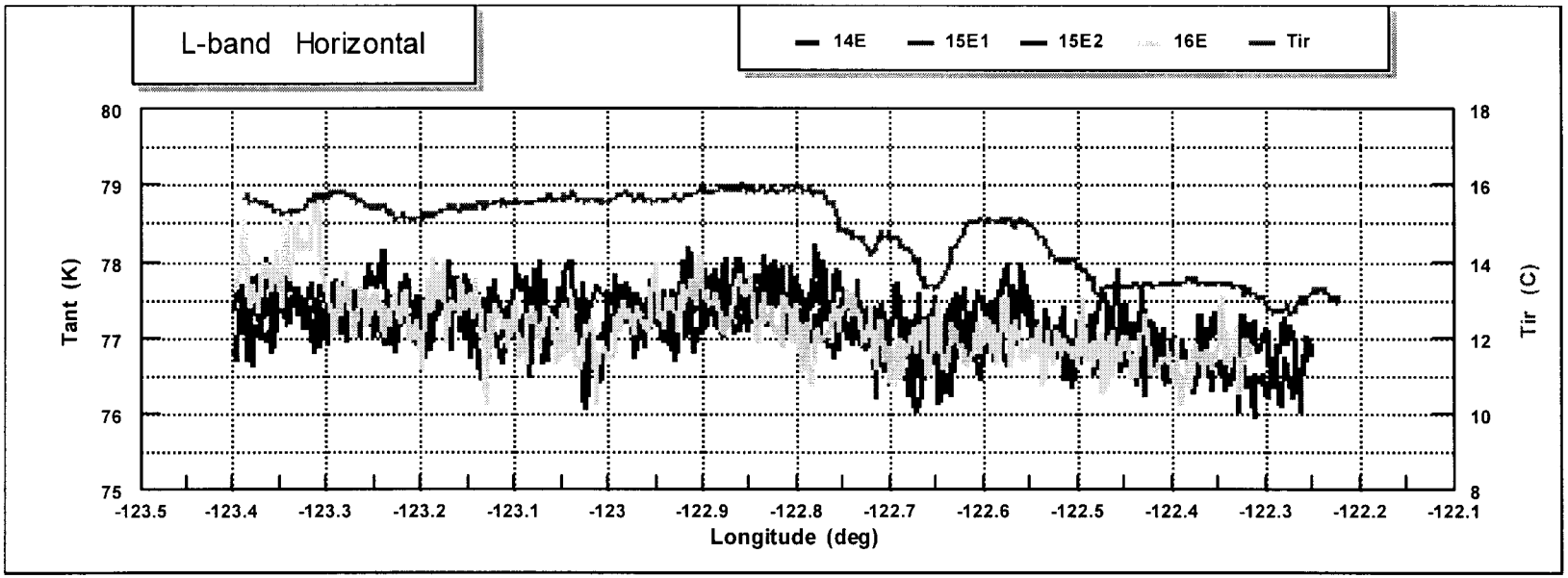


OC3570 Cruise Planning (Leg I)



Area of Sea Surface Salinity (SSS) measurements made from July 14 to 19, 2002, which is West and South of Monterey CA. The Pt. Sur ship measured the SSS and Sea Surface Temperature (SST).

PALS instrument for 2002 Salinity Measurements

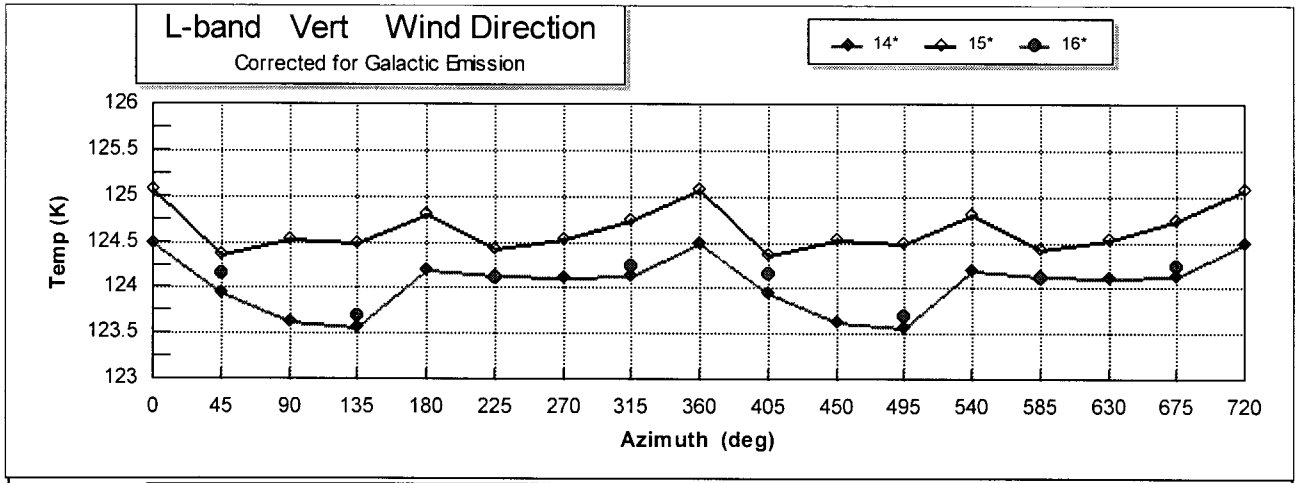


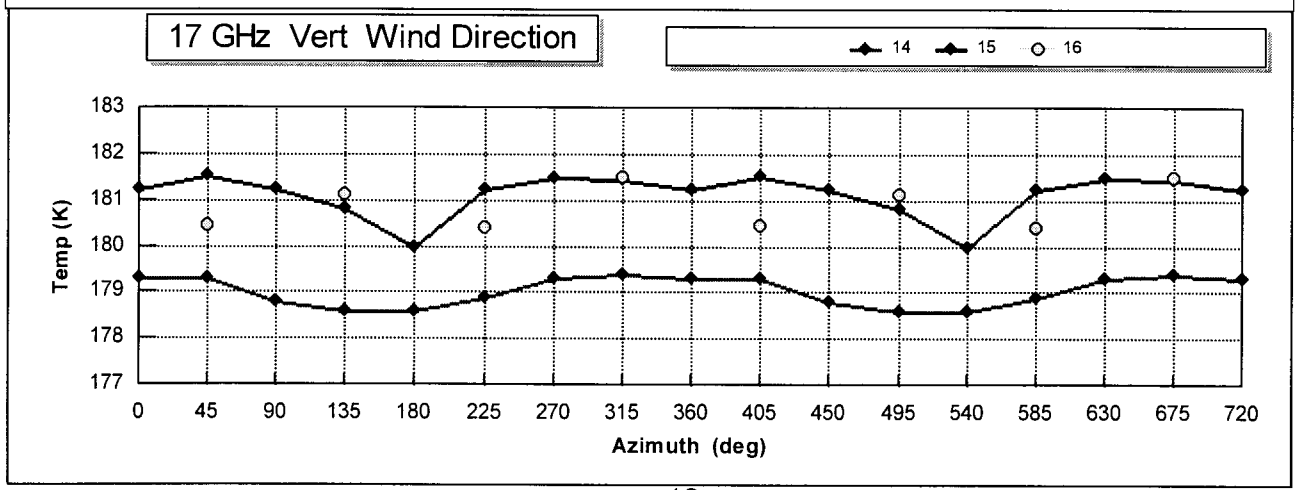
The East bound L-band H-polarization radiometer data on Line 67 from July 14 to July 16. No corrections have been made for surface roughness.

