An Airborne Pod-mounted Dual Beam Interferometer

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Abstract—Dual beam interferometer (DBI) has been developed by the University of Massachusetts (UMass) to study ocean surface waves and currents in coastal regions. This airborne radar operates at C-band (5.3 GHz) with a bandwidth of 25 MHz and VV polarization. DBI consists of two pairs of microstrip patch array antennas, one squinted 20º forward of broadside and the other 20º aft. Each pair of antennas is separated in the along-track direction a distance of 1.23 meters forming an interferometer. Over several years, DBI was flown on a National Oceanic and Atmospheric Administration's WP-3D research aircraft in a number of successful missions collecting the data both over land and ocean. These deployments and subsequent data analysis were carried out in collaboration with Naval Research Laboratory (NRL). This paper describes the hardware integration and use of the system to generate surface current vector maps.[1 2]

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1. INTRODUCTION

Recently along-track interferometric synthetic aperture radars (ATI-SAR) have been used extensively for surface current estimation and fine resolution mapping. Along track interferometric SAR requires two SAR antennas separated in the along-track direction to provide two complex SAR images. When collocated, they are separated by a time lag that is equal to the antenna baseline divided by the platform velocity. Hence both antennas observe the same scene at a slightly different time. The interferometric image is given by the covariance of the two collocated SAR images. The magnitude of the interferometric image is similar to a conventional SAR image while the phase includes Doppler velocity information from which the line-of-sight component of velocity of scatterers within the radar beam is derived [2]. A detailed description of SAR interferometry, describing along-track as well as cross-track interferometry is given in [1].

To date, interferometric measurements of surface currents have employed sidelooking SARs that implement a single beam. As such only one radial component of Doppler surface velocity is obtained in any one pass of the aircraft. To obtain a vector measurement of the current two intersecting (ideally, orthogonal) passes over the area of interest are required. Between the times of overflight the current field is assumed to be constant. Even though this assumption is valid for large scale features, it still requires

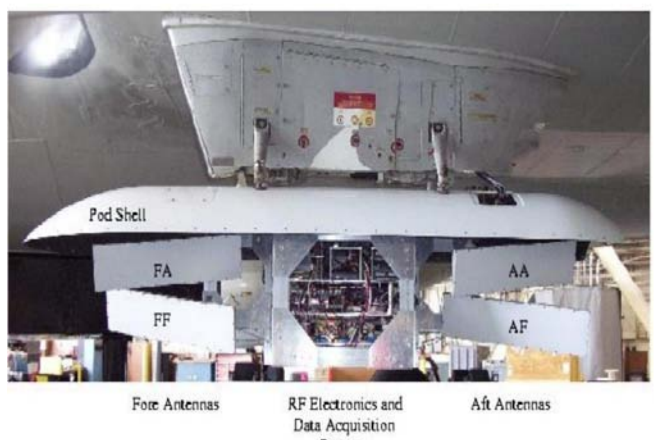

Figure 1. Photograph of DBI installed on the pylon of WP-3D aircraft

[1] 0-7803-8870-4/05/$20.00 © 2005 IEEE
[2] IEEEAC paper # 1366, Version 1, Updated December 9, 2004

