A Wideband Microwave Airborne Imaging System for Hydrological Studies

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Abstract - The development of the NOAA Polarimetric Scanning Radiometer (PSR) system commenced in the fall of 1995, with the first-generation system operated on the NASA P-3B aircraft to study passive microwave ocean surface wind signatures in March, 1997 [1]. The PSR system consist of sets of polarimetric radiometers housed within standardized gimbal-mounted scanhead drums. Each scanhead is rotatable by a gimbaled positioner so that the radiometers can view any angle within 70° elevation of nadir and at any azimuthal angle (1.32π sr solid angle), as well as external hot and ambient calibration targets. The configuration supports conical, cross-track, along-track, fixed-angle stare, and spotlight scan modes. Scanheads are designed for in-flight operation without the need for a radome (i.e., in contact with the aircraft slipstream), thus allowing precise calibration and imaging without superimposed radome signatures. The conical scan mode allows the full Stokes' vector to be imaged without polarization mixing.

The PSR has been used in several successful airborne missions, demonstrating the first 2-dimensional ocean surface wind vector mapping, high-resolution hurricane rainband imaging and satellite rainfall rate validation, C-band soil moisture imaging, high-resolution sea-ice mapping, and ocean internal wave imaging. Since its inaugural mission there have been several new hardware developments that have extended the capability of the PSR system in terms of the observable spectrum, polarizations, and compatibility with various aircraft. Currently in progress are developments which will provide the capability to perform wideband airborne hydrological studies with a single suite of synchronized, compatible sensor heads. This suite will include the PSR/CX, PSR/S, and PSR/L scanheads, which collectively extend the capabilities of the original PSR/A scanhead. Four positioners are anticipated to be available for operation in 2003. Each assembly (scanhead and positioner) was designed for integration into several aircraft, including the NASA DC-8, Orion P-3B, and WB-57F, Scaled Composites' Proteus, Airplatforms, Inc. Canberra B-6, U.S. Navy P-3A, and NASA ER-2. Upon completion, the PSR system will provide passive polarimetric microwave imagery at most of the channels in the range of 1.4 to ~800 GHz that are useful for spaceborne or airborne hydrological remote sensing. Studies planned using the system include vapor-to-runoff phase monitoring of precipitation, estuarian runoff and mixing, targeted forecasting, and cirrus generation by convection.

I. SYSTEM DESCRIPTION

The PSR system consists of three major components: a scanhead, positioner, and equipment rack. Figure 1 illustrates the positioner and PSR/CX scanhead as integrated into the NASA WB-57F high-altitude aircraft. The scanhead houses all radiometer hardware and supporting electronics, including the data acquistion computer. The positioner serves to move and point the scanhead. The scanning drum can be positioned to view any angle with 0.1^{o} precision using a two-axis high-torque stepper motor positioner system. The positioner also houses external blackbody calibration targets, one at ambient temperature and one heated to a higher preset temperature. The equipment rack contains data acquisition, archival, and motion control systems and is typically located within the aircraft cabin. Three new positioners being built at NOAA