This plot shows the excellent stability of the PALS instrument within 0.2 K over the 3-day period.

μCal 02 Radiometers for Ocean Salinity Measurements

Wind direction signal around MBARI Mooring M2 on July 14-16, 2002. The wind speed was ~8 m/s at direction 320 deg. Corrections were made for galactic emission reflection. The 17 GHz wind direction signal is plotted for comparison, since it is stronger directional signal.





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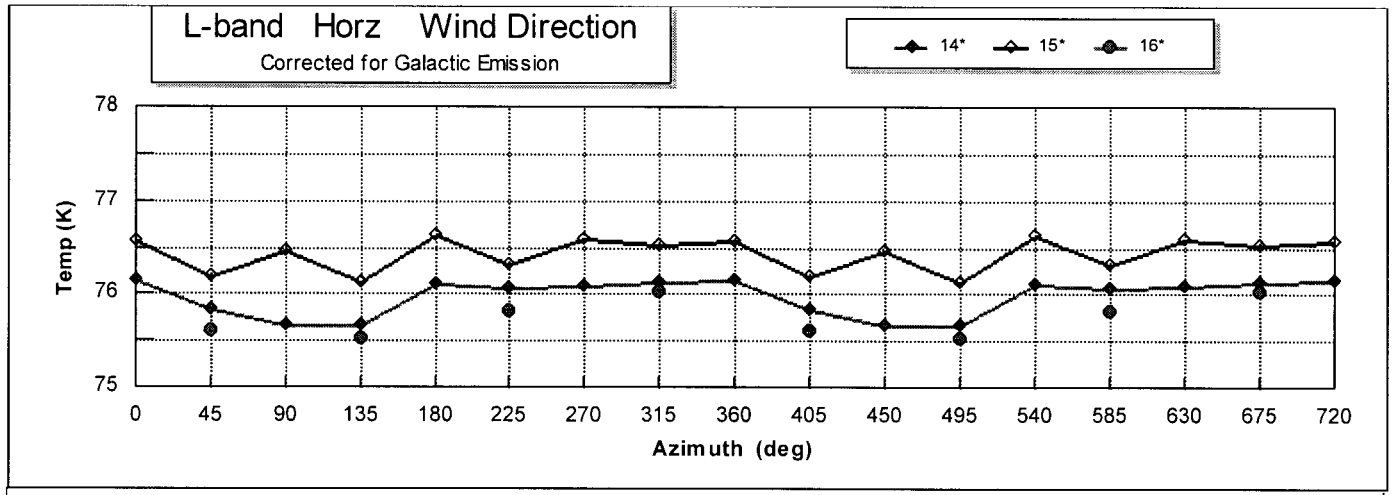

