Digital Receiver with Interference Suppression for Microwave Radiometry

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2001 IIP Proposal

Abstract

A new receiver architecture for use in L-band microwave radiometers is proposed. The receiver is based on analog-to-digital conversion of a significant bandwidth of received emissions, and includes sufficient dynamic range so that digital processing can be performed to remove at least 30 dB of radio frequency interference (RFI). The resulting radiometer should be able to operate outside the 1400-1427 MHz frequency band allocated for passive observations, enabling more accurate brightness temperature measurements, use of alternate L-band frequency choices for improved geophysical parameter sensitivities, and/or reduced correlator complexities for interferometric systems. The interference suppression algorithms used, which have been successfully demonstrated with Earth based radio astronomy systems, are based on adaptive filtering and parametric approaches implemented in real time through reconfigurable digital hardware. A microwave radiometer using a 100 MHz bandwidth centered at 1413 MHz will be considered in this project. An instrument design, prototype development, laboratory tests, and ground-based measurements are proposed over the three year project period to demonstrate successful brightness temperature measurements even with significant interferers present. A basic instrument design concept and assessment for space-based operations will also be developed, along with advanced suppression algorithms which adapt to the RFI type encountered. The technology proposed (if successful) can play an important role in achieving ESE research goals related to soil moisture and sea surface salinity sensing, and can be incorporated into current and future plans for space based L-band radiometers. The technology proposed is also relevant to radiometers operating at other frequencies; basic design architectures for lower and higher frequency operations will also be explored. Other advantages of digital receiver architectures including improved calibration and diagnostic procedures, implementation of near-true-time-delay algorithms for interferometric systems, and flexibility for in-flight modification of receiver characteristics will also be evaluated for future systems.

I. Introduction

Microwave radiometers are important sensors for several surface and atmospheric properties, including soil moisture, sea surface salinity, ocean wind speed, and global precipitation rates. The 2000-2010 ESE research strategy [1] in the global water cycle and sea circulation areas in particular depends critically on low frequency (L-band) microwave passive observations. Because a microwave radiometer essentially is a highly sensitive incoherent receiver attempting to measure very small naturally emitted powers, any appreciable man-made radiation in the same frequency band can completely prevent current radiometers from operating. Because of this susceptibility to radio frequency interference (RFI), current systems operate only in bands allocated primarily to passive Earth observations (1400-1427 MHz, 1661-1668 MHz, 2690-2700 MHz, 10600-10700 MHz, 15350-15400 MHz, and 18600-18800 MHz are current allocations below 20 GHz [2]) where transmission is prohibited. At L-band, current systems are focusing on the 27 MHz of spectrum available from 1400-1427 MHz, and use only 20 MHz of this band to avoid contamination at band edges. Although RFI amplitudes continue to increase throughout the radio spectrum, RFI levels at L-band are the most problematic due to the large number of Earth and space based systems operating from 1 to 2 GHz.

Because the sensitivity of a radiometer (i.e. the amount by which a measured brightness temperature will fluctuate when observing a fixed target) is inversely proportional to the square root of the product of the sensor bandwidth and its integration time, limitations in sensor bandwidth place limits on the sensitivity that can be achieved. Increasing integration times can also improve sensitivities, but maximum integration times are determined by the orbital dynamics for a space-borne sensor. Current feasibility studies of large antenna, low orbit L-band space-borne systems [3]-[5] suggest that a radiometer sensitivity of 0.1 K should be achievable even with only 20 MHz of bandwidth, although such a highly stable L-band system in space has yet to be demonstrated. However, feasibility studies of space-borne interferometric radiometers [6]-[8] with 20 MHz bandwidth show that sensitivities of 0.5-1 K are expected due to the increased complexity of the image formation process compared to a real aperture system.

Increases in receiver bandwidth if possible would be likely to improve the performance of interferometric space-borne systems if such bandwidth increases can be performed without introducing RFI sources. Improvements in sensitivity to geophysical quantities such as sea surface salinity and surface soil moisture can be obtained for both real aperture and interferometric systems by operating at frequencies other than 1.4 GHz (allocated based on radio astronomy hydrogen-line considerations) again if such frequencies can be chosen without introducing RFI problems. The World Meteorological Organization lists 100 MHz of spectrum at L-band as one of the "do-or-die" quantities for remote sensing of the Earth [9].

This proposal describes a new receiver architecture for microwave radiometers which should allow operation even in the presence of RFI. The system is based on digitization of received noise signals combined with hardware implemented interference cancellation algorithms which have previously been shown successful in radio astronomy applications [10]. The proposed project will design, implement, and test a laboratory prototype 1.413 GHz system with a 100 MHz bandwidth and demonstrate the successful operation of this system even in the presence of significant RFI. Ground based observations of soil and water media will also be conducted to further demonstrate the instrument. Studies of operation in space, use in correlating radiometers, and of other gains obtained from digital architectures will also be performed as part of the project.

The next section summarizes the basic project objectives, and a detailed project description follows. Project significance and personnel are discussed in subsequent sections, followed by administrative and budgetary issues.

II. Objectives

1. To design, implement, and test an L-band radiometer digital receiver which will allow operation outside the allocated 1400-1427 MHz band even in the presence of significant RFI.

2. To demonstrate successful operation of this radiometer in ground based measurements of soil and water media.

3. To develop effective RFI cancellation algorithms which will enable operation in changing RFI environments.

4. To perform an assessment of issues for use of this technology in space-based instruments and alternate frequency systems.

5. To perform a study of the advantages of this technology for interferometric and polarimetric systems

6. To educate graduate and undergraduate students participating in the project in digital radiometer design, implementation, and testing.