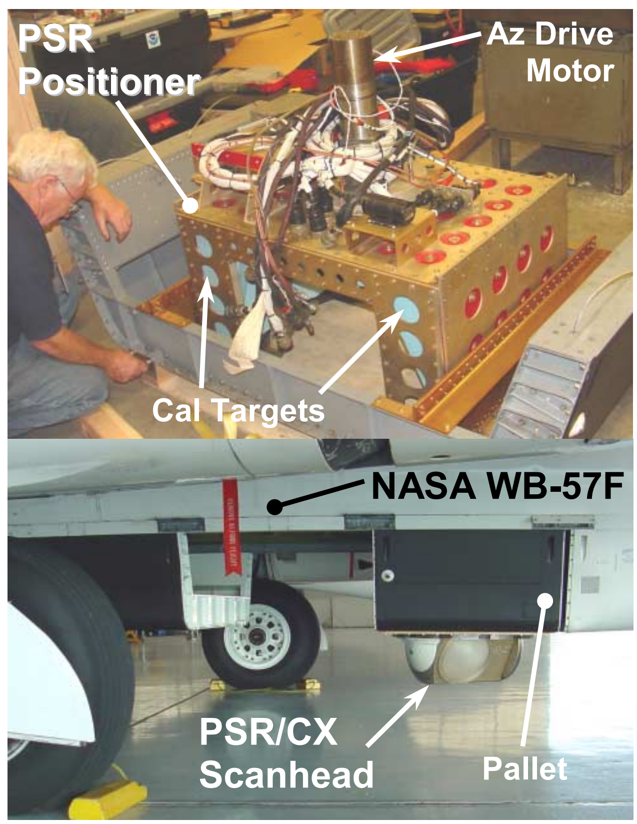

Figure 1. PSR positioner and scanhead as installed on the NASA WB-57F.

ETL will have the supporting electronics installed on the top of each positioner. In this scheme the interface to the operator is implemented using an ethernet connection to a notebook PC running a web-based control program.

The typical weight of a PSR scanhead is ~70 kg (~150 lbs). The weight of a scanhead/positioner unit depends on the positioner version and the specific design of the calibration targets, but typically does not exceed ~340 kg (750 lbs).

A. PSR Radiometers. Two interchangeable scanheads, PSR/A and PSR/CX, are currently operational. The precise radiometric bands for PSR/A are X (10.6-10.8 GHz), Ku (18.6-18.8 and 21.3-21.6 GHz), Ka (36-38 GHz), and W (86-92 GHz). These bands were selected to provide sensitivity to clouds, precipitation, and surface features over almost one decade of microwave bandwidth at octave intervals. The current PSR/A scanhead uses analog correlators, although digital correlators were demonstrated in the first version of this scanhead (PSR/D, see [1]). In addition, a color CCD video camera and 9.6-11.5 µm wavelength infrared sensor are installed. The camera is used to observe the scene for purposes of cloud clearing, ocean foam coverage estimation, surface feature detection, and scanhead operation. PSR/A is currently maintained by ETL as a complete and operational scanhead.

The second PSR scanhead (denoted "PSR/CX," for its implementation of C and X-band channels) consists of polarimetric sub-band radiometers at C- and X-bands. The C-band radiometer provides polarimetric measurements within four adjacent subbands at 5.80-6.20, 6.30-6.70, 6.75-7.10, and 7.15-7.50 GHz, with full Stokes' vector measurements at 6.75-7.10 GHz. The X-band radiometer uses the same antenna as the C-band unit and has subbands at 10.60-10.80, 10.60-10.68, 10.68-10.70, and 10.70-10.80 GHz. Applications of PSR/CX include ocean surface emissivity studies, soil moisture mapping, and imaging of heavy precipitation. The multiband capability of PSR/CX is also used to study the feasibility of frequency agile radiometry for use over interference prone regions. A color CCD video camera and IR sensor are included.

All PSR antennas are of the lens/corrugated feedhorn type and are dual orthogonal-linear polarized with grooved rexolite lenses. All main beam efficiencies are in the 95-97% range and all on-axis cross-polarization isolation ratios exceed -27 dB.

Each PSR scanhead contains an embedded data acquisition computer, all radiometers and detectors, power conditioning modules, and antennas inside a 51 cm (20") diameter and 51 cm (20") long rotating drum. Radiometric data are sampled and formatted by the embedded computer, then transmitted to an archival computer outside of the scanhead via a 10-base 2 LAN link through the sliprings. Thus, all radiometric detection is accomplished inside the scanhead drum.

Currently under development are two additional PSR scanheads: the PSR/S "Sounding/Sub-millimeter wavelength" scanhead and the PSR/L L-band imaging scanhead. Descriptions of each of these new scanheads are available at http://www1.etl.noaa.gov/radiom/psr.html .