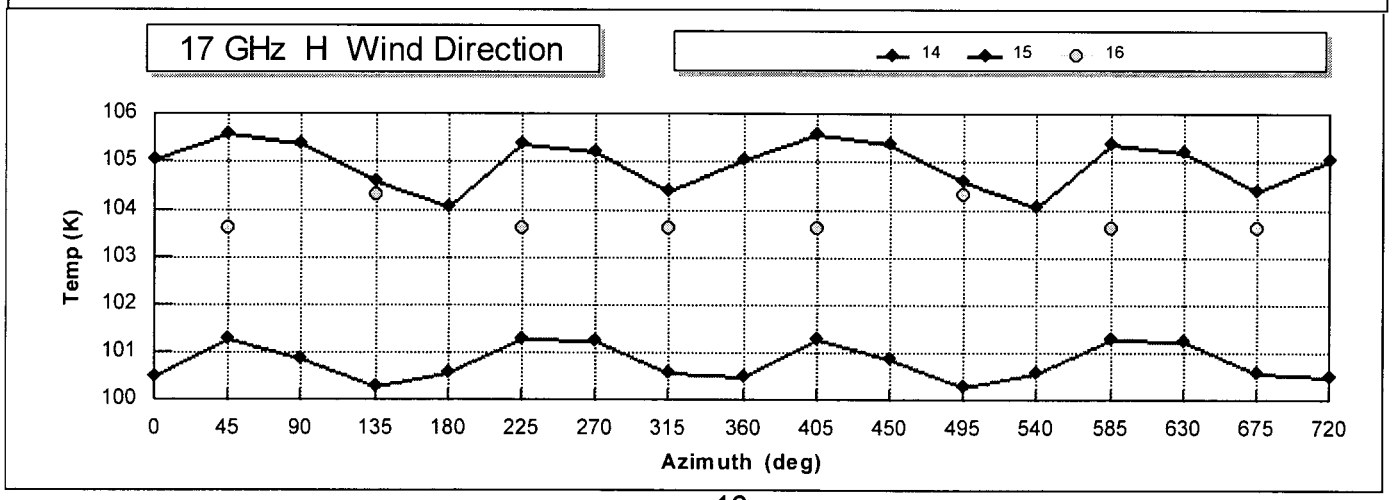

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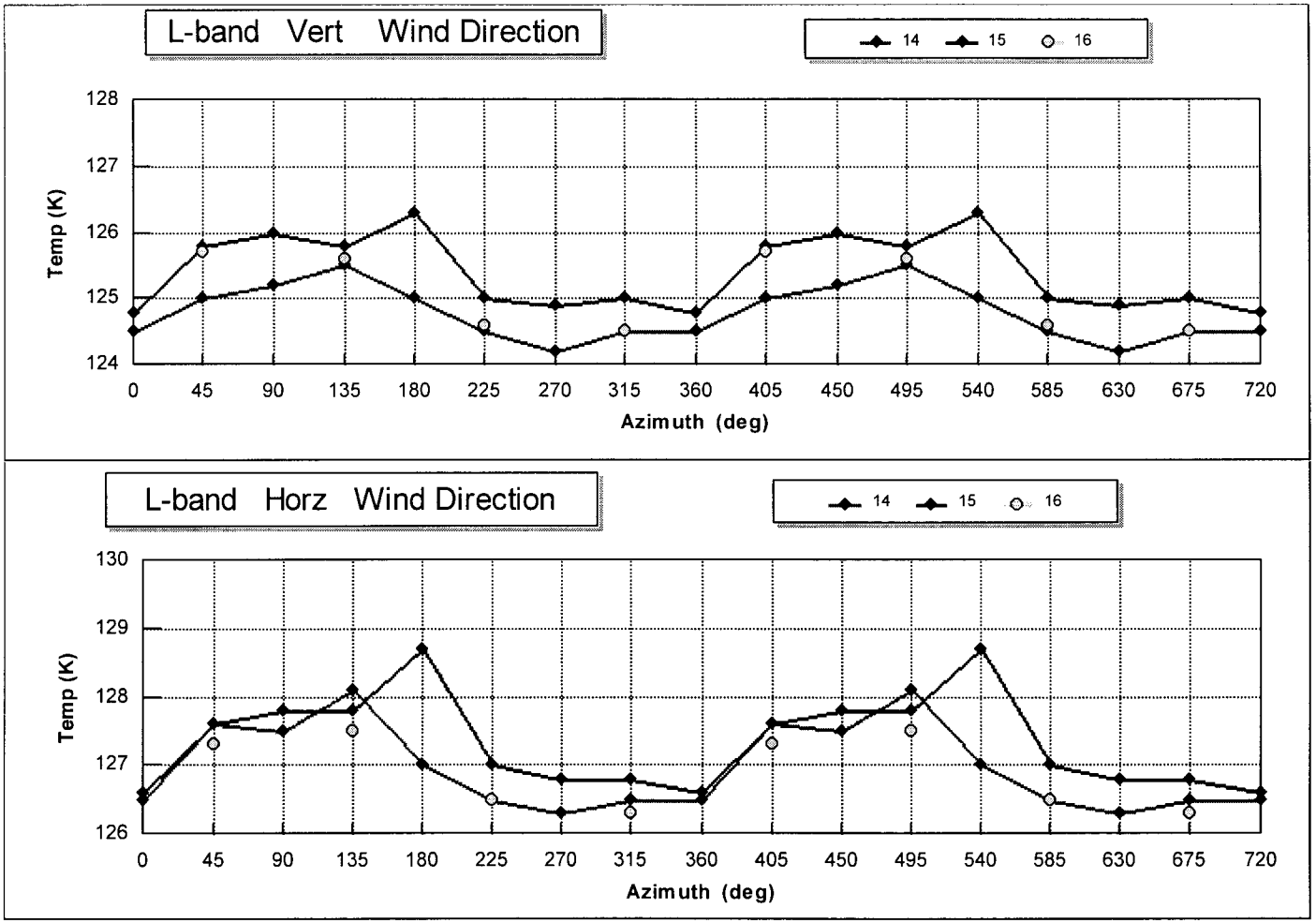
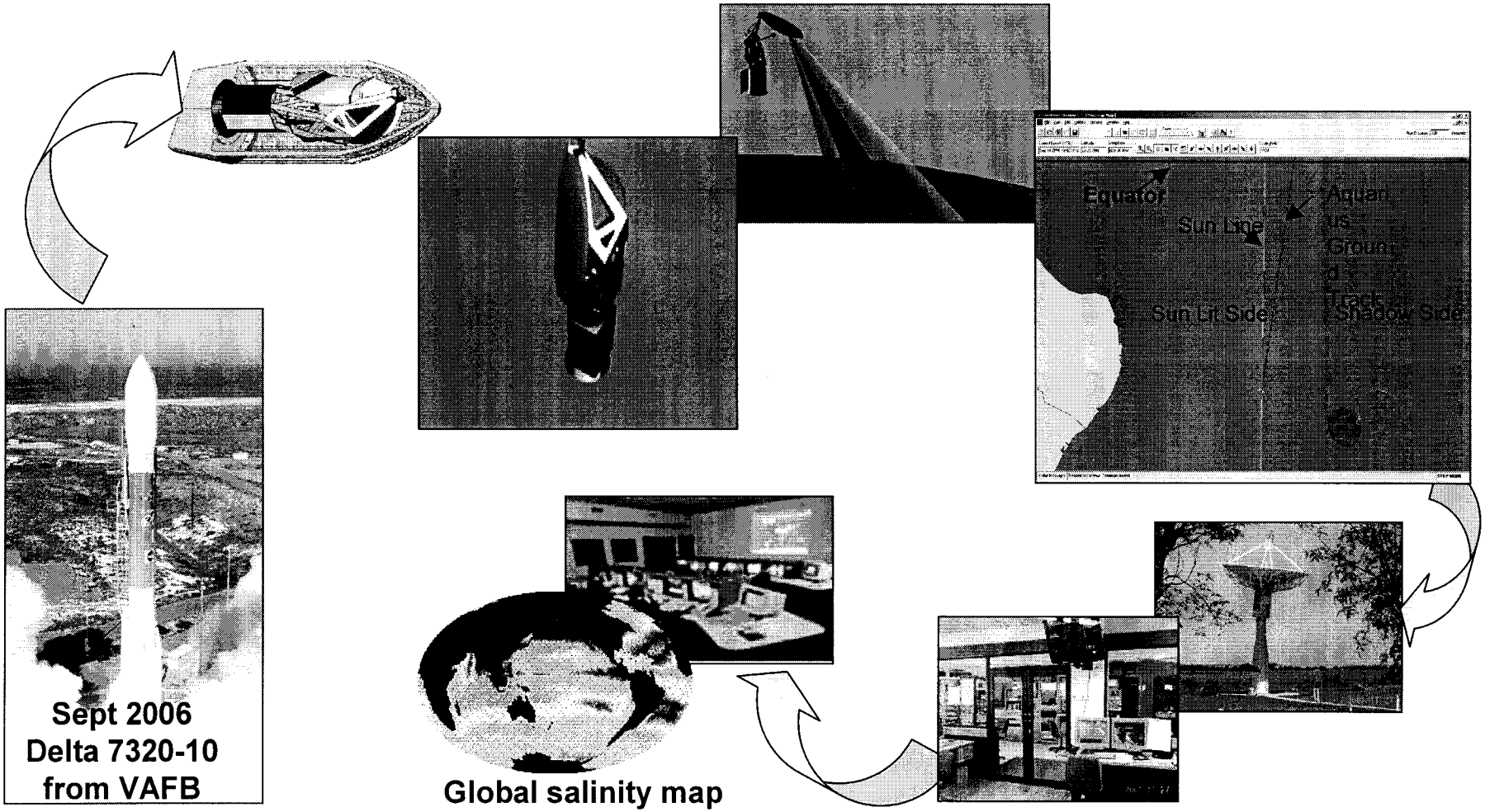
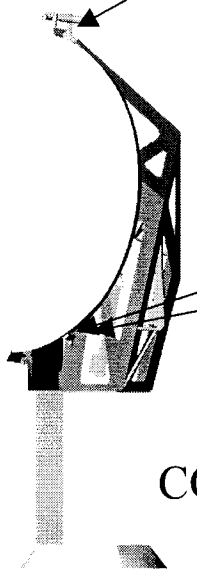
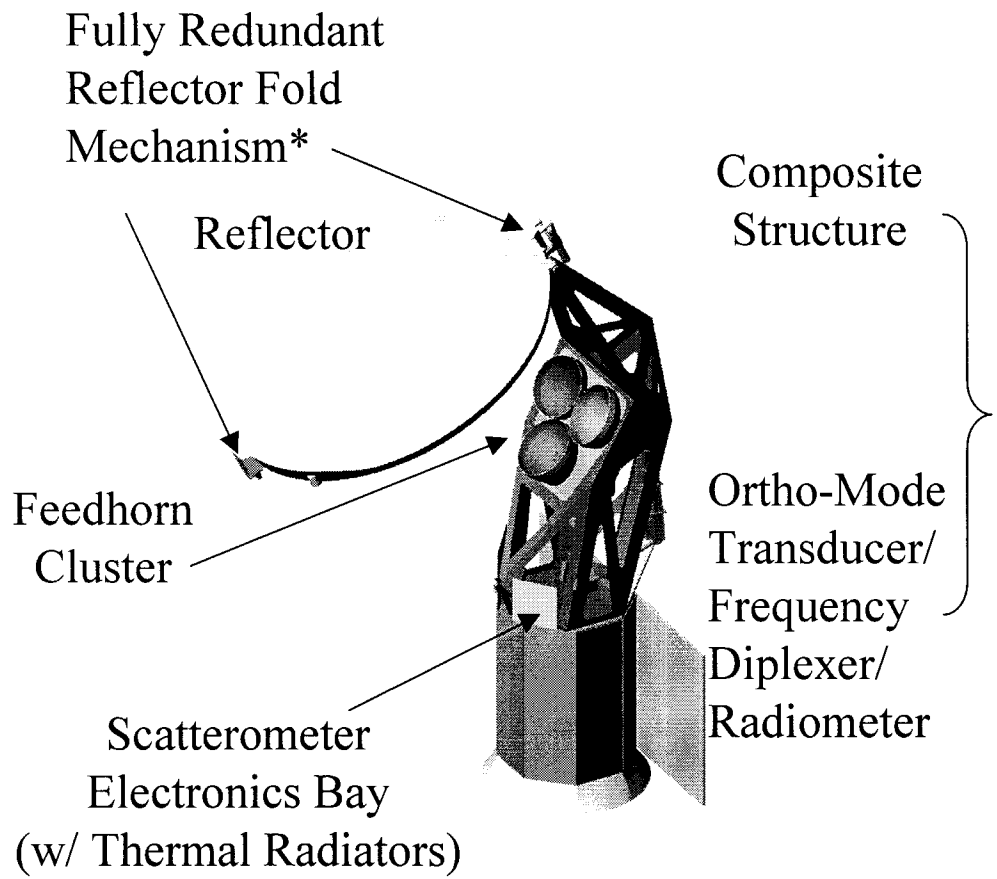