III. Project Description

A. Applicability to ESE Needs

The Earth Science Enterprise Research Strategy 2000-2010 describes L-band radiometer measurements as crucial to the "Global water and Energy Cycle" and "Climate Variability and Prediction" areas. The former primarily involves soil moisture sensing while the latter involves measurement of sea surface salinity, both requiring tens of kilometer resolutions and repeat intervals of a few days. Of these two areas, the salinity requirement is much more difficult to achieve and is the subject of much current research [11]. This is due to the relatively small variations in salinity which occur in the open ocean and the weak sensitivity of L-band brightness temperatures (around 0.3-0.7 K per practical salinity unit depending on observation angle and surface temperature [12]) to these variations. However, knowledge of sea salinity has been demonstrated to be very important for long term climate prediction, estimation of ocean rainfall and global hydrologic budgets, and ocean modeling and flux studies [11]. The small variations in brightness temperature which are expected demand that a highly sensitive radiometer be developed; current interferometric systems are expected to have problems measuring sea salinity without substantial averaging which severely degrades spatial and temporal resolutions [8] to the point that scientific requirements may not be met.

The proposed technology will address sea salinity and soil moisture measurements by improving the sensitivity and performance of radiometers which make these measurements and by potentially allowing operation outside the 1.4 GHz band. Extending the usable bandwidth of current sensors is likely to have a dramatic impact on the use of interferometric radiometers for salinity applications, and to bring their expected performance closer to that of real aperture systems. For both real aperture and interferometric radiometers, operation at lower frequencies (for example 1 GHz) if possible in the presence of RFI will increase the sensitivity of brightness temperatures to sea salinity; no other means exists for obtaining this direct increase in sensitivity to the desired geophysical parameter. Since currently planned salinity sensors will operate very close to technological limits, an ability to choose alternate frequencies potentially could dramatically improve the performance (i.e. accuracy, spatial resolution, and/or temporal resolution) of these systems. Thus the proposed interference suppressing receiver will enable new measurements not possible with current technologies.

While enabling new or improved radiometric measurements is the focus of the current project, the ability of a digital receiver to perform other error correcting functions in addition to interference suppression also suggests that the proposed technology can reduce the risk of future interferometric space-borne systems. Since digital systems can be reconfigured during flight, any modest system malfunctions which occur in space (somewhat probable in a large number of elements interferometric radiometer) can be corrected. The reconfigurable nature of the proposed system would also allow the receiver to operate only in the allocated 20 MHz of bandwidth if interference problems became excessive, so that performance at least identical to currently proposed radiometers would be obtained in the worst-case-scenario. Also, since many commercial organizations are currently pursuing similar architectures and since digital components continue to improve in performance while decreasing in cost, the potential for future cost reductions also exists. Finally, the basic receiver technology to be developed in this project can be integrated into almost any radiometer proposed for future Earth observations, regardless of frequency, and can provide additional improvements for

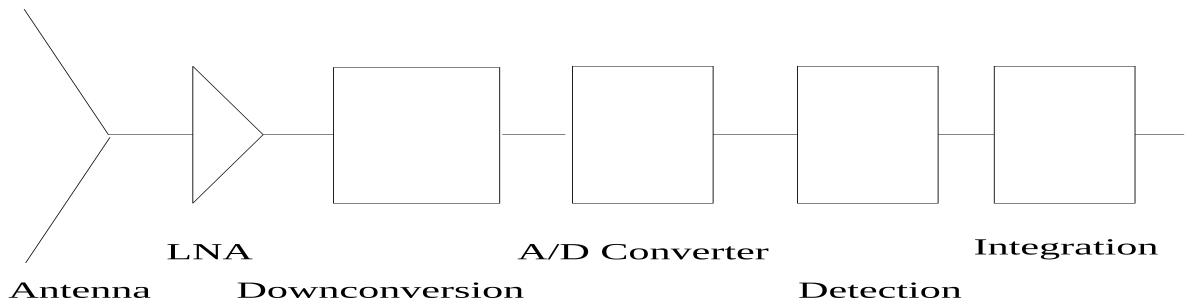

Figure 1: Architecture of a digital receiver

interferometric systems (e.g. hardware implementation of near-true-time-delay algorithms) beyond interference suppression alone.

B. Description of Proposed Technology

Digital receiver technologies are currently being evaluated for use in microwave radiometers by several organizations [7]-[8], [13]-[15]. The basic architecture of such systems is illustrated in Figure 1, which shows that generally a signal from an antenna is passed through a low noise amplifier, a single or double heterodyne downconversion stage, and an analog to digital (A/D) converter followed by detection and integration to obtain quantities proportional to measured brightness temperatures. Interferometric systems have additional antenna elements and receivers and perform cross-correlations between elements in addition to the power detection, while polarimetric systems perform cross-correlations between signals in horizontal and vertical polarizations. L-band systems which directly A/D convert signals without the downconversion stage have also been described [15].

Because the signals of interest in microwave radiometry are noise signals, and because only the total power integrated over a significant period of time is of interest, typical A/D converters for microwave radiometry use only one, two, or three bit representations of the digital signal [13]. It can be shown that integrated brightness temperatures using three bits experience only a slight degradation in accuracy from those obtained with a much larger number of bits. The complexity of the digital correlation hardware is then reduced with a smaller number of bits; the proposed "MIRAS" radiometer from the European Space Agency uses only a single bit correlation process. Earth-based radio astronomy interferometric systems have been applying similar methods since the 1960's [13].

The use of digital technology provides additional flexibility compared to analog technology in that the operations performed on received data can be modified even after the system is constructed. Digital systems are also much more stable than analog systems through their lifetime. The use of digital correlators in current polarimetric and interferometric systems has clearly demonstrated the advantages that can be expected from digital technology.

