Digital Receiver with Interference Suppression for Microwave Radiometry

NASA Instrument Incubator Program
Final Project Review

Joel T. Johnson, N. Niamsuwan, B. Guner, and
Steven W. Ellingson*
Department of Electrical Engineering
ElectroScience Laboratory
The Ohio State University

*Department of Electrical and Computer Engineering
Virginia Tech

19th April 2005
Outline

- Slides 1-6: Administrative review
- Slides 7-14: Introduction and system overview
- Slides 15-23: LISR1 Arecibo and LISA campaigns
- Slides 24-37: LISR2/3 local observations
- Slides 38-43: CISR airborne observations
- Slides 44-47: Algorithm and space deployment issues
Objective

- Future sea salinity and soil moisture remote sensing missions depend critically on L-Band microwave radiometry. RF interference is a major problem and limits useable bandwidth to 20 MHz. An interference suppressing radiometer could operate with a larger bandwidth to achieve improved sensitivity and more accurate moisture/salinity retrievals. A new receiver architecture will be developed that will significantly reduce radio frequency interference (RFI) in L-band radiometers.

Approach

A prototype radiometer will be designed, built, and used to demonstrate operation in the presence of interference. The design includes a processing component to suppress interference. Ground based tests will be conducted to demonstrate RFI suppression.

Key Milestones

- Complete Instrument Design - 08/02
- Complete Breadboard Fabrication - 11/03
- Initial Field Tests at OSU - 10-11/03
- Complete Large Scale Tests - 11/04
- Complete Space Applications Study - 11/04
- Final Report - 11/04

CoIs:
Grant Hampson, Ohio State
Steven W. Ellingson, Virginia Polytechnic

\[ TRL_{in} = 3 \]
### Project Schedule

**Project “year 1”** was 9 months, 3/11/02-11/30/02

**No cost extension of year 3 end date to 5/1/05**

---

#### Digital Receiver with Interference Suppression for Microwave Radiometry

<table>
<thead>
<tr>
<th>Task</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progress in Breadboard Instrument Fabrication and Algorithm Development</td>
<td>9/1-11/30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete Breadboard Instrument Fabrication; Progress in Laboratory Tests</td>
<td>6/1-11/30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Progress of Studies of Space Deployment and Advanced Algorithms; Progress of Larger Scale Observations</td>
<td>12/1-5/31</td>
<td>12/1-5/31</td>
<td></td>
</tr>
<tr>
<td>Progress of Studies of Space Deployment and Advanced Algorithms; Progress of Larger Scale Observations</td>
<td>6/1-11/30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Budget/Personnel

- Years 1-3 budget: 832.8K + 21K equipment
- Remaining as of 3/31: ~11.7K + 0K equipment for 1 month

- Personnel:
  - Co-Pis: J. T. Johnson, S. W. Ellingson
  - Lead Designer: G. A. Hampson (left OSU 4/30/04)
  - System Engineer: R. Krishnamarachi
  - RF Support (Research Scientist): Chi-Chih Chen
  - Technician: Jim Moncrief, Ray Feast
  - Graduate Students: David Wiggins (graduated 6/02), Nakasit Niltawach (graduated 6/03), Noppasin Niamsuwan
  - Undergrads: Scott Orlove, Ryan Schultz, Ben Sensheimer, Miguel Lafleche, Mark Frankford

- Document Server:
  http://esl.eng.ohio-state.edu/~swe/iip/docserv.html
Publications


RFI Issues for Microwave Radiometers

- A microwave radiometer is a sensitive receiver measuring naturally emitted thermal noise power within a specified bandwidth.

- Human transmission in many bands is prohibited by international agreement; these are the “quiet bands” ideal for radiometry.

- L-band channel quiet band is 1400-1427 MHz: larger bandwidth would improve sensitivity if RFI can be addressed. Ocean salinity missions require extremely high sensitivity. No protected bands at C-band.

- Even within quiet band, RFI has still been observed - possibly due to filter limitations or intermodulation products.