AQUARIUS Mission Overview



μCal 02 Radiometers for Ocean Salinity Measurements





Summary

- Excellent stability (± 0.2 K)was achieved with the PALS instrument both in the laboratory and on aircraft flights over the ocean.
- The key factor was the precise temperature control of the front-end components: OMT, Noise Diodes and Dicke Switches
- The AQUARIUS salinity mission was selected for the NASA ESSP program. This instrument will require Ultra-Stable radiometers in the Sea Surface Salinity measurements.

Ultra Stable Microwave Radiometers

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9 October 2002

Overview

- Basic Radiometer Model
- Optimum for NEDT
- Sensitivities
- Radiometer Testbed
    - Block Diagram
    - Circuits
    - Results
- Summary

Ultra-Stable Radiometer

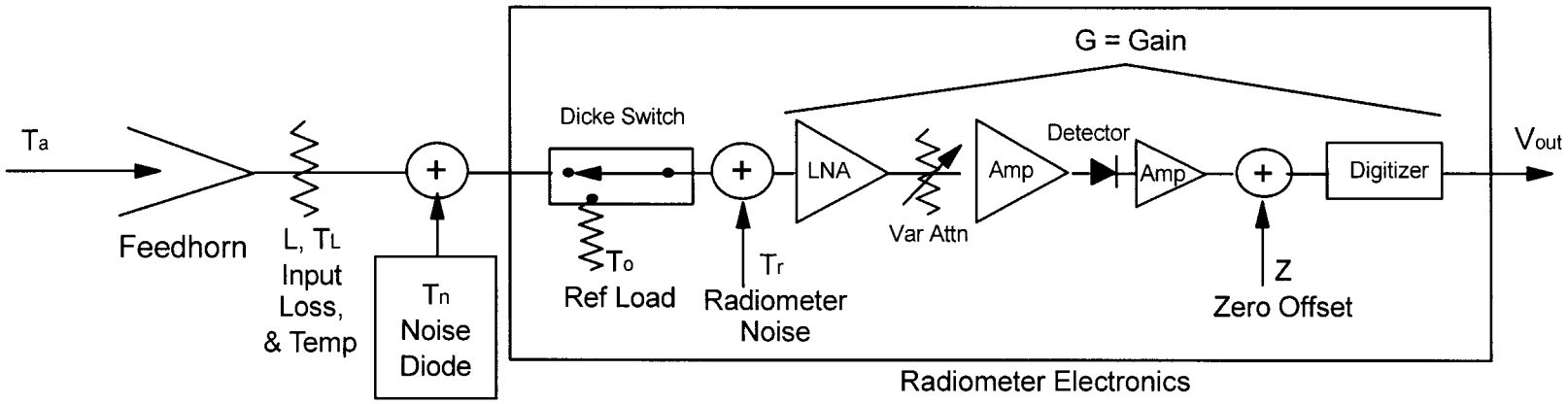
- **Goal: Develop L-band radiometers to have low NEDT and calibration stabilities of $\leq$ 0.05 K over 2 days**

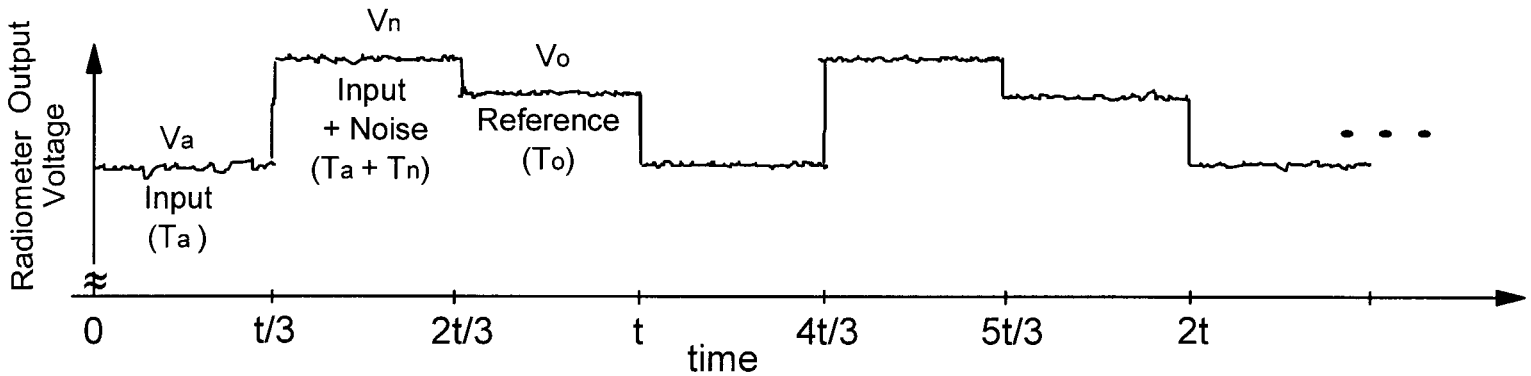
- **System Constraints: At microwave frequencies, with large antenna feedhorns, it is not possible to calibrate with external thermal loads through the feedhorn because the loads would be large, and have temperature variations**

- **Radiometer calibration must be done following the feedhorn using noise diodes and reference switch, and corrections must be made for front-end components**

Ultra-Stable Radiometer

Goddard Space Flight Center





Ultra-Stable Radiometer

Antenna: $V_a = G*(T_a/L + T_L*(1 - 1/L) + T_R) + Z$

T_a = antenna temperature

T_L = input loss temperature

L = input loss

T_R = radiometer noise temperature at switch input

G = Gain of radiometer

Z = Zero offset of output circuits

Antenna + Noise: $V_n = V_a + G*(T_n)$

T_n = noise diode temperature

Reference: $V_o = G*(T_o + T_R) + Z$

T_o = reference load temperature.