The receiver proposed in this project is distinct from other digital receivers in that an

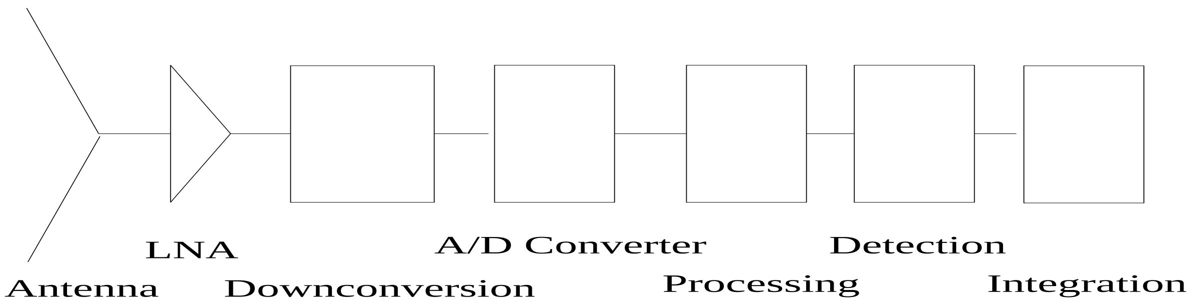

Figure 2: Architecture of proposed receiver

additional processing system is included before the detection/correlation step as illustrated in Figure 2. This processing system will implement the interference suppression algorithm, and can also include phase or amplitude calibration corrections, monitoring of receiver transfer characteristics, and additional processing steps. Because RFI at L-band is likely to result in much higher power levels at the receiver than the desired Earth brightness, a modification of the A/D converter to include a larger number of bits is required to insure sufficient dynamic range. An simple calculation for a low Earth orbit satellite located in a 0 dB gain sidelobe of a 25 kW transmitter on the Earth surface shows an interference level approximately 30 dB greater than an Earth scene of uniform 100 K brightness. An A/D with around 8 bits could still retain sufficient dynamic range to measure both the interfering signal and the Earth brightness. Note that once interference is removed, the output passed to the detection or correlating system needs only retain the small number of bits necessary for acceptably sampling noise powers (i.e. 2-3 bits); therefore increases in correlating hardware complexity are not required by the present system.

The proposed 100 MHz bandwidth system will thus require an 8 bit A/D converter combined with an 8 bit processing stage (implemented with FPGA and DSP hardware) capable of operation at 100 or 200 MSPS depending on the in-phase/quadrature-phase separation process chosen. Such systems are commercially available at present and are likely to continue to increase in performance and decrease in price during the project period. A complete detailed system design will be performed during the first project year along with an evaluation of design tradeoffs (in terms of detailed costs, performance, and power consumption) for standard downconversion versus direct sampling systems.

C. Comparative Technology and TRL Assessments

As stated in the introduction, current proposed L-band radiometers for soil moisture and sea salinity measurements are based either on interferometry [6]-[8] or on large antenna real-aperture systems [3]-[5]. Current interferometric systems are expected to achieve sensitivities of 0.5-1 K at present; here an expansion of the receiver bandwidth would be likely to improve current performance. Additional operations (such as near-true-time-delay phase shifting algorithms) in the proposed system processing stage could be implemented to further improve the accuracy and stability of a space-borne interferometric system. Large antennas are needed for the real-aperture systems to insure sufficient spatial resolution from space at 1.4 GHz, and in these systems radiometer sensitivities of 0.1 K have been suggested as feasible. Retrieval studies [5] show that a radiometric sensitivity of 0.1 K is sufficient to make radiometric errors less significant than other uncertainties in estimating sea salinity. However, in both the real aperture and interferometric cases, the proposed technology can allow operation outside of the 1400-1427 MHz protected band so that improved sensitivities directly to sea salinity can be obtained. Such improvements are not possible by any other means.

Since the basic technological aspects of digital receivers have previously been demonstrated in both radiometric and radio astronomy systems, the proposed project contains technology readiness levels ranging from TRL 3 to TRL 6. TRL 3 efforts in year 1 will produce the basic system design to be implemented, followed by TRL 4 implementation of the receiver and laboratory tests in year 2. Ground based measurements of soil and water media with the developed system in project years 2 and 3 represent the TRL 5 and TRL 6 aspects of the project.

D. Interference Cancellation Algorithms

Several methods exist to cancel interference for radiometric systems depending on the nature of the interference [10], [16]-[17]. A study of RFI considerations for the MIRAS system [7] shows that air traffic control and/or military radars are likely to be the strongest sources at L-band; broadcasts from these systems have specific properties in both the time and frequency domains. For interference which is localized within a portion of the instrument frequency band, a simple cancellation algorithm would implement a band-stop filter at the location of the interference. Such a filter can be modified in real time depending on the nature of the interferer. If the interferer occupies only a small fraction of the system bandwidth, the loss in sensitivity would not be significant. A switchable band-stop filter at the hydrogen line frequency (1420.405 $\pm$ 0.1 MHz) can also be used to eliminate the corruption of salinity measurements discussed in [5] when galactic emissions enter the antenna pattern. A "time domain" filtering approach is also possible by stopping the integration process when pulsed type interference is detected. Again, if the "turn-off" period is small compared to the total integration time, the reduction in radiometer sensitivity will not be appreciable.