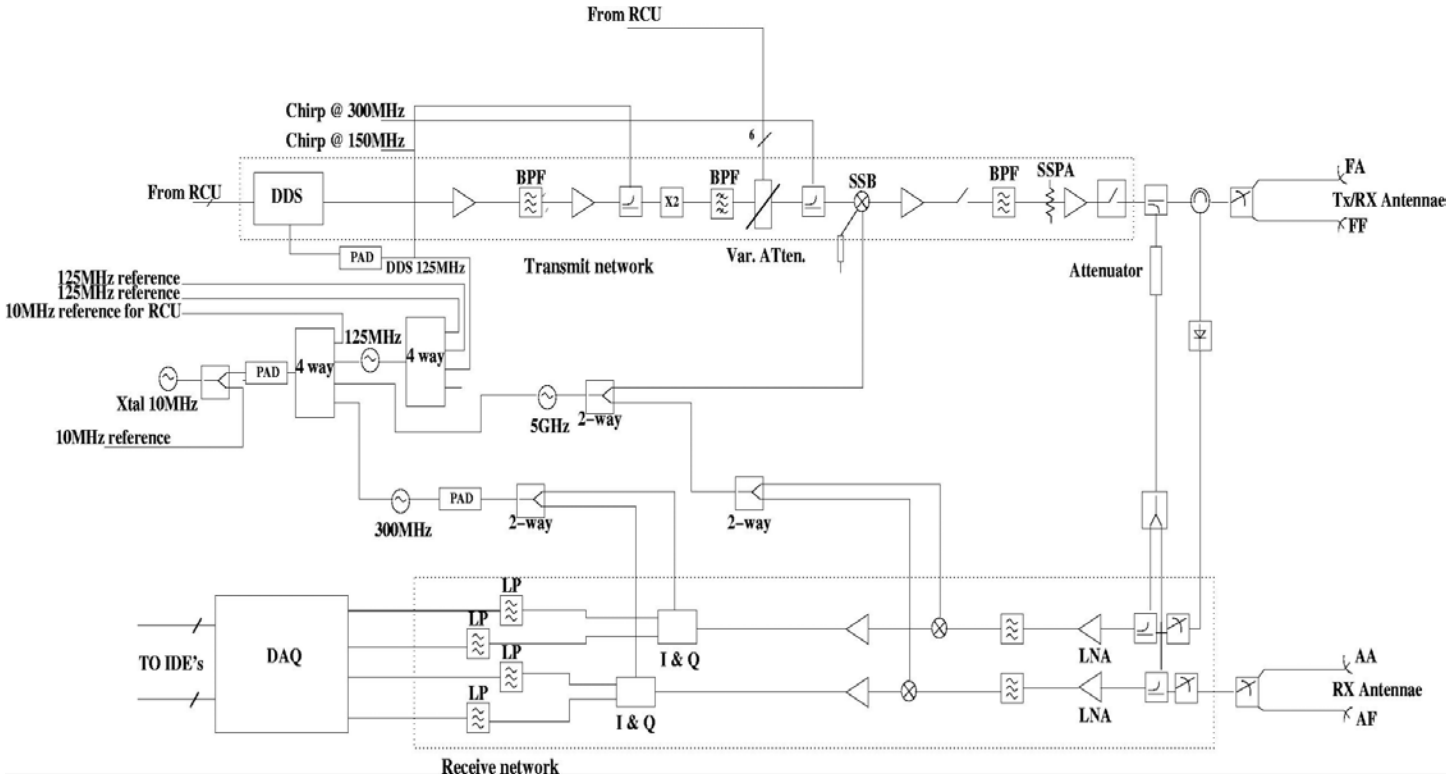

Figure 2. DBI block diagram

the passes to be made as close as possible in time. In such a setup vector measurements can only be obtained for the small overlapping areas making the stripmap SAR impractical.

A logical extension of the single beam along-track interferometry is to form two squinted beams thus obtaining two components of velocity [2]. The Dual Beam Interferometer described in this paper is a C-band Synthetic Aperture Radar designed to enable estimates of the surface current vectors in a single pass of the aircraft. The radar is housed within a wing-mounted microwave transparent pod chosen as an economical platform for airborne remote sensing.

2. SYSTEM DESCRIPTION

Figure 1 presents a photograph of DBI mounted on the wing of National Oceanic and Atmospheric Administration's (NOAA) WP-3D research aircraft. The top pod shell is attached to a pylon that is fixed to the wing. The system encompasses two pairs of squinted antennas that form fore- and aft-looking interferograms, a pulse compression radar transceiver, data acquisition and control system and an inertial-GPS velocity/attitude measurement system. A short summary of the system characteristics is given in [7]. The radar parameters used to date are given in Table 1.

The two interferometers consist of a pair of C-band microstrip patch array antennas separated in along-track direction by a baseline distance of 1.23 m.

Table1. DBI parameters

Parameter	Specification
Center Frequency	5.3 GHz
Polarization	VV
Bandwidth	25 MHz
Pulse width	6.25 µs
Pulse repetition frequency	10 kHz
Transmitted power	16 W
Receiver noise figure	3 dB
Platform height	600 m
Platform velocity	100 m/s
Antenna baseline	1.23 m
Boresight incidence angle	70º
Squint angle	20º
Azimuth beamwidth	7º
Elevation beamwidth	30º