Antenna Temperature Calculation

$$T_a = T_L + L * \left[T_o - T_L - \frac{(V_o - V_a)}{(V_n - V_a)} * T_n \right]$$

- However, the temperatures T_L, T_o and T_n, must be known to a high precision, and loss L must be stable
- Advantage is that all the variable radiometer parameters (T_R, G, and Z) are either subtracted or divided out

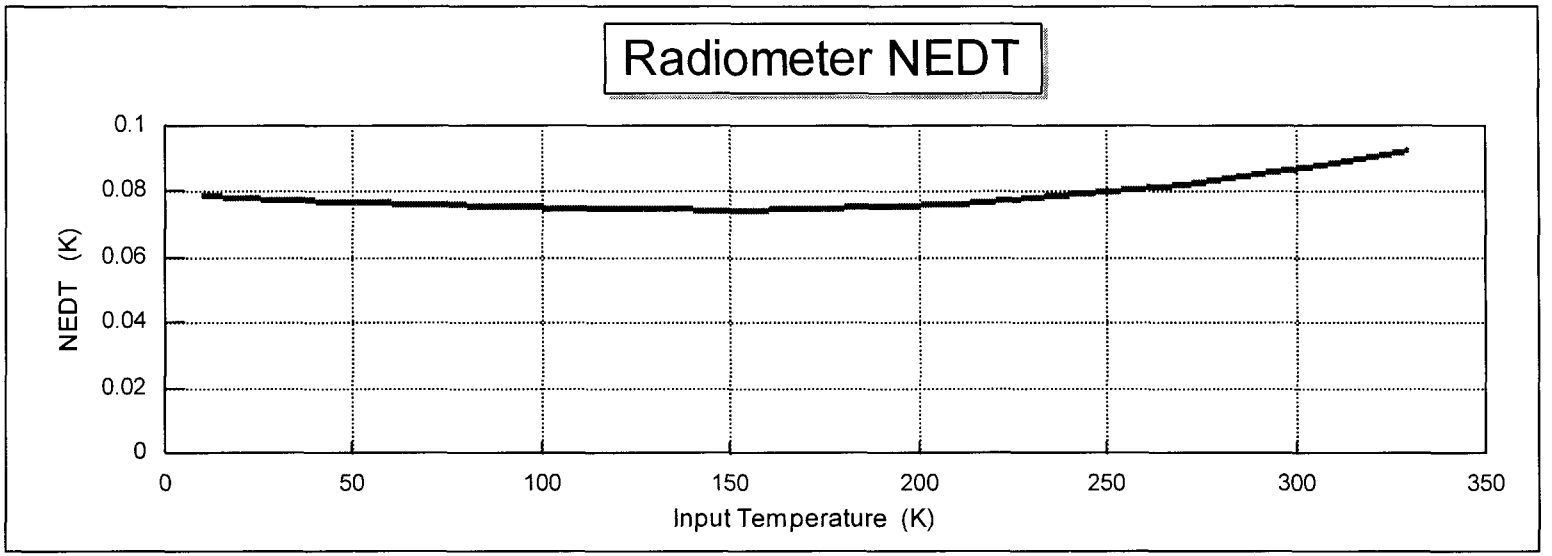
NEDT Calculation

Let $V_i = \langle V_i \rangle * (1 + \delta_i)$, then

$$\Delta T_a = L * \sqrt{\frac{3}{B\tau}} * \sqrt{(T_o + T_r)^2 + (T_1 + T_r + T_n)^2 * \left[\frac{T_o - T_1}{T_n}\right]^2 + (T_1 + T_r)^2 * \left[1 - \frac{T_o - T_1}{T_n}\right]^2}$$

where $T_1 = \frac{T_a}{L} + T_L * \left(1 - \frac{1}{L}\right)$

Ultra-Stable Radiometer



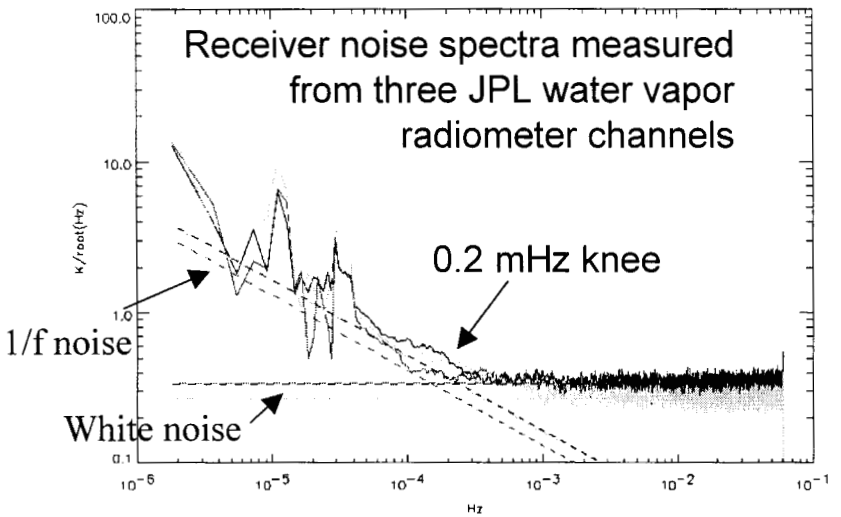
Radiometer NEDT using 3-position switching sequence. A set of parameters that is representative for ocean measurements with the Aquarius radiometer: T_o = 295 K, T_r = 250 K, T_n = 500 K, L = 1, B = 20 MHz and τ = 12 sec, were used for this plot. This NEDT is ~3 times that of the ideal total power radiometer.

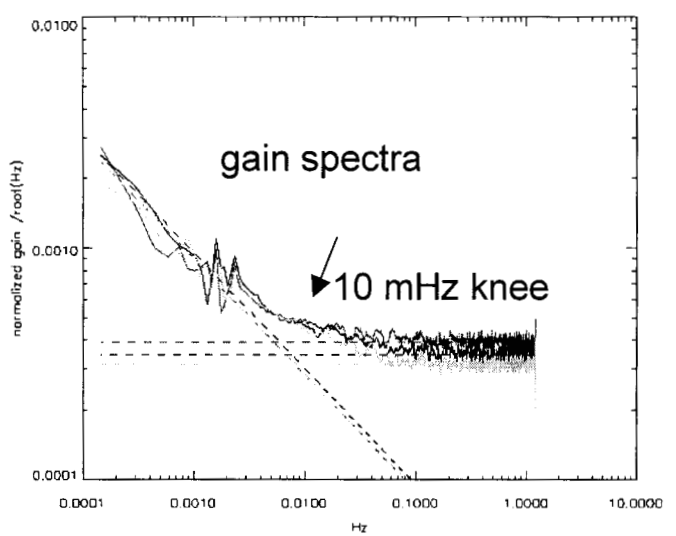
Modeling: Noise Equivalent Delta-T (NEDT)

Objective is to determine optimum timing of calibration sources (noise diodes and Dicke switch).