For more complex interferers, algorithms based on parametric estimation combined with a limited knowledge of the interfering signal have been developed [10],[16]. The success of these algorithms is based on the fact that even highly complex man-made spectra can be analyzed in terms of a few parameters which determine the modulated signal. A parametric algorithm has been shown successful in removing interference in radio astronomy data from the Russian GLONASS navigation satellite system, even when the interference power level is comparable to the noise power of interest [10].

It is expected that similar algorithms should be successful in canceling a wide range of interfering signals with only slight real-time modifications. Note that L-band measurements will be affected by both strong interference (with power levels tens of dB greater than the desired noise power) and by moderate interference (with power levels only a few dB or even similar to the desired noise power.) Parametric algorithms can perform well in both these cases, and repeated application of the algorithms if necessary can be used to remove multiple interfering signals.

Selection, refinement, and implementation of interference cancellation algorithms will occur throughout the project as the system is designed, constructed and tested. The reconfigurable digital architecture of the receiver processing stage allows modification of algorithms as the project progresses.

Recent measurements of radio frequency interference near the frequency band of interest performed at the ElectroScience Laboratory of Ohio State University show intermittent interference at frequencies 1.19, 1.30, and 1.48 GHz, with power levels between -150 and -120 dBm at the terminals of a small log-periodic antenna directed toward the southeast (roughly in the direction of a nearby urban area and large airport.) The 1.30 GHz signal is pulsed with total bandwidth about 1.6 MHz, and is believed to be an airport radar. The other sources are about 300 kHz bandwidth and are believed to be second harmonics of the sound subcarriers of local television stations. Other interference sources with very short pulse lengths or lower power levels are also likely to be important, but were not easily detectable with the test equipment available (i.e. broadband preamplifier and spectrum analyzer). In any event, it is clear that local sources of interference exist that will provide a useful test of the algorithms developed. Determination of the algorithms most likely to be successful for a space-based instrument will also be performed as part of the space-based instrument study in project year 3.

E. Demonstration of System

Because similar L-band radio-astronomy systems have been previously constructed and tested at the ElectroScience Laboratory [18] a relatively efficient construction phase is expected. After implementation, several laboratory tests will be performed to insure that the system is operating correctly and producing accurate and stable brightness measurements. Laboratory tests of both filter-based and parametric cancellation algorithms will be performed with injected interference sources to insure that no noise power corruption is introduced by the algorithms or other hardware contributions. Obtained power performance of the system will also be monitored and contrasted with that expected from the initial system design. Thermal tests of the system will be performed to investigate its temperature stability. If necessary, a thermal control system will be added to insure accurate measurements in the lab and outdoor environment, although such a system is not proposed for the initial design since only a mild range of temperatures should be encountered in the proposed system demonstration.

To further demonstrate the system in a more realistic environment, a series of ground based measurements is proposed in years 2 and 3. A large (> 2 m diameter) L-band reflector antenna will be used and mounted on the roof of the ElectroScience Laboratory to provide sufficient angular (i.e. spatial) resolution in the experiments. Observations of natural soil media in the field adjoining the laboratory and of a large water pool constructed in this field will be used to demonstrate soil and water medium tests. The water observations in particular will provide an effective test of system performance since the brightness temperature of a smooth water surface can be predicted relatively accurately [12], [19]. External calibration tests with standard absorbing targets at different temperatures will also be used to demonstrate successful operation of the system even in the presence of significant interference.

F. Space Instrument Considerations

If successful laboratory and ground based initial demonstrations of the system are achieved in project year 2, an initial study of issues for a space-borne instrument will follow as part of year 3 project efforts. Since the distinction between the proposed system and other currently proposed radiometers lies in the A/D and processing stages, the key technological issue lies in the ability of 100 or 200 MSPS 8 bit digital systems to function and remain stable in space environments. Accurate knowledge of the power requirements of these components in space is also critical. A study of these issues will be performed in project year 3 taking into account all hardware technological improvements which have taken place during the course of the project. Currently, a U.S. Satellite Industry Code Consortium comprised of several industrial members exists at the ElectroScience Laboratory, so expertise from this group regarding satellite digital hardware technology can potentially contribute to this stage of the project. Partner expertise from within NASA will also be sought as part of the space instrument study to insure that current information is used. It is anticipated that the prototype developed will have power requirements which may not be reasonable for deployment in space, but that hardware technology improvements will reduce this problem as a post-2007 mission is approached. Studies of the receiver architecture for alternate frequency radiometers will also be performed; it is expected that no significant modifications will be required, although the larger bandwidths and smaller aperture sizes already available at higher frequencies may reduce the advantages of the proposed technology. Due to the similarity of the proposed system to other proposed radiometric systems, no significant differences in brightness temperature data archiving or processing are anticipated (again the increased dynamic range of the A/D is not used once interference has been suppressed.)

G. Correlating Instruments

A final aspect of the proposed system to be evaluated in project year 3 involves the additional advantages to be gained from the processing stage of the receiver for cross-correlating systems (i.e. polarimetric and/or interferometric.) Since forming correlations between different receiver channels generally increases measurement error due to increased sensitivity to receiver fluctuations, developing highly sensitive correlating radiometers is difficult with current technologies. A simple use of the improved radiometric sensitivity obtained from an increased bandwidth would reduce the number of bits used in the correlation phase to reduce correlator complexity. However, the processing stage of the proposed receiver will allow improvements beyond those gained from increased bandwidths alone, since algorithms to correct receiver fluctuations in real time can be implemented, along with near-true-time-delay algorithms to insure that proper phase relationships between elements are maintained throughout the band. In addition, portions of the correlation process can be incorporated into the low bit-output stage of the processor to reduce the complexity of the multi-element correlation hardware stage. Total gains obtained from increases in bandwidth and from additional processing steps for multi-element correlating systems have the possibility of exceeding the direct sum of gains from these steps individually if performed in an advantageous fashion. Algorithms which combine these steps will be investigated in the space borne instrument study in year 3. The cost and feasibility of the proposed technology in a multi-element space borne interferometer will also be evaluated as part of the study. Depending on the progress of the ground based system demonstrations and on feedback obtained at program reviews, construction of a polarimetric system (i.e. a two channel correlating system) may be possible in project year 3 to directly illustrate gains for correlating systems.