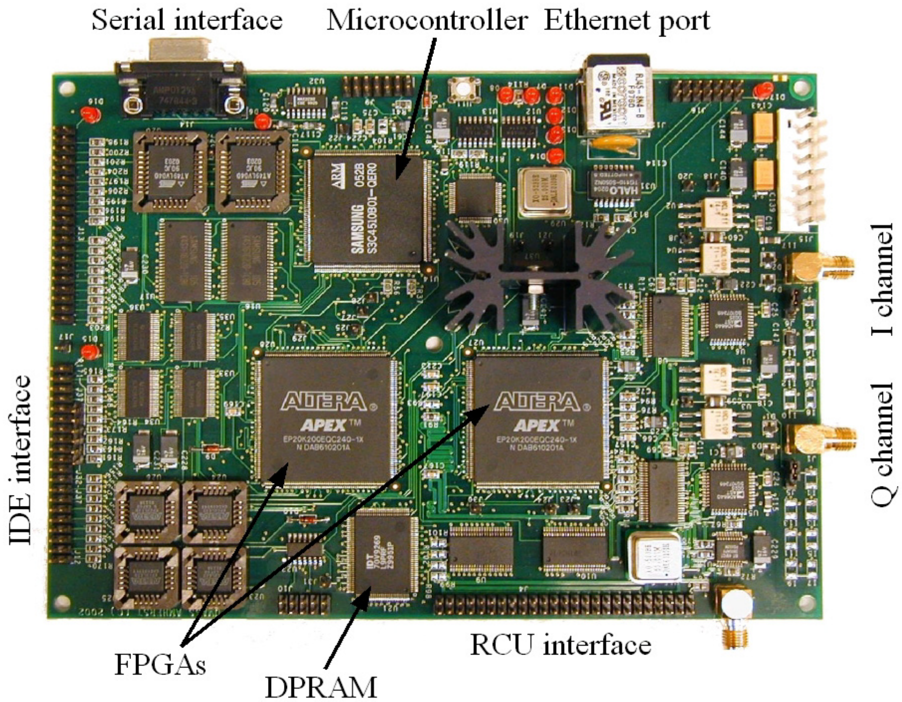

Figure 3. Photograph of the Data Acquisition Board

The antennas are squinted 20º aft and fore off the broadside and are referred to by their location (aft and fore) and orientation (aft and fore). Hence, AA is the Aft-located and Aft-squinted antenna, as shown in Figure 1. The AA and FA antennas form the aft-looking interferometer while the FF–AF pair represents the fore-looking interferometer.

The forward-located antennas are transmit-receive while the aft-located are receive only, resulting in the effective baseline being half of the physical baseline. All four antennas are vertically polarized with half beamwidths of 7º (H-plane) and 31º (E-plane). They are oriented towards 70º boresight incidence angle to deliver high gain at low grazing angles. The large incidence angle lowers signal-to-noise ratio however it enables us to have larger swath and insures that the Bragg scattering is the primary scattering mechanism. Changing range gate position results in coverage of different incidence angle spans within the antenna beam, further discussed in description of radar control unit. The radar electronics are housed within a rigid metal frame that is attached to the top pod shell when the instrument is mounted on the wing.

Figure 2 depicts a block diagram of the system in its present state. A linear FM chirp with a programmable bandwidth between 5 and 25 MHz is generated by a direct digital synthesizer (DDS) producing the resolution as high as 6 m (currently used). DDS operates at the frequency of 125 MHz, one of its aliased harmonics is upconverted yielding 5.3 GHz radar center frequency. Further on, the signal is amplified using a solid state amplifier (SSA) with the gain of 49 dB and then transmitted through one of the fore located antennas. The power output of the amplifier is 70 W but due to cable and duplexer losses the transmitted power at the antenna is approximately 16 W. The radar is periodically switched between aft- and fore-looking antennas (both fore-located) in a “ping-pong” fashion. The period of switching is programmable and dependent on the sampling rate.

The transmit network is common to both interferometers while the receive network consists of a pair of receivers connected to fore and aft located antennas through low noise amplifiers (LNAs). The received signal is demodulated with an intermediate frequency of 300 MHz. Each receiver produces an in-phase (I) and quadrature (Q) outputs that are fed to digital data acquisition system. The transmitted signal is periodically recorded into the received stream of data thus providing monitoring of the transmitted chirp signal.

The radar control unit (RCU) is composed of the embedded PC and a set of stacked PC-104 boards. One of the boards includes a field-programmable array (FPGA) configured to generate timing and switching signals. The timing signals are passed to the Data Acquisition Board (DAQ) through a custom bus interface while the switching signals are routed to transmit and receive switches (TX/RX). The embedded

PC is equipped with a wireless PCMCIA card used to communicate to the operator's computer installed inside the aircraft. The operator uses a graphical user interface (GUI) developed specifically for configuration of DBI operation modes. The GUI runs on the embedded PC and communicates to the RCU through an Industry Standard Architecture (ISA) bus. Each run of the radar requires the desired parameters (bandwidth and length of the chirp signal, sampling frequency, distance to first range gate, number of pulses for coherent averaging, etc.) to be entered through GUI to RCU. As such, DBI represents a versatile research platform for monitoring and mapping of currents and current features in littoral regions.

Data acquisition system consists of a pair of custom designed boards, one of which is shown in Figure 3, developed at the University of Massachusetts [3]. Each board incorporates two 12-bit 65-MSPS analog-to-digital converters followed by real-time coherent integration and dual Integrated Drive Electronics (IDE) disk interfaces for data storage. Currently each board is interfaced to a single hard drive. Coherent integration of up to 16 pulses can be implemented for each look. The radar switches beams between the integration periods so that the data from both looks is recorded on each drive. The coherent integrator, data packaging and storage interfaces are implemented using a pair of field-programmable gate arrays (FPGAs). The board is controlled by a microprocessor that is able to access data in shared onboard memory (DPRAM). DPRAM is needed because one of the FPGAs writes the data packets to onboard memory and the microprocessor reads the packets from the memory transferring them to the IDE interface, with reading and writing processes occurring concurrently. Data acquisition boards also include a serial and an Ethernet connection. The embedded PC is interfaced to the DAQ through the serial port while the ethernet link is used for data backups. The GPS timestamps are written into the data stream through serial interface. Presently the system supports data rates up to 6.2 MB/s per receiver. With 160 GB of onboard storage at the highest data rate it can acquire up to 3.5 hours of raw data between backups.