B. Calibration. In-flight calibration of all PSR radiometer is accomplished using a three-stage process employing radiometric views of i) noise diodes or internal thermal standards at ~100 msec intervals, ii) external (unpolarized) hot and ambient blackbody targets at intervals of approximately several minutes, and iii) upward-looking views of cold space performed approximately once per sortie.

Internal noise diodes are available for all PSR channels up to 89 GHz (above which - for PSR/S - stable free-space thermal standards are being developed). Frequent views of these stable internal references permit identification of time-varying radiometer gains and offsets. These references, however, are not considered good absolute standards, and are further referenced to the external standards to determine their radiometric temperatures.

The unpolarized external targets consist of identical arrays of iron-epoxy absorbing pyramids installed in a two-bounce L-shaped corner configuration. The absorbing pyramids are canted at an angle of 45° so as to provide maximum absorption in the direction of PSR antennas. The pyramidal arrays are encased in transparent insulating foam and overlie a thermally-conducting substrate of aluminum pyramids so that the physical temperature of the entire structure remains homogeneous to within ~1 K. The microwave emission temperature of the structure is precisely calculable through 8-fold redundant physical temperature measurements and target emissivity estimates obtained using cold space views.

The cold space views permit a comprehensive empirical estimation of the external target temperature, and include the effects of residual scattering, thermal gradients, and beam spillover. The cold space views are obtained using a steep roll of the aircraft. The procedure consists of pointing the PSR scanhead 65° above nadir to starboard, then rolling the aircraft up to 60° port for ~3-5 seconds. The procedure provides the radiometers an unobstructed view of cold space for which the brightness temperature is typically very cold (~3-40K, depending on altitude, humidity, and channel) and calculable to better than ~0.5-1 K uncertainty.

An additional ground-based pre- and post-flight calibration procedure using a fully polarized target is being developed to provide accurate 3rd and 4th Stokes parameter calibration of all PSR polarimetric radiometers.

II. PSR MISSIONS

To date, the PSR has flown for over 430 flight hours on three different aircraft (NASA P-3B, DC-8, and NAWC P-3A). A list of missions is provided in Table 1. A versatile bomb bay fairing and support structure for the P-3 integration has been developed and successfully flown for the two P-3 integrations. Hardware for integration of the PSR on the NASA WB-57F has recently been completed, and similar hardware for integration on Proteus, the ER-2, and a Canberra B-6 is under design. An aerodynamic fence has been fabricated for the DC-8 integration. Fabrication of hardware to permit two PSRs to operate synchronously on the P-3Bs and WB-57F is underway. During the entire series of flights the PSR exhibited excellent aerodynamic, mechanical, and electrical performance in ambient conditions as cold as -51° C and at true air speeds up to 400 knots.

The precise configuration of the PSR system for a given mission depends on the specific scientific goals. These goals impact the selection of scanheads, platform, accompanying instruments, and aircraft altitude and airspeed.

TABLE 1 - PSR MISSIONS

Mission	**Dates**	**Approximate Airtime (hrs)**	**Aircraft & Scanhead**
Ocean Winds Imaging Experiment (OWI `97)	March 1997	40	NASA/WFF P-3B PSR/D
Hurricane Winds Experiment (HOWEX)	August 1997	25	NASA/WFF P-3B PSR/D
Over-the-Horizon Experiment (OTH `97)	November 1997	20	NASA/WFF P-3B PSR/D
Third Convection and Moisture Experiment (CAMEX-3)	August-September 1998	80	NASA/DC-8 PSR/A
North American Polar Scanning Radiometer Experiment (NAPSCAR98)	October-November 1998	40	NASA/DC-8 PSR/A
Southern Great Plains Experiment (SGP99)	July 1999	40	NASA/WFF P-3B PSR/C
North American Polar Scanning Radiometer Experiment (NAPSCAR00)	May 2000	50	NAWC P-3A PSR/A
Meltpond 2000	June-July 2000	40	NAWC P-3A PSR/A & PSR/C
North American Polar Scanning Radiometer Experiment (NAPSCAR01)	July-August 2001	35	NAWC P-3A PSR/A
Cold Land Processes Experiment (CLPX02)	February 2002	60	NASA/DC-8 PSR/A
Total		**430**	