H. Educational Aspects

Two graduate students will be directly involved throughout the three year project period, participating in system design, implementation, and testing. Undergraduate researchers will be added to the project (minimal cost) once suitable candidates are recruited. The project will thus provide a complete instrumentation development experience for these students, and should produce well trained microwave engineers upon project completion. These students will represent a human-resource creation aspect of the project, and the expertise gained by these students should be important to their careers in the industrial, scientific, or governmental research communities.

I. Research Management Plan

A "milestones" chart illustrating expected project progress is provided in Figure 4. The project will begin in year 1 at TRL 3 by finalizing the system design, determining the components to be used, and performing analysis to evaluate expected performance. A six month period is allocated to this process to insure that all important issues are considered, including the decision to include or not include the downconversion section of the receiver. Initial system construction work (TRL 4) and interference cancellation algorithm development then complete year 1; it is expected that significant order times will be required for some system parts, but that in-house construction of other system components can occur during this period. In addition, a detailed initial design of the system digital processing block will be pursued in this period through use of standard software tools for digital design. Completion of system construction is scheduled for the first three months of project year 2, followed by initial laboratory and ground based tests and concurrent system improvements (TRL 4 and 5). The allocation of 15 project months to complete the system design and construction will represent a challenging task, but previous experience and the expertise of team members Drs. Steven Ellingson and Grant Hampson with construction of similar systems for radio astronomy and communication applications suggests that this figure is reasonable for a laboratory prototype. Larger scale ground based demonstrations in the ElectroScience Laboratory fields follow in year 3; several demonstrations will be formed during the entirety of year 3 to provide convincing evidence of system success and to continue to refine performance. Studies of use of the technology in space-borne and correlating radiometers occur in parallel with demonstration efforts in year 3, along with continued development of improved interference cancellation algorithms that can be field tested during the demonstration phase.

All project personnel will be involved all aspects of the project. Dr. S. Ellingson will lead system design and construction efforts, and will supervise Dr. Hampson, technician staff, and graduate students in this phase. Dr. Johnson will lead the test and demonstration phase of the project, and will supervise technician staff and student team members in this phase. All team members will participate in the feasibility studies in project year 3. Additional senior level support will also be available to the project from Research Scientist members of the ElectroScience Laboratory as their particular expertise is required.

IV. Significance and Impact

The proposed system, if successful, will represent a revolutionary change in passive remote sensing of the Earth. Microwave radiometer systems operating outside the "quiet" bands at present are not feasible, severely limiting the quality and type of Earth observations which can be performed. If operation in significant RFI is shown possible, many of the passive remote sensing community's concerns for frequency allocation will be alleviated (although at the cost of some increased system complexity). Clearly frequency allocation is a political process over which the scientific community has little control, as demonstrated by the ever decreasing size of the allocations available. Thus the proposed system will demonstrate a new technique for all microwave radiometers, regardless of their application. The specific L-band receiver technology to be developed will influence and improve the accuracy