The radar integrates a GPS/inertial navigation system (GPS/INS) time stamps into the data stream. Attitude/position information is provided by Boeing CMIGITS-II and is stored on the embedded PC. CMIGITS-II is a digital quartz inertial (DQI) measurement unit with five-channel L1 Coarse/Acquisition (C/A) code GPS engine [4]. It is mounted on the frame of the instrument to precisely give the attitude information of the radar needed for motion compensation during data processing. The system also accepts differential GPS (DGPS) corrections provided by the U.S. Coast Guard network of 300 kHz beacons. A VLF beacon receiver is also included within the instrument frame to enable real-time differential GPS. CMIGITS-II is turned on before the radar in order to lock its precise position before the data collection starts. It is interfaced to the embedded PC through an RS-232 (serial) link. The GPS data stream is received at the embedded PC where the 8 byte time stamp is stripped and sent over a serial interface to the DAQ to be included with the radar data packets for collocation of data from fore and aft receivers. The full GPS stream is also saved at the embedded PC to be used in post-processing.

The system is turned on after take-off and the operator communicates to the embedded PC through the wireless link. The radar is then set to a particular mode of operation and the data collection can begin. The versatility of the radar comes from the ability to select radar parameters at each data collection run. DBI was designed to study the feasibility of current mapping in costal areas using a variety of radar modes that could accommodate significant changes in altitude and speed of the aircraft.

3. Deployment overview

DBI was deployed several times over the course of the past two years. The first two deployments, December 2002 and June 2003 were engineering tests while the August 2003 and March 2004 were scientific missions. Throughout the deployments DBI has flown on NOAA's WP-3D "Hurricane Hunter" research aircraft based at the NOAA

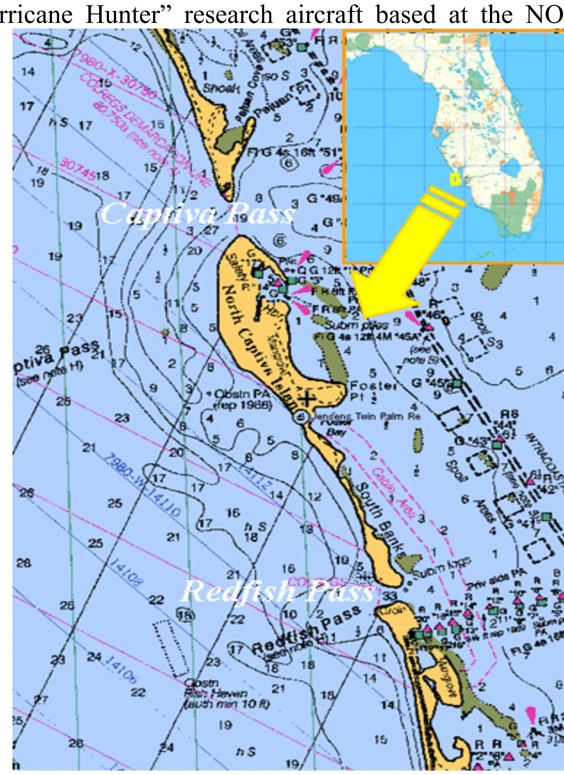

Figure 4. Barrier islands Gulf coast of Florida

Aircraft and Operations Center in Tampa, FL. The flights were accomplished jointly with remote sensing scientists from NRL who provided flight-hour and data processing support.