For example, to study the potential for retrieving ocean surface wind fields by passive microwave radiometry the PSR was flown at medium-to-low altitude on the NASA P-3 over the Labrador Sea as part of the 1997 Ocean Winds Imaging Experiment. This study demonstrated that one and two-dimensional ocean surface wind fields could be retrieved using passive polarimetric microwave imagery of the ocean surface, and illustrated the robustness of polarimetric measurements of the surface state in the presence of clouds (Figure 2) [1]. The use of digital correlators along with appropriate calibration techniques for polarimetric measurements was also demonstrated [2], and a wideband surface emission harmonic model was developed. The PSR model both corroborated and extended one proposed earlier by Wentz (see [1]) that was obtained earlier using SSM/I data. The results of this study have been used to support the further development of passive microwave wind vector retrieval for the U.S. NPOESS.

Validation of TRMM rain rate retrievals was performed using PSR/A data obtained from the NASA DC-8 during the Third Convection and Moisture Experiment (CAMEX-3). High-resolution PSR/A rain rate retrievals based on a 10.7-GHz emission algorithm compared favorably to coincident data from the JPL ARMAR Ku-band rain radar and the TRMM Microwave Imager (TMI) level 2A12 rain rate product [3]. The intercomparison revealed the greatest discrepancies at rain cell edges where the relatively large footprint of the TMI could be expected to produce beam-filling errors in the retrieved rain rate. The study illustrates the potential use of PSR to validate rain rate maps from the DMSP SSMIS and NPOESS CMIS instruments.

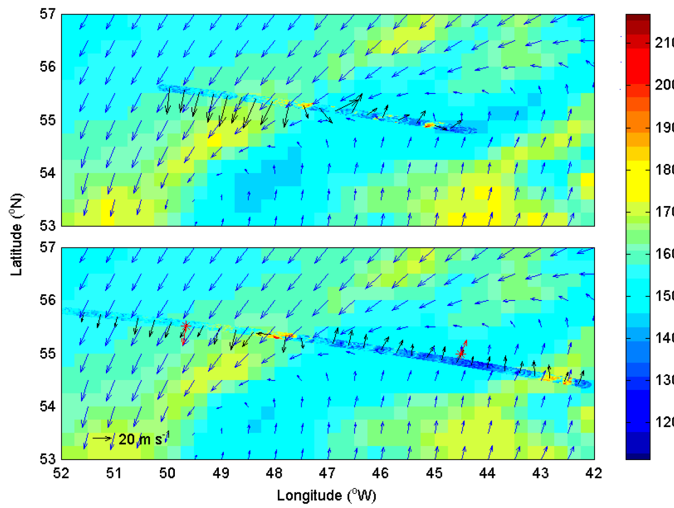

Figure 2. One-dimensional full-scan oceanic wind vector retrievals during two crossings of a cold cyclone centered in the Labrador Sea. Retrieved wind vectors are overlaid onto PSR and SSM/I 37H GHz brightness imagery (color scale). Blue arrows are wind data from the NOAA/NCEP ETA analysis, and the two orange arrows are dropsonde surface winds. Tight cyclonic rotation of retrieved and model wind fields is revealed.

The PSR/C scanhead was initially developed to determine the impact of vegetation on C-band mapping of soil moisture (SM), for example, using AMSR-E or CMIS. Although SM is more directly measurable using L-band, the high cost of implementing a viable L-band aperture in space warrants the use of smaller C-band apertures. The PSR/C was first operated during the 1999 Southern Great Plains Experiment (SGP99), providing the first high-resolution (~2.3 km) C-band SM maps under conditions of low vegetation biomass. (Figure 3). The SM algorithm developed from the PSR aircraft data suggested that C-band will be useful for SM retrievals under such conditions. The relatively small footprint size provided watershed-scale spatial resolution that revealed a range of drydown rates within the SGP99 region of interest (central Oklahoma). The experiment also offered the first opportunity to demonstrate anthropogenic RFI interference mitigation using a radiometric a sub-band technique [5].