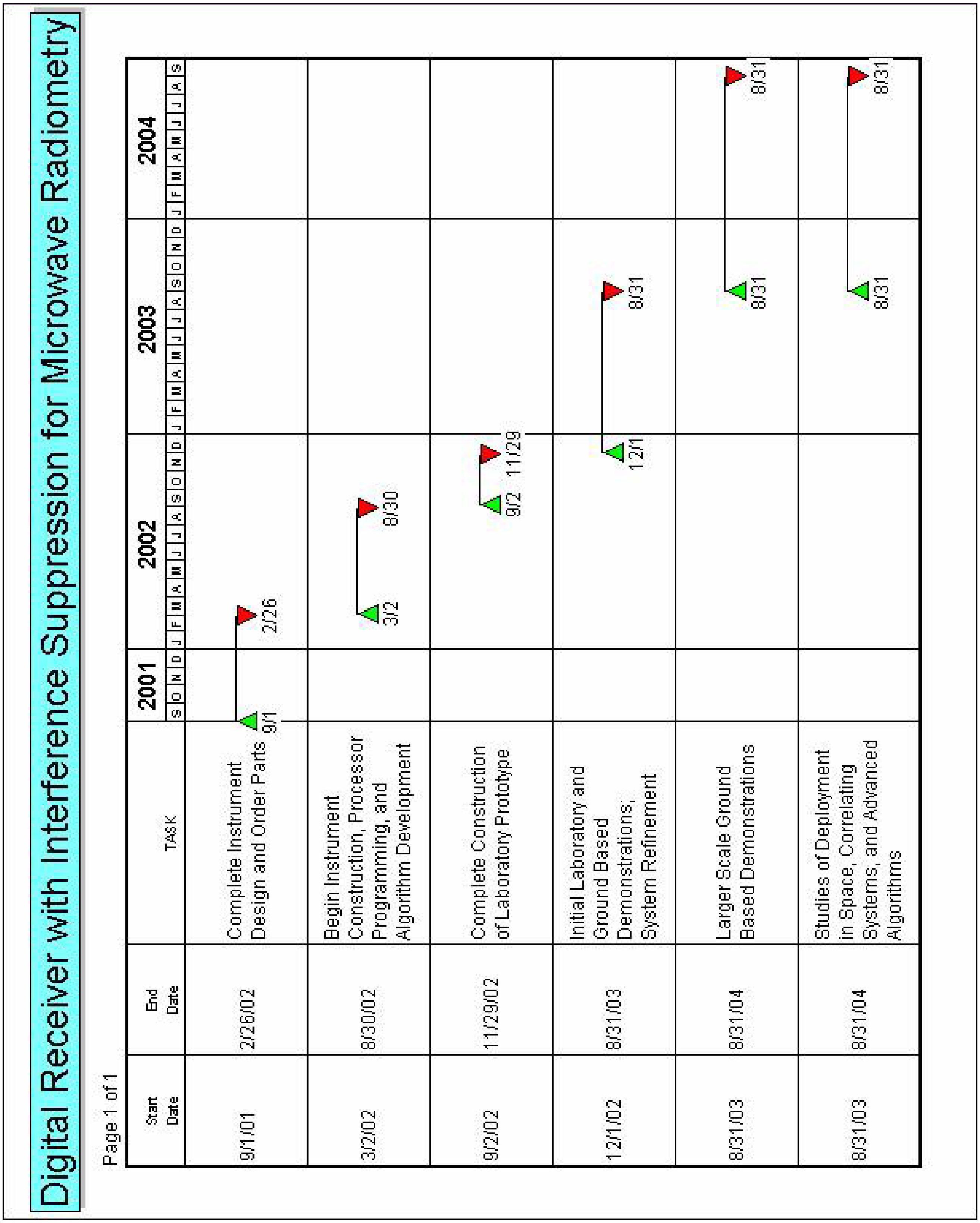

Figure 3: Milestones of Project

of future interferometric radiometers, and can enable use of lower frequencies so that better measurements of sea surface salinity can be obtained for studies of the global water cycle and sea circulation.

V. Facilities and Equipment

The Ohio State University ElectroScience Laboratory maintains office and laboratory space for the PI, Co-PI, and all affiliated student and professional staff. For the current project, use of the RF systems laboratory will be allocated, along with necessary tools and measurement equipment to insure that the system design and tests can be completed. The field space adjoining the laboratory will be available for field demonstrations of the radiometer. Computer (numerous Linux based PC systems) and software resources are also available for project use.

VI. Security

All project work will be unclassified; no security issues are anticipated.

References

[1] *NASA Earth Science Enterprise Research Strategy 2000-2010,* available from *earth.nasa.gov/visions.*

[2] Wende, C. D., "NASA remote sensing and frequency issues," *International Geoscience and Remote Sensing Symposium (IGARSS) 2000,* conference proceedings.

[3] Njoku, E. G., Y. Rahmat-Samii, J. Sercel, W. Wilson, and M. Moghaddam, "Evaluation of an inflatable antenna concept for microwave sensing of soil moisture and ocean salinity," *IEEE Trans. Geosc. Rem. Sens.*, vol. 37, pp. 63–78, 1999.

[4] Njoku, E. G., W. Wilson, S. Yueh, and Y. Rahmat-Samii, "A large-antenna microwave radiometer-scatterometer concept for ocean salinity and soil moisture sensing," *IEEE Trans. Geosc. Rem. Sens.*, vol. 38, pp. 2645–2655, 2000.

[5] Yueh, S. H., W. Wilson, E. Njoku, F. Li, and R. West, "Retrieval modeling and error sources for microwave remote sensing of ocean surface salinity," *International Geoscience and Remote Sensing Symposium (IGARSS) 2000,* conference proceedings.

[6] LeVine, D. M., "Synthetic aperture radiometer systems," *IEEE Trans. Micro. Theory Tech.,* vol. 47, pp. 2228–2236, 1999.

[7] Camps, A. J., I. Corbella, F. Torres, J. Bara, and J. Capdevila, "RF interference analysis in aperture synthesis interferometric radiometers: application to L-Band MIRAS instrument," *IEEE Trans. Geosc. Rem. Sens.*, vol. 38, pp. 942–950, 2000.

[8] *Soil Moisture and Ocean Salinity EEO Proposal,* Y. Kerr, PI, available at *www.cesbio.ups-tlse.fr/indexsmos.html.*

[9] *Handbook on the Use of Frequency Spectrum for Meteorology,* World Meteorological Organization, available at *www.wmo.ch/web/www/TEM/SG-RFC/Handbook.htm*.

[10] Ellingson, S. W., J. Bunton, and J.F. Bell, "Removal of the GLONASS C/A signal from OH spectral line observations using a parametric modelling technique", to appear, *Astrophysical Journal Supplement,* vol. 135, July 2001 (downloadable from *esl.eng.ohio-state.edu/people/researchers/ellingson.html*).

[11] Lagerloef, G. S., ed., "Report of the third workshop," *Salinity Sea Ice Working Group (SSIWG),* San Antonio, TX: 22-23 January 2000 (available at *www.esr.org/ssiwg/mainssiwg.html*).

[12] Ellison, W., A. Balana, G. Delbos, K. Lamkaouchi, L. Eymard, C. Guillou, and C. Prigent, "New permittivity measurements of seawater," *Radio Science,* vol. 33, pp. 639–648, 1998.

[13] Piepmeier, J. R., A. J. Gasiewski, and J. E. Almodovar, "Advances in microwave digital radiometry," *International Geoscience and Remote Sensing Symposium (IGARSS) 2000,* conference proceedings.

[14] Skou, N., B. Laursen, and S. Sobjaerg, "Polarimetric radiometer configurations: potential accuracy and sensitivity," *IEEE Trans. Geosc. Rem. Sens.*, vol. 37, pp. 2165–2171, 1999.