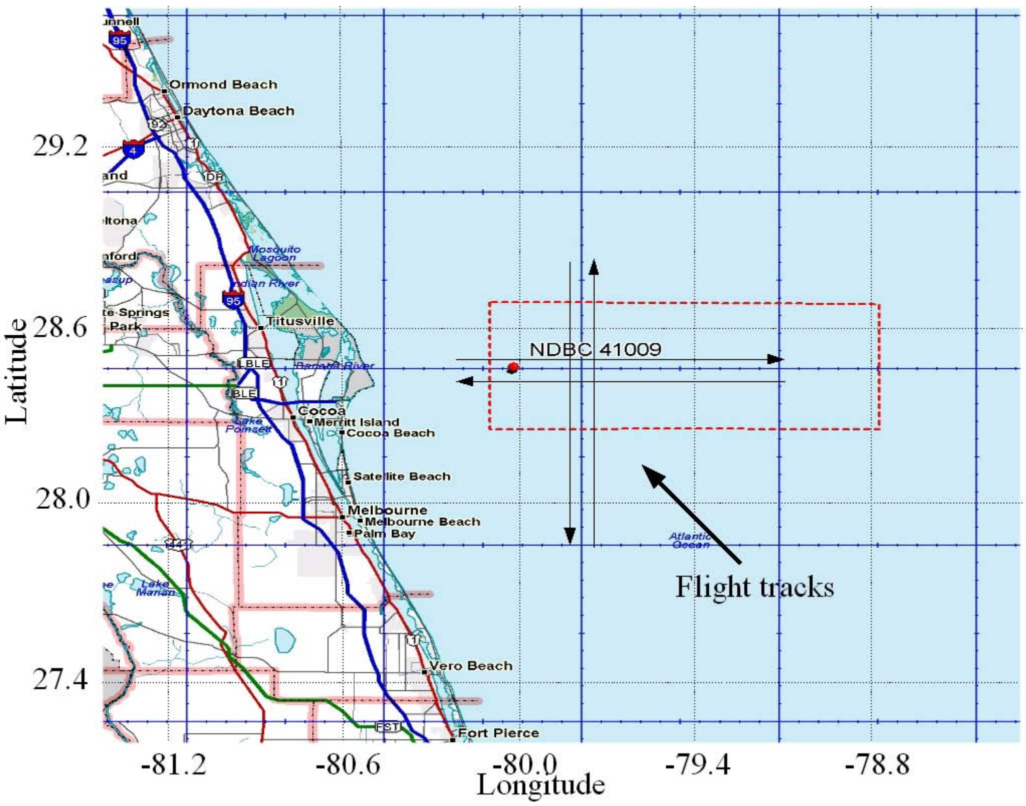

Figure 5. East coast of Florida deployment map

The March 2004 campaign lasted 2 weeks and was mainly focused on the Western boundary of Gulf Stream, East of Cape Canaveral, FL (Figure 5). Several overflights of the Florida barrier islands west of Fort Meyers (Figure 4) were made as well, where DBI was used to image the tidal flow through the inlets.

The following section provides the synopsis of the main results. A more detailed discussion can be found in [8, 9].

4. RESULTS

The flight path over Gulf Stream, shown in Figure 5 was set close to the weather buoy station NDBC 41009 in order to have in situ wind data that would be used in the interpretation of data. The western boundary of the Gulf Stream is located roughly at 80º W. The flight pattern was chosen to provide a range of viewing angles at the boundary. The data presented below were taken from an East-West transect on March 12th 2004 over the time interval 19:40:19 local (Eastern standard) time to 19:42:03. The images shown below have been synthesized using the extended chirp scaling (ECS) algorithm [6] modified and adapted by NRL to fit the data format and physical set-up of DBI.

During this flight an infrared (IR) camera mounted on the belly of the aircraft was operated simultaneously. The real time data from the IR camera was used to note the times of boundary crossings and later to verify the features observed by both instruments.

Figure 6 shows a SAR magnitude image from one of the fore looking antennas (a) and the interferometric phase for the fore look (b). On the left-hand side of the magnitude image one can distinguish darker features, known as slicks, whilst none are visible on the right. Slicks form due to presence of organic films on the surface and are generally visible at low wind speeds (less than 6 m/s) [5]. Organic material changes the surface tension of the ocean, which dampens small scale surface roughness and reduces backscatter; hence these regions appear dark in SAR magnitude images. At the time of data collection the weather buoy station NDBC 41009 reported winds from South-East of average speed of 4.9 m/s. The obvious phase change in Figure 6 (b) indicates a presence of a strong current on the right hand side, i.e. Gulf Stream current.