- Many interferers are localized either in time or frequency: should be relatively easy to detect and remove with an appropriate system.
System Overview

- Typical radiometer is a very “slow” instrument: power received is integrated up to msec scales by analog system before being digitized.
- Typical radiometer has a single, large bandwidth channel: susceptible to narrow band interference.
- Our design uses a digital receiver to allow much more rapid sampling of incoming data; this rapid sampling improves the ability to mitigate temporally localized RFI.
- Our design also performs a 1024 point FFT operation; improves ability to mitigate spectrally localized RFI.
- Processor must operate in real time so that final data rate can be reduced to a manageable level; implement processor in hardware (FPGA’s).

![Graph showing pulsed interferer and radiometer integration period](image-url)
APB algorithm

- APB updates mean/variance of incoming time domain signal; a sample > $\beta$ standard deviations above the mean triggers blanker

- Parameters are threshold ($\beta$), blanking window size (NBLANK), pre-trigger blanking region (NWAIT), and minimum delay between blanking events (NSEP)

- Data zeroed when blanked; effect of this on FFT and calibration will be discussed later
Four Receiver Prototypes Through Project

- **LISA (L-band interference surveyor/ analyzer)**
  - Existed at OSU prior to IIP project
  - Capable only of “capture” mode, 20 MHz BW

- **LISR1 (L-band interference suppressing radiometer)**
  - Developed by 9/20/02
  - Samples 50 MHz, incl. all basic functionality
  - FFT only 14% duty cycle

- **LISR2/CISR**
  - Developed by 4/24/03
  - Samples 100 MHz, incl. extended functionality
  - Full duty cycle FFT
Final Receiver Prototype and RF Hardware

- **LISR3**
  - Developed by 3/15/05
  - Samples 100 MHz, incl. full functionality on a single FPGA
  - Allows greater communication among system blocks, incl. APB scaler

- **Antennas, front ends, downconverters**
  - Developed as needed for experimental campaigns
  - LISA/LISR1: pre-existing components
  - LISR2/LISR3: developed
    - Antenna, antenna mount
    - Thermally controlled front end
    - Tuned downconverter
  - CISR: shares PSR systems
Digital Back-End

- System design includes digital IF downconverter (DIF), asynchronous pulse blanker (APB), FFT stage, and SDP operations

Digital Back-End Diagram:

- Analog Devices 9410
  - ADC
  - DIF
  - APB
  - FFT
  - SDP
- 200 MSPS
- 100 MSPS I/Q

  - LISR3: one Stratix FPGA: approx 30000 LE, $950

- Recent work has added an APB calibration scaler

- Microcontroller interface via ethernet for setting on-chip parameters
  - Possible modes:
    - Direct capture of time domain data, sampled every 10 nsec
    - Integration, blanker on/off, integration lengths 0.01 to 21 msec
    - Max-hold, blanker on/off
LISR2 Implementation

- Modular form used for processor boards: note microcontrollers
- EEPROM's on each card for autoprogramming of FPGA's on power-up
Outline

- Slides 1-6: Administrative review
- Slides 7-14: Introduction and system overview
- Slides 15-23: LISR1 Arecibo and LISA campaigns
- Slides 24-37: LISR2/3 local observations
- Slides 38-43: CISR airborne observations
- Slides 44-47: Algorithm and space deployment issues
LISR1 Arecibo and LISA observations

- An opportunity arose early in the project (Nov 02) to joint observe using the radio astronomy system at Arecibo, Puerto Rico

- LISR1 was the prototype at this time; collected data from 1230-1375 MHz

- Results not calibrated, but qualitatively demonstrate APB effectiveness

- A plan to develop an airborne RFI observing sensor was initiated early in the project through discussion with E. Kim, NASA GSFC

- Airborne observations would provide samples of RFI in varying environments

- LISA system developed for this purpose; deployment early in project period forced use of pre-existing receiver prototype
The radio telescope at Arecibo, PR suffers from RFI from distant ground-based air search radars; LISR co-observed on 11/3/02

1325-1375 MHz spectra including digital IF, APB, FFT, and integration (42 msec)

Before: ATC radar pulses visible
After: APB removes radar
LISA: L-Band Interference Surveyor/Analyzer
S.W. Ellingson, J.T. Johnson, and G.A. Hampson, The Ohio State University

Nadir-looking cavity-backed spiral antenna w/ custom LNA & calibration electronics in tail radome