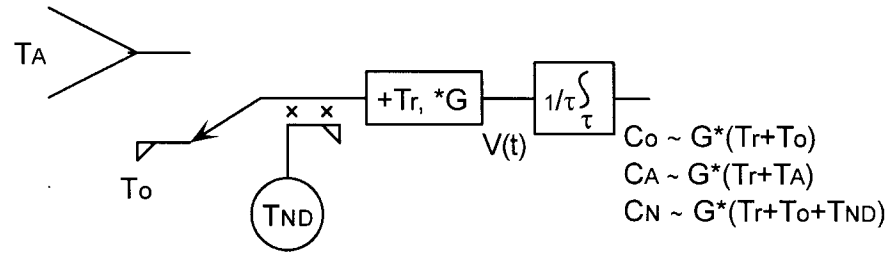
New model has been developed which accounts for separate spectra of receiver noise temperature (T_R) and gain (G)

Idea is to form running averages of G and T_R and then adjust the duty cycle of noise diode and reference load until antenna temperature error (NEDT) is minimized

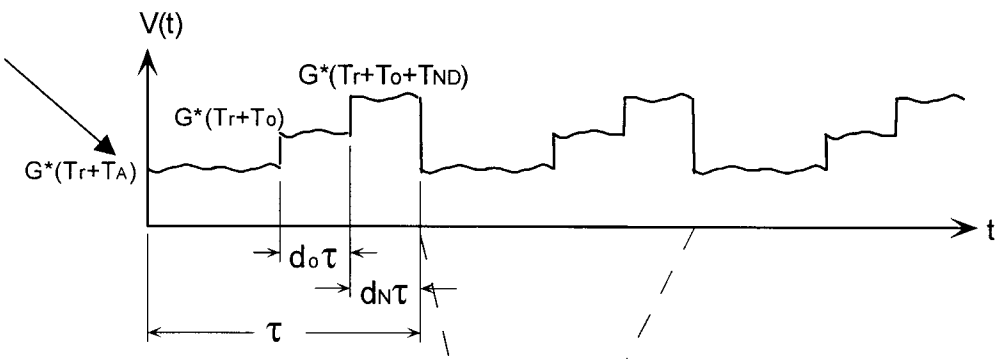




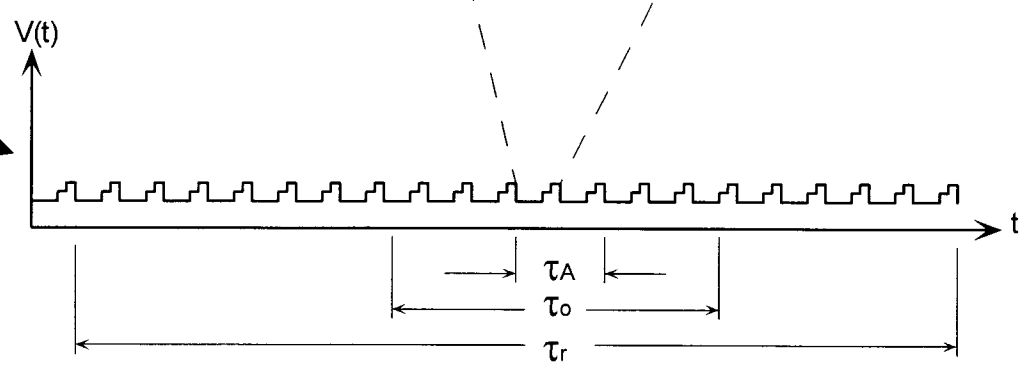
NEDT model (cont): Radiometer timing model



Reference and noise diode are measured with duty cycles, d_o and d_n, within a short measurement cycle, τ.



Antenna brightness temperatures are estimated within the interval τ_A based on τ_o second average of gain and τ_r second average of recever noise temperature.



Ultra-Stable Radiometer

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T_a = antenna temperature

L = input loss

T_L = input loss temperature

Reference: $V_o = G*(T_o + T_R) + Z$

G = Gain of radiometer

T_o = reference load temperature

T_R = radiometer noise temperature at switch input

Z = Zero offset of output circuits

Reference + Noise: $V_n = V_o + G*(T_n)$

T_n = noise diode temperature

Ultra-Stable Radiometer

Gain:

$$G = \frac{\langle V_n - V_o \rangle}{T_n}$$

Receiver Noise:

$$T_R = \langle \frac{V_o - Z}{G} - T_o \rangle$$

Antenna Temperature:

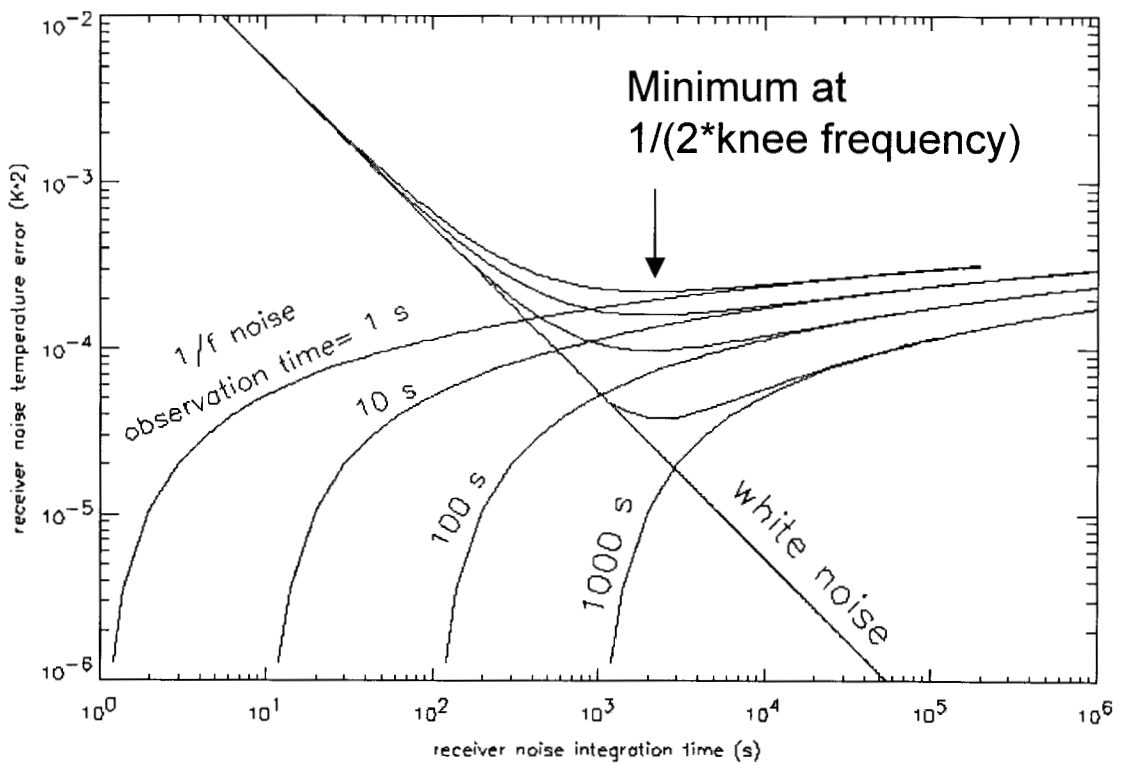
$$T_a = L * \left[\frac{V_a - Z}{G} - T_R \right] - T_L * (L - 1)$$