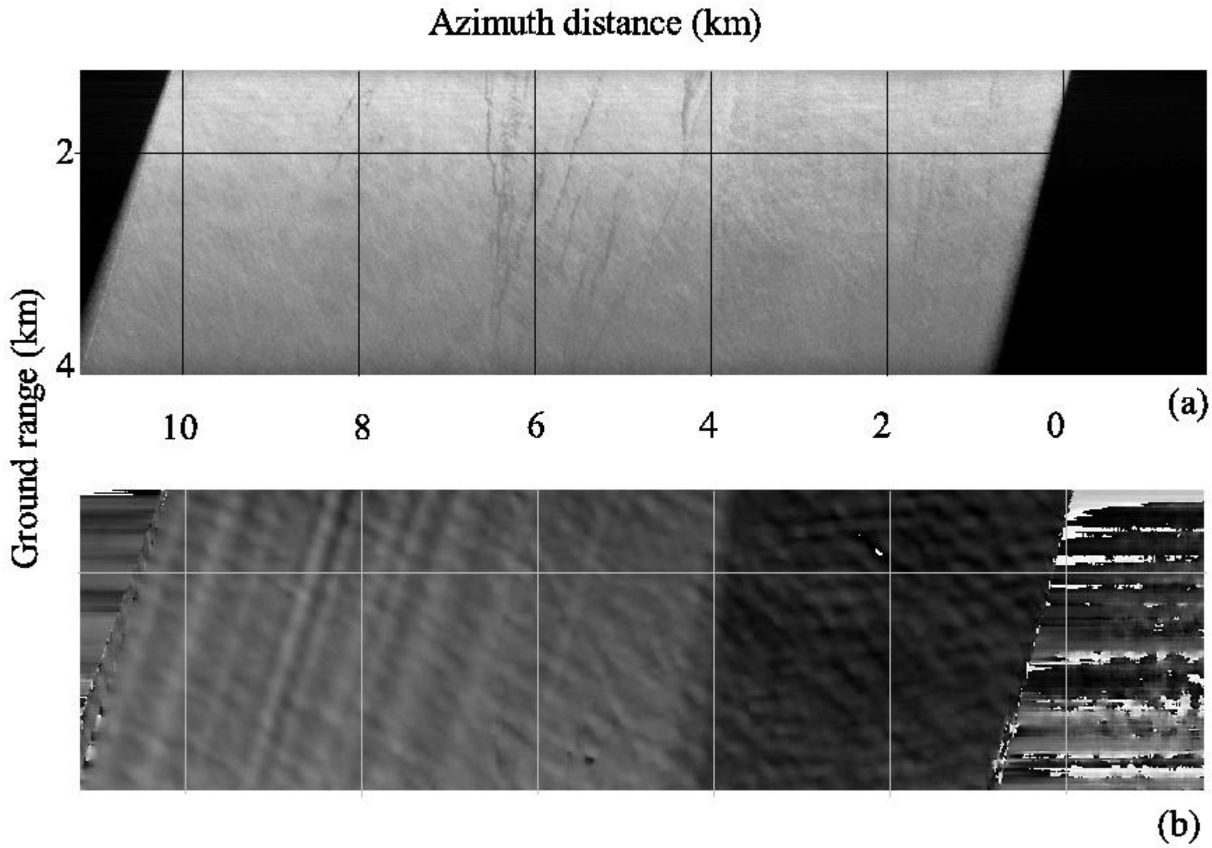

Figure 6. (a) SAR magnitude image (b) interferometric phase for the fore look

Figure 7 represents the same area as Figure 6 with the vector velocity field superimposed. The directional surface velocity field was retrieved from the interferometric phase of the fore and aft interferometers. Without removing the contribution of wind-generated surface roughness (believed to be small), the velocity magnitude within the Gulf Stream is estimated to be 1.5 m/s. Indeed, as mentioned above, the wind conditions that day were rather low, often resulting in little backscatter; therefore the velocity measurement should be dominated by the Gulf Stream current. Contribution from surface roughness to overall velocity estimate is perhaps more prominent on the left hand side of the image since there is no underlying current in this area.

Figure 8 shows the data collected on the following day, March 13th, over the barrier islands south of Boca Grande (cf. Figure 4). A strong change in phase is observed in both inlets, indicating a presence of tidal currents. Similar to Figure 7, vector velocities can be retrieved using fore- and aft-looking interferograms. Figure 9 shows detailed vector field in Redfish pass that conforms to the expected outflow pattern. The retrieved velocities can be compared to data from the NOAA's National Ocean Service (NOS) that predict times and speeds of the peak tidal currents. According to NOS, the maximum ebb current of 1.62 m/s occurred in Captiva pass that day around 22:10:00 EST. The radar data was collected about 27 minutes later (22:36:50-22:38:34 EST) and yield the velocity estimate of 0.75 m/s for the Captiva pass. The NOS data was unavailable for the narrower Redfish Pass, where our measurements indicated velocities of up to 2.2 m/s, as perhaps should be expected. As before, no adjustments for wind-roughness component was made, given the retrieved current patterns but not an exact agreement with the NOS data, that contribution could be more significant than predicted. The extracted velocity field is shown