Snowpack emissivity in cold land regions can vary considerably depending on the initial properties and melt history of the snow crystals. The wide variation in emissivity compromises the interpretation of satellite microwave imagery for snowpack estimation. The NASA Cold Lands Processes Experiment in 2002 (CLPX02) was designed to study remote measurement of snowpack within three intensive study areas in the Rocky Mountains of Colorado. The PSR/A instrument was used on the NASA DC-8 during CLPX02 to image snowpack emission with ~180 meters spatial resolution at 89 GHz and ~600 meters resolution at 10.7 GHz. Large brightness temperature drops (of up to ~100K at 89 GHz and horizontal polarization) were observed after fresh snowfalls (Figure 4) over kilometer scale regions. The high resolution of the PSR was required to provide unambiguous registration of observed snowfield emission with snow parameters obtained through surface sampling. The results of CLPX02 will be used to support satellite-based snow cover depth retrieval algorithm development.

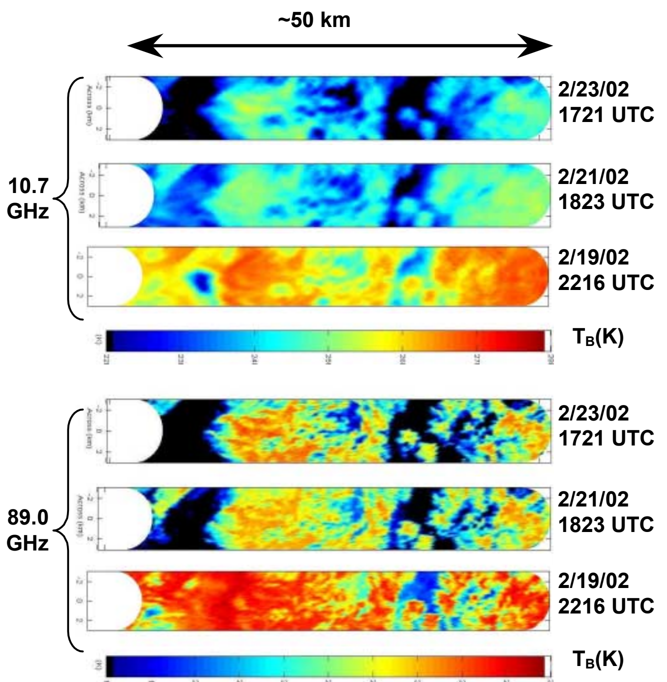

Figure 4. PSR/A 10.7 and 89 GHz images of surface emission from snowpack in the Rocky Mountains on three days during the CLPX02. The spatial resolution is ~600 m and ~180 m, respectively. Strong surface scattering - as revealed by cold brightness temperatures - was observed after fresh snowfall, as occurred between 2/19/02 and 2/21/02.

Further information on PSR data sets from the above missions can be found at http://www1.etl.noaa.gov .

IV. CONCLUSION

The PSR system provides a means of high-resolution imaging of several hydrological and related meteorological variables, including ocean surface winds, soil moisture, and cryospheric parameters. This parameter list will be extended to include water vapor and temperature profiles, cloud water and ice content, and ocean/estuarian salinity upon completion of PSR/L and PSR/S. The high spatial and temporal resolution available using this system is anticipated to facilitate detailed hydrological studies, targeted weather forecasting, and NPOESS and NASA satellite calibration and validation.

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Figure 3. PSR/C 7.3 GHz soil moisture maps retrieved during the 1999 Southern Great Plain Experiment (SGP99) [4]. The raw T_B maps show a ~60 K decrease in brightness for horizontal polarization after 1-2" rainfall. The spatial resolution of ~2 km reveals watershed scale moisture features