NEDT model (cont.):

Optimum receiver noise estimation

Model predicts NEDT versus τ_r for a given receiver noise spectra and observation time τ_A

Similar solution formed for gain estimate



Duty cycles are determined numerically from forward calculation of NEDT for given t_A

Optimum for 12 s observations:

- 10% duty cycles for reference and noise diode
- 342 second running average of gain
- >5000 second running average of receiver noise

```
; test case for Aquarius
Tr=250. ; receiver noise temp (K)
To=295. ; reference temp (K)
Ta=100.  ; antenna brightness temperature (K)
BW=20e+6 ; bandwidth (Hz)
Tnd=500.  ; noise diode deflection (K)
br=1.34e-10 ; 1/f spectra coefficient of normalized Tr (/Hz)
bg=7.3e-10  ; normalized gain 1/f spectra coefficient (/Hz)
```

NEDT	/TP	τ_A	τ_r	τ_o	d_o	d_N
0.253	1.02	0.1	5000.	3424.7	0.01	0.01
0.253	1.02	0.1	5000.	3424.7	0.01	0.01
0.0864	1.10	1.0	5000.	1369.9	0.03	0.02
0.0865	1.11	1.0	5000.	1141.6	0.03	0.03
0.0350	1.42	10.0	5000.	380.5	0.12	0.06
0.0351	1.42	10.0	5000.	380.5	0.09	0.09
0.0329	1.46	12.0	5000.	342.5	0.13	0.07
0.0330	**1.46**	**12.0**	**5000.**	**342.5**	**0.10**	**0.10**
0.0159	2.03	100.0	5000.	152.2	0.30	0.15
0.0160	2.04	100.0	5000.	148.9	0.23	0.23

This NEDT is ~1.5 times that of the ideal total power radiometer

Sensitivity Analysis for $\Delta T_a < 0.025$ K

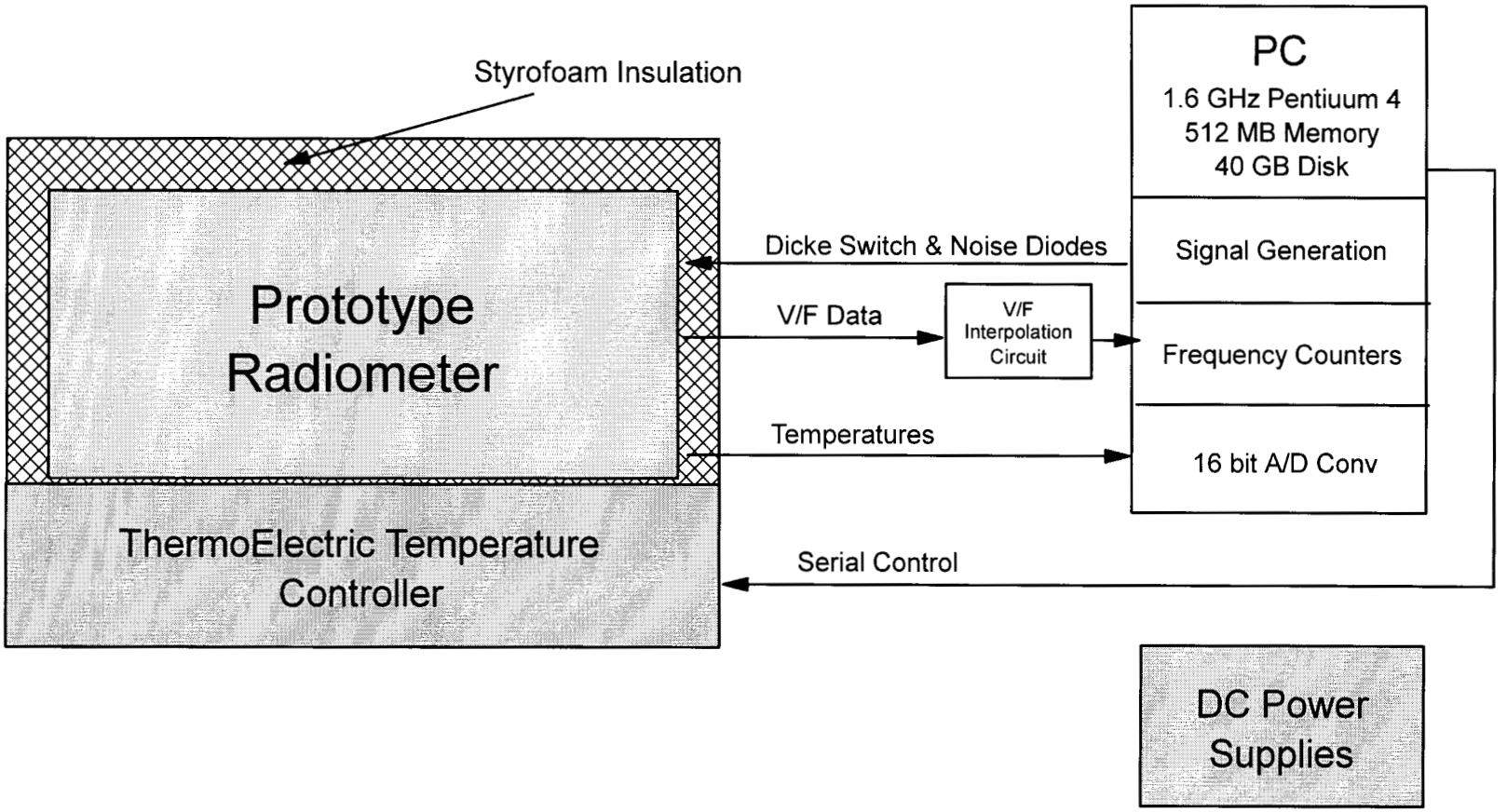
$$\partial T_a = L * \partial T_o$$ => Know T_o to 0.02 C

$$\partial T_a = -(L - 1) * \partial T_L$$ => Control T_L to ± 0.1 C

$$\partial T_a = -L * \frac{(V_o - V_a)}{(V_n - V_a)} * \partial T_n$$ => T_n stable to 2×10^{-2}

(L = 1.25)