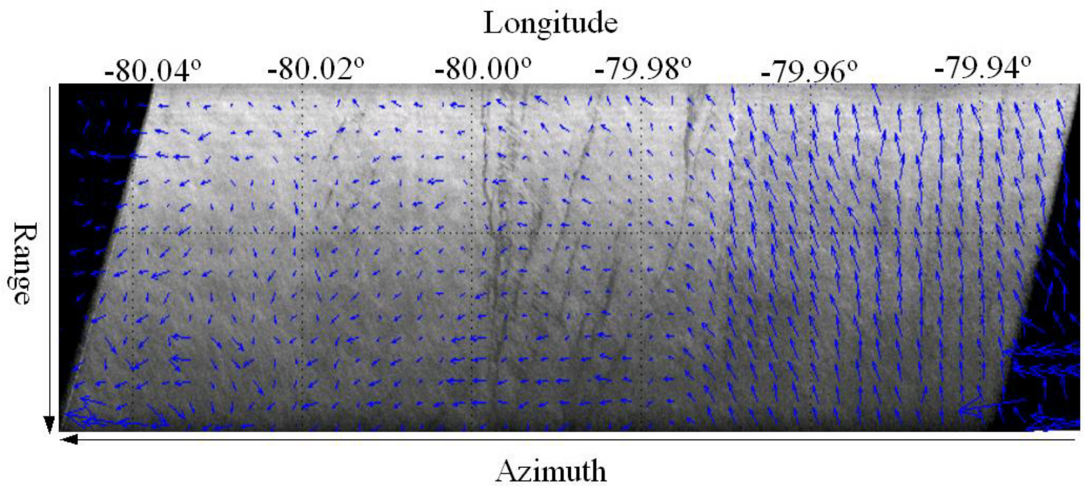

Fig.7. DBI directional surface velocity field over the Gulf Stream

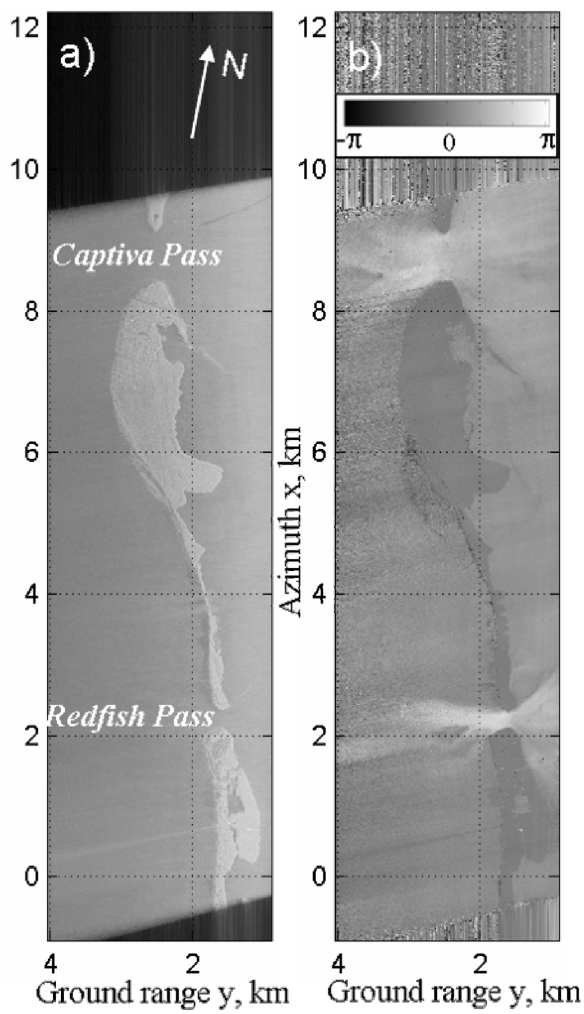

Figure 8. (a) SAR magnitude image, (b) interferometric phase for the aft look

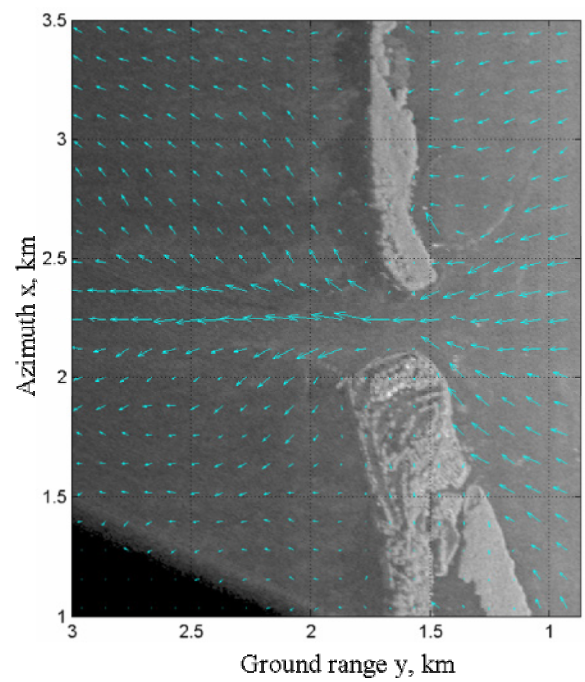

Figure 9. Directional velocity field in Redfish pass

superimposed on the magnitude image in Figure 9 in Redfish pass.

5. CONCLUSIONS

In this paper we have described the operation of the Dual Beam Interferometer and showed some results from the analysis of its data. DBI is fully contained within the aircraft pod that makes it platform independent. Its autonomous nature combined with versatility of operational modes makes the instrument suitable for mounting on almost any aircraft.

The initial test-flights confirmed the full functionality of the radar while the further scientific data collected during March experiment show the capability of DBI to produce detailed vector maps of surface velocity in a single pass of the aircraft. When quality processing and retrieval algorithms such as the ones used by NRL are applied, the resulting surface velocity maps both conform to the expected patterns and show good quantitative agreement with the in-situ data. The retrieved velocities from other passes over the Gulf Stream and the coastal regions during the March campaign consistently confirmed these findings. Further efforts are being put into hardware improvements and removal of surface wave contributions to the vector velocities.

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REFERENCES

[1] P. Rosen, S. Henesley, I. R. Joughin, F. K. Li, E. Rodriguez and R. M. Goldstein, “Synthetic aperture radar interferometry”, IEEE Proceedings, vol. 88, no. 3, pp. 333-382, March 2000.

[2] S. Frasier and A. Camps, “Dual-beam interferometry for ocean surface current vector mapping”, IEEE Trans. Geosci. Remote Sensing, vol. 39, no. 2, pp. 401-414, February 2001.

[3] A. Ramanathan, “Acquisition of remote sensing data on a reconfigurable platform”, Master’s Thesis, University of Massachusetts, Amherst, 2003.

[4] “Miniature Integrated GPS/INS system, CMIGITSTM II: Preliminary information sheet”, Rev. 04-22-1997, Boeing Corp., Seattle, WA, April 1997.

[5] A. R. Ochadlick et al., “Synthetic Aperture Radar Observations of Currents with Slicks”, J. Geophys. Res. Vol. 97, no. C4, pp. 5325-5330, April 1992.