RF distribution, antenna unit control & coherent sampling subsystem

Maiden LISA Flight: January 2, 2003 from Wallops Island, VA

Examples of RFI observed at 20,000 feet

LISA co-observes with existing passive microwave sensors to identify sources of damaging radio frequency interference (RFI)

- 1200-1700 MHz using broadbeam spiral antenna
- Spectrum analyzer for full-bandwidth monitoring of power spectral density
- 14 MHz (8+8 bit @ 20 MSPS) coherent sampling capability for waveform capture and analysis
- Flexible script command language for system control & experiment automation
LISA Wakasa Bay Campaign

- LISA was deployed in the AMSR-E "Wakasa Bay" cal-val campaign; thanks to E. Kim and R. Austin (Co. State) for operations
- Antenna in P-3 radome: high loss decreased sensitivity
- On board, permanent RFI for frequencies <~1320 MHz
- Problems with receiver compression in many cases; high loss helped!
- Some software/control issues resulted in a few cases of data loss

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
<th># of files</th>
<th>&quot;Pulses&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>Wallops test flight</td>
<td>615</td>
<td>1.79%</td>
</tr>
<tr>
<td>1/3</td>
<td>Wallops to Monterey</td>
<td>4372</td>
<td>1.85%</td>
</tr>
<tr>
<td>1/4</td>
<td>Monterey to Kona</td>
<td>1616</td>
<td>0.06%</td>
</tr>
<tr>
<td>1/6</td>
<td>Wake to Japan</td>
<td>5287</td>
<td>0.15%</td>
</tr>
<tr>
<td>1/14</td>
<td>Sea of Japan</td>
<td>3987</td>
<td>1.58%</td>
</tr>
<tr>
<td>1/15</td>
<td>W. Japan</td>
<td>2342</td>
<td>2.04%</td>
</tr>
<tr>
<td>1/19</td>
<td>W Pacific</td>
<td>78</td>
<td>0.00%</td>
</tr>
<tr>
<td>1/21</td>
<td>W Pacific</td>
<td>2480</td>
<td>0.00%</td>
</tr>
<tr>
<td>1/23</td>
<td>W Pacific</td>
<td>3643</td>
<td>2.25%</td>
</tr>
<tr>
<td>1/26</td>
<td>W Japan</td>
<td>1033</td>
<td>1.45%</td>
</tr>
<tr>
<td>1/28</td>
<td>Sea of Japan</td>
<td>3212</td>
<td>1.00%</td>
</tr>
<tr>
<td>1/29</td>
<td>Sea of Japan</td>
<td>3421</td>
<td>2.22%</td>
</tr>
<tr>
<td>1/30</td>
<td>Sea of Japan</td>
<td>3824</td>
<td>2.01%</td>
</tr>
<tr>
<td>2/1</td>
<td>W Japan</td>
<td>1870</td>
<td>1.39%</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>37165</strong></td>
<td><strong>509</strong></td>
</tr>
</tbody>
</table>
LISA Results Summary

- Campaign produced 8 GB of data: basic unit is an 819.2 microsecond “capture”; requires 1 second, repeated 5 times successively
- Numerous ARSR systems observed both in Japan and US; can correlate data versus ARSR position to examine range effects
- Other radars also observed: chirped, varying pulse widths, multiple frequencies, etc.
- Japanese data show some wideband channels, also a satellite downlink (1698 MHz); tests with these will challenge simple suppression algorithms
- Detailed examination of 1411-1425 MHz channel shows numerous triggers, but signal properties are difficult to classify
- Used cross-US flight data at present to evaluate APB performance; software implementation of APB algorithm
APB Study Results: Problematic Cases

We can perform a chi-square test on the data after blanking as a test; the left LISA example shows a successful case, while for the right case, chi-square values were never satisfactory.