JPL Ultra Stable Radiometer Testbed



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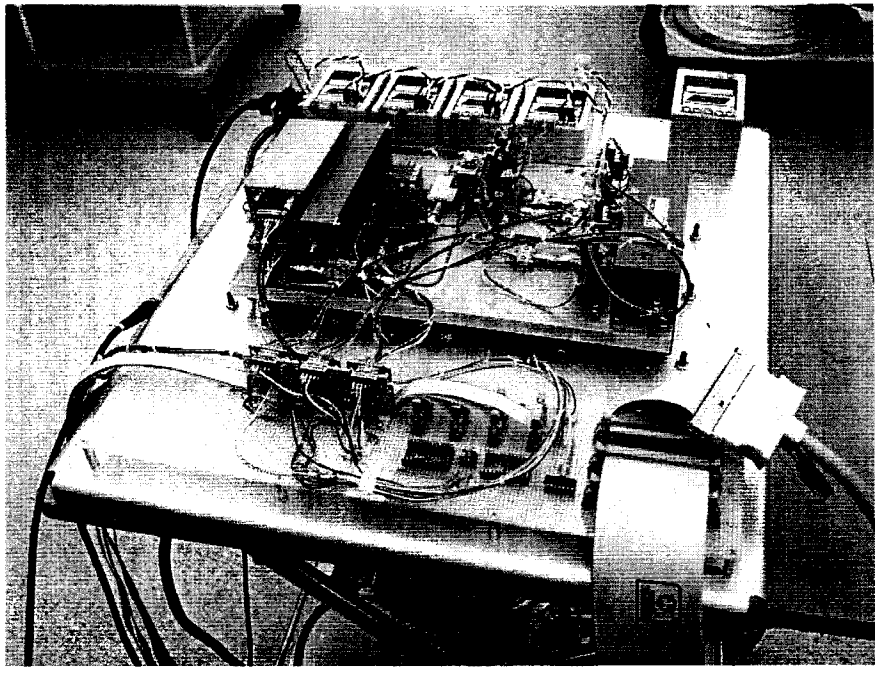
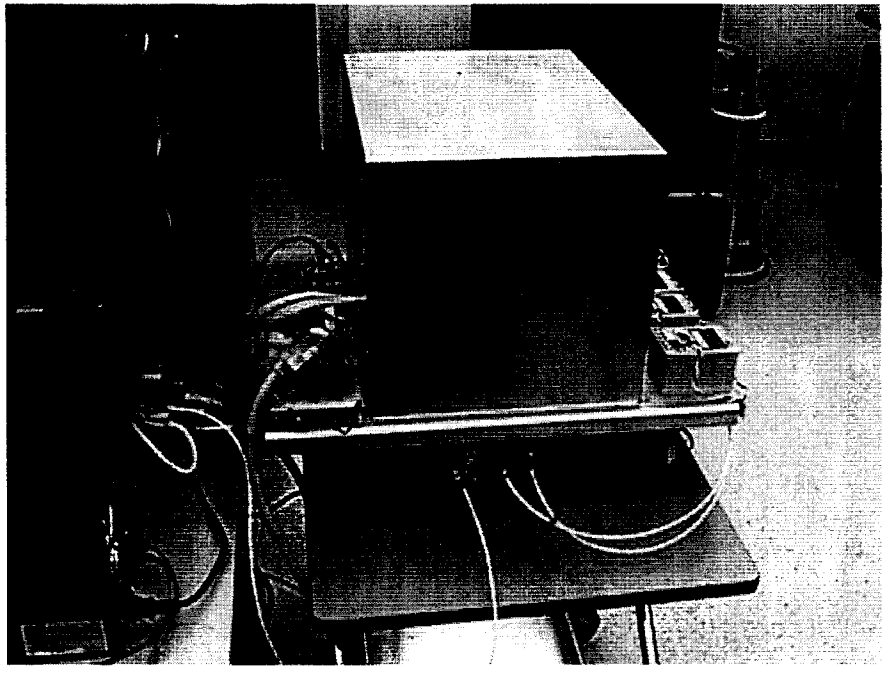
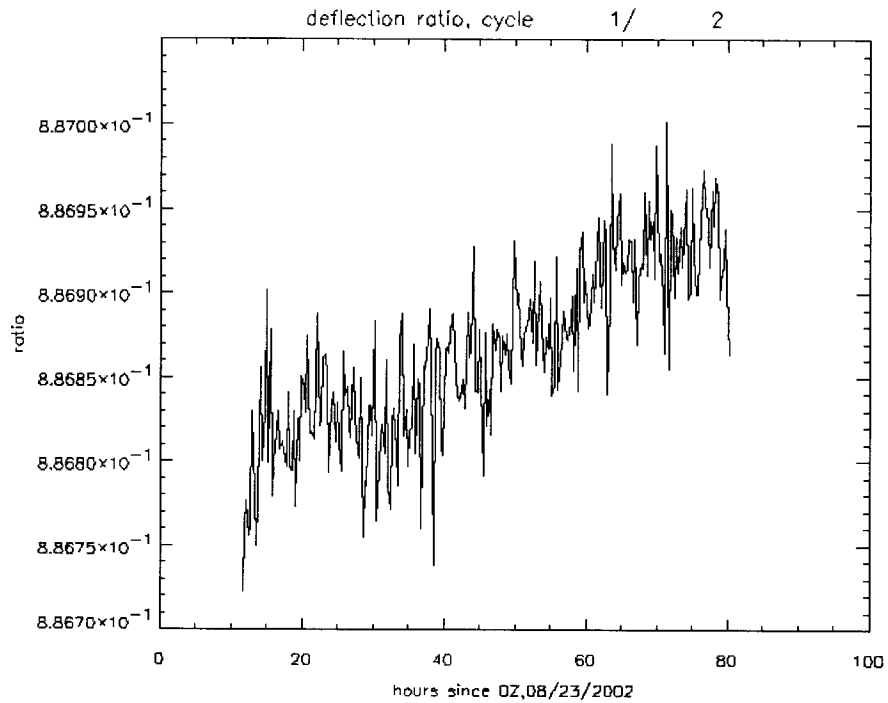




Features of Radiometer Testbed

- Temperature control stability ~ 0.1 °C
- Multiple noise diodes to cross-check stability
- Noise diode current supply stability ~6×10^{-5} per °C
- Can measure Zero offset
- Dual detectors with two V/F converters to determine differences
- Capability to vary the temperature of any component to see effect on stability
- Calibration and Dicke switching sequences easy to change to test our analysis for optimum NEDT and stability
- Data system is a PC with National Instruments interface cards
- Data system is programmed using MS Visual Basic

Initial Test Results



Ratio of noise diode deflections (noise diode A divided by noise diode B). The signal was integrated for 1000 seconds. The short term noise is consistent with theoretical NEDT limits. The long term drift, of about 150 parts per million after 70 hours, indicates a small drift in the calibration system. This corresponds to a radiometer stability of 0.03 K over 70 hours.

Summary

- Careful temperature control of the critical radiometer components, makes it possible to achieve excellent calibration stabilities
- However, the 3-position Dicke switching sequence increases the NEDT to larger than desired levels
- Using running averages of gain and radiometer noise temperature will provide the required stability and reduce the NEDT to within a factor of 1.5 over a total power radiometer
- Results of this analysis will be demonstrated in the laboratory on the testbed radiometers
- A radiometer using small microwave integrated components is also being built to reduce the size to enable the tight temperature control required in space