[15] Fischman, M. A. and A. W. England, "Sensitivity of a 1.4 GHz direct-sampling digital radiometer," *IEEE Trans. Geosc. Rem. Sens.*, vol. 37, pp. 2172–2180, 1999.

[16] S.W. Ellingson, "Interference mitigation techniques," EF White Conference on RFI Mitigation Strategies at CSIRO/ATNF, Sydney, Australia, December 1999. (available at *www.atnf.csiro.au/SKA/intmit/atnf/conf*)

[17] A. Leshem, A.-J. van der Veen, and A.-J. Boonstra, "Multichannel Interference Mitigation Techniques in Radio Astronomy", *Astrophysical Journal Supplement,* vol. 131, pp. 355, 2000.

[18] *ElectroScience Laboratory RF Systems Group* web page, esl.eng.ohio-state.edu/rfse/.

[19] Johnson, J. T., J. A. Kong, R. T. Shin, K. O'Neill, D. H. Staelin, and A. Lohanick, "Third Stokes parameter emission from a periodic water surface," *IEEE Trans. Geosc. Remote Sens.,* vol. 31, pp. 1066-1080, 1993.

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M. Zhang and J. T. Johnson, "Comparison of modeled and measured second azimuthal harmonics of ocean surface brightness temperatures," *IEEE Trans. Geosc. Remote Sens.,* vol. 39, pp. 448–452, 2001.

J. T. Johnson and M. Zhang, "Theoretical study of the small slope approximation for ocean polarimetric thermal emission," *IEEE Trans. Geosc. Remote Sens.,* vol. 37, no. 5, pp. 2305–2316, 1999.

J. T. Johnson, R. T. Shin, J. A. Kong, L. Tsang, and K. Pak, "A numerical study of ocean polarimetric thermal emission," *IEEE Trans. Geosc. Remote Sens.,* vol. 37, no. 1 (part I), pp. 8–20, 1999.

J. T. Johnson, R. T. Shin, and J. A. Kong, "Scattering and thermal emission from a two dimensional periodic surface," Chapter 11 in *Progress in Electromagnetic Research 15,* J. A. Kong, ed., Cambridge: EMW Publishing, Jan 1997.

J. T. Johnson, J. A. Kong, R. T. Shin, K. O'Neill, D. H. Staelin, and A. Lohanick, "Third Stokes parameter emission from a periodic water surface," *IEEE Trans. Geosc. Remote Sens.,* vol. 31, pp. 1066-1080, 1993. **(1993 Best Paper Award)**

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PERSONNEL: Steven W. Ellingson

Education: B.S. Electrical and Computer Engineering (1987), Clarkson University
M.S.E.E. (1989) and Ph.D. (2000), The Ohio State University.

Positions: 2001-Present: Research Scientist, The Ohio State University
1997-2001: Senior Research Associate - Engineer, The Ohio State University
1995-1997: Senior Systems Engineer, Raytheon E-Systems, Inc.
1993-1995: Senior Consultant, Booz-Allen and Hamilton, Inc.
1992-1993: Captain, Battalion Staff Officer, U.S. Army, Signal Corps
1989-1991: Lieutenant, Platoon Leader, U.S. Army, Signal Corps

Relevant Publications:

S.W. Ellingson and G.A. Hampson, "A Subspace-Tracking Approach to Interference Nulling for Phased Array-Based Radio Telescopes", to appear, *IEEE Trans. Ant. Prop.*, Jan 2002.

S.W. Ellingson, J. Bunton, and J.F. Bell, "Removal of the GLONASS C/A Signal from OH Spectral Line Observations Using a Parametric Modelling Technique", to appear, *Astrophysical Journal Supplement* , July 2001.

S.W. Ellingson, "Design and Evaluation of a Novel Antenna Array for Azimuthal Angle-of-Arrival Measurement", to appear, *IEEE Trans. Ant. Prop.*, June 2001.

S.W. Ellingson, I.J. Gupta, and W.D. Burnside, "Analysis of Blended Rolled Edge Reflectors Using Numerical UTD", *IEEE Trans. Ant. Prop.*, vol. 38, no. 12, 1990.

S.W. Ellingson, "A Parametric Approach to RFI Suppression",*URSI National Radio Science Meeting*, conference proceedings, Boulder, CO, 2000.

S.W. Ellingson, "RFI Suppression for Radio Astronomy: Frequency-, Time-, Space-, and Multidomain Approaches", *XXVI General Assembly of the Int'l URSI*, conference proceedings, Toronto, ON, 1999.

S.W. Ellingson and M.P. Fitz, "A Software Radio Based System for Experimentation in Wireless Communications", *IEEE Vehicular Technology Conference*, conference proceedings, Ottawa, ON,1998.

Reprints of the above are available through the World Wide Web at
http://esl.eng.ohio-state.edu/people/researchers/ellingson.html

Awards and Activities:

1999 Research Accomplishment Award, OSU College of Engineering

Session chair and organizer, APS (1999).

Reviewer, IEEE Trans. Signal Processing.

Chair (2001) and Vice-Chair (2000), Columbus Joint APS-MTT IEEE Society

Proposed Costs

NASA summary budgets for project years one through three are attached, with each followed by a detailed expenditure summary. The project includes personnel allocations for the PI, Co-PI, Dr. Hampson, additional senior level support from research scientist personnel, funding for two graduate student assistants, and a staff component for computer system administration, secretarial assistance, and project reporting editorial components. A travel allocation is also included to support PI and Co-PI attendance at required NASA review meetings and one project conference presentation per year. Component costs for system construction are included primarily in year one when the initial parts will be ordered; due to the relatively low frequency of operation and the ground based system planned, total component costs are relatively moderate at $34K. Additional reduced component costs are included in years two and three as refinements to the system and improvements are performed. An small allocation to support use of ElectroScience Laboratory test and measurement equipment and telephone and postage allocations are also included.