Moral of the story: difficult to recover noise with too many pulses.
APB Study Results: Partially Blanked Frames

- Using NBLANK=2048 (102.4 µsec), $\beta^2=90$

Split 16K sample into 32 x 512 point frames

Frames separated into “NO BLANK”, “ALL BLANK”, and “PARTIAL BLANK”

Spectra over 32 frames power averaged either including or not including partially blanked frames

Results fairly insensitive to inclusion of partially blanked frames
APB Result: A Partially Blanked Frame

- Partially blanked frames do distort spectrum – see example below
- At present, no scaling is implemented, so contribution of greatly blanked frames to average is small
- With scaling, spectral distortion could be an issue
- Computing an average scale factor is a way around this; greatly blanked frames remain reduced – approach of “APB Scaler”
Outline

- Slides 1-6: Administrative review
- Slides 7-14: Introduction and system overview
- Slides 15-23: LISR1 Arecibo and LISA campaigns
- **Slides 24-37: LISR2/3 local observations**
- Slides 38-43: CISR airborne observations
- Slides 44-47: Algorithm and space deployment issues
LISR2/3 Local Observations

While the LISR1 and early LISR2/3 local observations show qualitatively the success of the system, it is necessary to perform well calibrated experiments to quantify this success.

A series of local observations was initiated at the laboratory beginning Sept 03:
- First campaign (9/03-4/04): observations of a large water pool
- Second campaign (4/04): sky observations with pre-existing front end
- Third campaign (6/04-present): sky observations with IIP front end

All these experiments have been susceptible to calibration instabilities due to cross-talk problems, temperature control issues, cable instabilities, and cal target problems.

No completely calibrated L-band data at present; will continue trying to achieve this goal.
Pool Campaign (9/03-4/04)

- Experiments designed to demonstrate radiometric accuracy in the presence of interference

- Observations of a large water tank; external cal sources are ambient absorbers and a sky reflector

- Highly accurate ground-based radiometry is tough due to contributions from objects not under view, including reflections

- Keep cal targets exactly the same size as pool to reduce these effects; observations of pool as ambient temp varies also
Antenna/Front End Unit for Pool Campaign

- Front end Tsys approx. 200K neglecting antenna

Observing in band 1325-1425 MHz; local ATC radar at 1331 MHz

Thermal control of front end appears acceptable; some cross talk issues problematic

Antenna/mount located on ESL roof for observation of water pool on ground

ElectroScience Lab
Dual Channel Downconverter

- One channel is ~1325-1375 MHz, other is ~1375-1425 MHz

- Downconverter, digital receiver, computer, and thermal control systems in rack inside lab

- Recently added thermal control to downconverter after data shows need
Terminator Test of System Stability

Terminator Spectra

+0.25 dB

15 hrs

Total Power vs. Time

Sensitivity vs. Integration

-0.25 dB
Pool and Cal Targets

Absorbers: Assume $T_b = T_{phys}$

Reflectors: Assume $T_b = T_{ref} \sim T_{sky}$?

Water: $T_b \sim \alpha t + Q_{Tref}$
Best Calibrated Brightnesses

- Water observation using absorber/reflective cal, horizontal pol

Blanker dramatically reduces influence of radar at 1331 MHz

CW RFI in band not affected by blanker

Some spectral features remain in blanker data; caused by calibration issues

Absolute value near expected water brightness

Results not stable or repeatable
More Typical Calibrated Brightnesses: 4/20/04

- Data still show strong spectral variations that are unreasonable for water pool; clearly some kind of RFI or calibration problem.

- Patterns in frequency are not repeatable from one measurement to the next.
Relative Power Variations: Pool Observation

Blanker Off: H pol

Blanker On: H pol

240 secs

Noise Generator

Terminator
First Sky Observations (4/04-5/04)

- An alternate experiment was initiated using observations of the sky; a 3 m reflector with an existing L-band feed plus LNA was available
- Sky observations at declination angle 17 degrees
- Expect to see cold sky plus astronomical sources; minor atmospheric influence
- Potential for using cold sky plus moon in a calibration
- Initial results use software FFT's and integration; low duty cycle as a result
- 24 hour observations of astronomical sources
Sky Observation Results: Blanker on

- Software FFT’s allow very high spectral resolution (~4 kHz); sufficient to observe Doppler shift of neutral Hydrogen line

Hydrogen line emission around 1420 MHz; “S-curve” is due to Doppler shift associated with galactic region observed.
LISR 2 Sky Observations: Relative Power

- Measurements were taken on successive evenings – not contiguous

Blanker off

Blanker on

- Simple front end here may be source of some of these variations; replace with front end from pool observations
- Central variations associated with moon passing through beam
- Use this measurement to assess hardware versus RFI versus pool environment variations
LISR3 Sky Observations Using IIP Front End: Early results