[6] A. Moreira and Y. Huang, “Airborne SAR Processing of Highly Squinted Data Using a Chirp Scaling Approach with Integrated Motion Compensation”, IEEE Trans. Geosci. Remote Sensing, vol. 32, pp. 1029-1040, September 1994.

[7] G. Fraquharson et al., “A Pod-Based Dual-Beam SAR”, IEEE Geosci. Remote Sensing Vol. 1, no. 2, pp. 62-65, April 2004.

[8] J. V. Toporkov et al., “Initial Vector Velocity Estimates from UMass Dual Beam Interferometer”, IEEE IGARSS 2004 Proceedings Vol. 1, no. 2, pp. 62-65, September 2004.

[9] D. Perkovic et al., “Gulf Stream Observations Obtained with the UMass Dual Beam Interferometer and an Infrared Camera”, IEEE IGARSS 2004 Proceedings Vol. 1, no. 2, pp. 62-65, September 2004.

BIOGRAPHY

Dragana Perkovic has received the B.S. in electrical engineering from the University of Malta in 2002 with the major in telecommunications and computing. Currently she is pursing a PhD degree at the University of Massachusetts, Amherst at the Microwave Remote Sensing Laboratory (MIRSL). She is working on the Dual Beam Interferometer hardware improvements and data processing.

Stephen J. Frasier received the B.E.E. degree in 1987 from the University of Delaware, Newark and the Ph.D. degree in 1994 from the University of Massachusetts, Amherst. From 1987 to 1990 he was with SciTec, Inc., a subsidiary of TRW, where he worked on signal processing and analysis of EM and IR signatures of rocket plumes, evaluation of laser detection systems, and development of data acquisition systems for airborne IR sensors. In August 1990 he joined the Microwave Remote Sensing Laboratory of the University of Massachusetts. His graduate work involved the development and application of a phased-array imaging radar for oceanographic research. From 1994 to 1997, Dr. Frasier was been employed by the University of Massachusetts as a Research Engineer and Senior Research Fellow. In 1997 Dr. Frasier joined the faculty of the Electrical and Computer Engineering Department as an Assistant Professor. He was promoted to Associate Professor in 2002, and he currently directs the Microwave Remote Sensing Laboratory. His research interests include microwave imaging and interferometric techniques, radio oceanography, and remote sensing of the atmospheric boundary-layer. Dr. Frasier is an associate editor of the journal Radio Science and has served as chair of the Springfield (MA) chapter of the IEEE Geoscience and Remote Sensing Society. He is a member of the American Meteorological Society and the American Geophysical Union.

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Jakov V. Toporkov was born in Sverdlovsk (now Yekaterinburg), Russia. He received the M.S. degree (with distinction) in Electronics Engineering from Moscow Institute of Physics and Technology, Russia, in 1989, and the M.S. and Ph.D. degrees in Physics from Virginia Tech, Blacksburg, VA in 1996 and 1998, respectively. From 1989 to 1993, he was employed in Russia as an engineer-researcher and was involved in the design of synthetic aperture radars (SAR). In particular, his research interests at the time included SAR imaging of moving targets. In 1998-1999 he held a postdoctoral appointment at the Bradley Department of Electrical and Computer Engineering at Virginia Tech where he worked on the numerical studies of scattering from randomly rough ocean-like surfaces. In 1999, Dr. Toporkov joined SFA, Inc., Largo, MD and was stationed at the Naval Research Laboratory, Washington, DC. There he was engaged in development of image processing capabilities for ultrawideband light airborne SAR system and in studies of scattering from ocean surface at low grazing angles. Since 2002, Dr. Toporkov is a Research Physicist at the Naval Research Laboratory. His present research interests include physics of wave scattering by ocean surface and SAR remote sensing. Dr. Toporkov is a member of Commission F of the U.S. National Committee of the International Union of Radio Science (USNC-URSI) and a Senior Member of IEEE. In 1999, together with his co-authors R. Marchand and G. Brown, he was a recipient of the IEEE Antennas and Propagation Society Schelkunoff Best Paper Award.

Mark A. Sletten received the BS, MS, and Ph.D. degrees in electrical engineering from the University of Wisconsin, Madison in 1984, 1987, and 1991, respectively. From 1985-1987, he was a Research Assistant and ECE Department Fellow at the Wisconsin Center for Applied Microelectronics. As a doctoral student under the Rockwell International Doctoral Fellowship Program, his research included experimental and theoretical investigations of polarization-altering, guided wave optical devices. Since joining the Naval Research Laboratory in 1991, he has been engaged in radar-based ocean remote sensing research. This work includes the development of ultrawideband, polarimetric systems for determining the fundamental physics underlying low-grazing-angle radar sea scatter, and the development and use of airborne radar systems (both real and synthetic aperture) for remote sensing of the coastal ocean. Past work has included a real-aperture radar study of the Chesapeake Bay outflow plume, and the development of a lightweight, multiband, interferometric SAR for use on a light aircraft. More recently, Dr. Sletten has conducted several field experiments that investigate the use of interferometric SAR systems for measuring ocean surface currents and mapping the space-time evolution of sub-mesoscale oceanic eddie.