An equipment purchase of a high dynamic range computer-controlled spectrum analyzer (priced at $30K) is also proposed for year 1; this component is crucial to project success due to the need for complete knowledge of RFI sources during system testing. The proposed spectrum analyzer has the ability to "track" more complex interferers than the spectrum analyzer currently available due to increased flexibility in system triggering and data handling controls, and also has a significant improvement in noise figure over the current spectrum analyzer. The Ohio State Unviersity will contribute 30% of the cost of the equipment, resulting in a project equipment charge of $21K in year one. Graduate student assistant tuition and fees of $63K are also provided by the university as a cost-sharing aspect of the project; a total cost-sharing contribution of $72K is thus obtained for the project.

(I. A) Current Fiscal Year Support for J. T. Johnson:

(i) Surface scattering effects in mine detection and remote sensing systems

`Source:` National Science Foundation

`PI:` J. T. Johnson

`Current FY Amount:` $50,000

`Period:` June 2000 through May 2001

`Person-Months:` 1.0

`Project Abstract:` Experimental and modeling studies of soil surface scattering effects on active systems for detecting buried objects or soil moisture are performed. Measurements of surface profiles are used to insure accurate soil surface characterization.

(ii) Theoretical studies of microwave radiometry for buried object detection

`Source:` Subcontract from Duke University as part of the Department of Defense "Multi-Disciplinary Research for Demining" MURI program

`PI:` J. T. Johnson

`Current FY Amount:` $40,000

`Period:` December 2000 through November 2001

`Person-Months:` 0.9

`Project Abstract:` Modeling studies on the use of passive microwave sensors for detecting sub-surface objects are performed.

(iii) Analytical and numerical studies of active and passive microwave ocean remote sensing

`Source:` Office of Naval Research

`PI:` J. T. Johnson

`Current FY Amount:` $100,000

`Period:` January 2001 through December 2001

`Person-Months:` 1.5

`Project Abstract:` Modeling studies of sea surface scattering and emission are performed by combining numerical models for electromagnetics and hydrodynamics.

(iv) An ultra-wideband radiometer for surface and buried object remote sensing

`Source:` Department of Defense University Research Instrumentation Program (DURIP)

`PI:` J. T. Johnson

`Current FY Amount:` $250,000

`Period:` March 2001 through Feb 2002

`Person-Months:` 0.0

`Project Abstract:` This purely equipment grant is supporting purchase of a multi-channel traditional radiometer for use in buried object and surface remote sensing studies.

(I. B) Pending Proposals for J. T. Johnson:

(i) Numerical studies of the nonlinear interaction between turbulent air flow and sea surface waves, with application to ocean surface wave turbulence

`Source:` National Science Foundation

`PIs:` G. Baker, K. Berger, and J. T. Johnson

`Proposed Amount:` $500,000

`Period:` September 2001 through September 2006

`Person-Months:` 1.0 (per year)

`Project Abstract:` Development of a combined air-water flow hydrodynamic model is proposed to allow numerical simulation of the development of sea surface waves from wind forcing.

(II. A) Current Fiscal Year Support for S. W. Ellingson:

(i) Lucent-OSU Collaborative Project on Base Station Antenna Systems

`Source:` Lucent

`PI:` S.W. Ellingson

`Current FY Amount:` $100,000

`Period:` November 2000 through October 2001

`Person-Months:` 4.0

`Project Abstract:` An 8-element dual frequency array receiver is being developed for measurements of propagation at 2.4 GHz in support of proposed terrestrial mobile radio systems using BLAST modulation. Measurements of spatial and polarization diversity as well as channel rank will be obtained for near-line-of-sight, suburban, and urban environments.

(ii) Smart Antenna Array Processing for 3G Wideband Cellular CDMA Mobile System

`Source:` Electronics and Telecommunications Research Institute (South Korea)

`PI:` I.J. Gupta

`Current FY Amount:` $155,000

`Period:` September 2000 through July 2001

`Person-Months:` 4.0

`Project Abstract:` In this second year of a proposed 3-year collaboration, various techniques are being developed and evaluated for deployment in third-generation wideband CDMA mobile radio systems. These techniques include forward-link (base-station-to-mobile) beamforming using antenna arrays and mobile user geolocation using time-difference of arrival. In support of these studies, a field measurement campaign will be conducted.

(iii) Space-Frequency Adaptive Processing for GPS Interference Suppression

`Source:` U.S. Air Force

`PI:` I.J. Gupta

`Current FY Amount:` $159,986

`Period:` June 1999 through April 2001

`Person-Months:` 2.0

`Project Abstract:` Space-frequency adaptive processing (SFAP) is a candidate technique for removing jamming signals from military GPS receivers using antenna arrays. The technique is being evaluated using quasi-analytic and simulation methods.

(iv) Argus Telescope Development

`Source:` SETI Institute

`PI:` S.W. Ellingson

`Current FY Amount:` $198,590

`Period:` May 1998 through October 2001

`Person-Months:` 8.0

`Project Abstract:` "Argus" is a concept for a radio telescope with omni-directional (horizon-to-horizon) field of view, using large numbers of small, ultrawideband antenna elements. In this project, various prototype systems are being developed to test the feasibility of the idea, with emphasis on antenna elements, low-cost receivers, and signal processing architectures.

(II. B) Pending Proposals for S. W. Ellingson: None

(III) Neither this proposal nor any part of it has been submitted to any other agency.