Radar contributions greatly decreased by APB

APB Off

APB On

+ .25 dB

- .25 dB

ElectroScience Lab
Outline

- Slides 1-6: Administrative review
- Slides 7-14: Introduction and system overview
- Slides 15-23: LISR1 Arecibo and LISA campaigns
- Slides 24-37: LISR2/3 local observations
- Slides 38-43: CISR airborne observations
- Slides 44-47: Algorithm and space deployment issues
CISR campaigns

- Results from the project were presented to the NPOESS IPO in Feb 03

- Discussions led to IPO support of OSU for studies at C-band beginning 8/03; joint project with NOAA ETL using Polar Scanning Radiometer (PSR) system

- PSR provides antenna, front end, and tuned downconverter for CISR digital backend (based on LISR2 implementation)

- System provides tuned observation from 5.5-7.7 GHz at C-band; possible to calibrate using PSR calibration scheme

- First deployment in SMEX04 campaign (August 04), followed by the AASI04 campaign (Oct-Nov 04)

- Although several hardware issues occurred in both experiments, a substantial data set has been obtained
CISR Example: AASI04 Test Flight

- The largest CISR dataset is from a test flight on October 8th, 2004 in preparation for the AASI04 campaign.

- Note PSR includes 4 analog C-band channels for RFI mitigation.

- Comparison of PSR/CISR data enables test of digital vs. analog methods.

- Circles in Figure mark WFF and NDBC Buoy.
PSR Images: AAS104 Test Flight over Buoy

PSR Channel 1: Forward

PSR Channel 2: Forward

PSR Channel 3: Forward

PSR Channel 4: Forward

ElectroScience Lab
Corresponding CISR Data

Provides precise knowledge of RFI center frequency

Allows possibility of frequency domain blanking to remove RFI

Calibrations show frequency domain blanking effective against narrowband RFI
Use of APB at C-band

- APB on/off data was recorded by CISR throughout C-band
- Results >5.8 GHz show no influence of blanker
- Results < 5.8 GHz show strong influence of blanker
- As expected from freq. allocations in US
Algorithm Issues

- Although our prototypes perform temporal blanking in real time, frequency domain blanking remains in software.

- This is reasonable for suppression since most narrowband RFI can be expected to vary slowly.

- However in practice, this requires an increased data rate since all FFT output bins must be recorded.

- A cross-frequency blanker and/or per-bin time blanker remain desirable; basic algorithms have been developed and tested but not implemented in hardware.

- Some debate regarding FFT versus channelization filters: our results indicate FFT truncation effects can be manageable with appropriate blanking.
Proposal for Hydros

- The NASA Hydros mission includes an L-band radiometer system, and clearly can be susceptible to L-band RFI problems due to focus on overland observations.

- A proposal was submitted to the current IIP solicitation in partnership with C. Ruf of the Univ. of Michigan and J. Piepmeier of NASA GSFC.

- Proposal will deploy IIP backend in airborne observations, along with a simpler digital and analog backends under development by NASA and UM.

- Tests intended to motivate inclusion of digital backend for the Hydros system, based on FPGA hardware; exact algorithms will be finalized during studies.
Space Deployment

- An issue throughout the project has involved the deployment of large, high-speed FPGA’s in space

- An FPGA contractor was commissioned in 2004 to perform a survey of space-qualified devices to address this issue

- Results show that rad-tolerant FPGA’s currently exist commercially that exceed the requirements of the IIP system

- Important to distinguish between “rad-hard” and “rad-tolerant”: “rad-tolerant” systems achieve successful space operation through continual reprogramming as well as embedded backup logic

- Tools for automatically incorporating such programming provided by part vendors (primarily Xilinx)
Conclusions

- We appreciate the support of the IIP program as well as the NPOESS IPO for these efforts.

- Our work has provided the first demonstration of the use of digital receivers for radiometer backends to provide RFI suppression.

- All results qualitatively show the success of the algorithms implemented; we continue to work toward a completely calibrated L-band result.

- C-band results can be calibrated and show that the digital receiver backend can achieve improved RFI removal compared to an analog sub-band approach.

- Deployment in space highly likely in the future due to increasing RFI environment and desires for higher radiometric accuracy; proposal for Hydros currently under consideration.