AIRSAR Along-Track Interferometry

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Abstract: Although an along-track interferometric (ATI) capability was demonstrated for the AIRSAR (Airborne Synthetic Aperture Radar) instrument over a decade ago, only recently has the motion measurement and processing technology allowed this capability to become a standard mode of data collection. Data collected during the PacRim mission are being used to develop, calibrate and validate the processor for this mode. We present the new AIRSAR ATI processor and describe its calibration and performance. We present example ATI data sets collected during PacRim as well as more recently and we discuss future AIRSAR ATI capabilities.

1 Introduction

In Along-Track Interferometric (ATI) data[1] the interferometric phase at each pixel is related to the motion of the scatterers within the pixel. [*Slide 1*] ATI mode data has been collected by the AIRSAR instrument as early as 1987—originally as a classified experiment. Although a few ATI data sets have been published, in each case the processing was experimental and each data set required significant "special processing" because of the immaturity of both the motion measurement system available and the state of interferometric SAR processing. We have since acquired a much more accurate embedded GPS/INU system and have gained experience in interferometric SAR processing which we have applied to the development of an operational ATI processor.

1.1 Why ATI?

There are several advantages of ATI data over conventional radar and other existing oceanographic monitoring systems. [*Slide 2*] Some of these advantages and applications of ATI include:

- ATI (unlike altimetry, for example) provides a direct measurement of the surface velocity—no geostrophic assumption is required.
- Ocean signatures of boundary layers are much greater in the phase than in the brightness of a radar return, since the backscatter tends to be proportional to wave-height while phase is proportional to wave direction and speed.

[1] For the convenience of the reader, an abbreviated Bibliography is provided at the conclusion of this paper.

- With an ATI system the coherence time is measured directly and may be useful for monitoring micro wave-breaking events which control the ocean-atmosphere gas transport/mixing process.
- Wave spectra measured by the ATI phase are less distorted than those obtained by brightness imagery alone.
- ATI data may provide enhanced indication of man-made moving targets, with significant slower minimum detectable velocities than conventional moving-target radars.
- ATI data may be useful for mapping surfactant and pollution dispersion paths.
- ATI data can be used to map coastal surf-zones, identifying areas of heavier surf or relatively protected shores.

1.2 Concept

As an electromagnetic wave propagates a round-trip distance 2ρ to and from a scatterer its phase changes by

$$\phi = -\frac{4\pi}{\lambda}\rho \tag{1}$$

due to the propagation, where λ is the wavelength of the radiation and the sign is given by noting that the doppler shift due to a scatterer with a range changing in time is:

$$f_D = \frac{1}{2\pi}\frac{\mathrm{d}\phi}{\mathrm{d}t} = -\frac{2}{\lambda}\dot{\rho} \tag{2}$$

where $\dot{\rho}$ is the time rate of change of the propagation distance, i.e., a "blue-shift" as the scatterer approaches the radar and a "red-shift" as it recedes. The ATI phase is formed at each pixel in an image by a conjugate-multiply of the first image (C_1) by the second (C_2), i.e.,

$$\Delta\phi = \arg(C_1 C_2^*). \tag{3}$$

For a scatterer moving at a velocity $\mathbf{u}$ and a radar with a line of sight to the target, $\mathbf{n}$ the change in phase is

$$\Delta\phi \approx \frac{4\pi}{\lambda}\mathbf{n}\cdot\mathbf{u}\Delta t \qquad (|\mathbf{u}|\Delta t \ll \rho) \tag{4}$$

where Δt is the time between two consecutive observations. This is the phase measured in an along-track interferometric SAR.

Note that we have assumed that the signal propagates to the scatterer and back at from the same location. It is important that the spatial interferometric baseline for ATI data is zero—the only baseline is temporal. Ideally, one would use an array of large stationary antennas to map the phase, $\Delta\phi$ of a scene. This is impractical. Instead, we use a pair of SAR antennas displaced in the direction of the travel of a moving platform. If the platform moves at a speed v and the phase centers of the antennas are displaced a distance b, then the time interval between the two SAR images formed using the two antennas will be $\Delta t = b/v$, assuming that the radar transmits alternately from each antenna, and receives the signal with the same antenna used to transmit (so-called "ping-pong" mode).

There is an important subtlety being overlooked in the above discussion: since we are using a SAR to form each image, each image will be formed by integrating the return over a synthetic aperture of length $S = \rho\theta$ where θ is the antenna beamwidth, $\theta \approx \lambda/L$. The time to integrate each image is therefore

$$T = \frac{\rho\lambda}{vL} \tag{5}$$

where L is the antenna length. This time is on the order of a few seconds for the AIRSAR L and C-band radars, which can be fairly long compared to the correlation time of the ocean. This will be discussed further at the end of the paper. Meanwhile, it is clear that short-timescale oscillatory motions will be averaged out in favor of longer-time scale motion (swell and ocean currents).

1.3 AIRSAR ATI Capability

AIRSAR *[Slide 3]* has both L-band and C-band systems. Table 1 details the geometry of these systems. For a time interval between observations of Δt, the ambiguous velocity component is given by

$$\Delta\phi = -\frac{4\pi}{\lambda}(\mathbf{n}\cdot\mathbf{u})_{\mathrm{amb}}\Delta t = 2\pi \tag{6}$$

The maximum unambiguous velocity components for each AIRSAR ATI system are also given in Table 1.

2 The AIRSAR ATI Processor

The AIRSAR ATI processor *[Slide 4]* consists of a typical range-doppler front-end SAR processor for image formation, followed by interferogram formation, phase unwrapping (which is typically less important for ocean applications than it would be for a cross-track interferometer, since ocean currents rarely wrap the interferometric phase for the AIRSAR along-track baselines) and geo-location. In this section we highlight some of the details of the AIRSAR ATI processor.

2.1 Motion Alignment

A crucial component of the ATI processing is the alignment of the interferometric channels. The trajectory of the phase center of each interferometric channel is determined from the platform motion and attitude data *[Slide 5]* combined with the lever arms from the embedded GPS/INU to the antenna phase centers. Based on these trajectories, a common reference

ATI Mode	b	Δt	$(\mathbf{n} \cdot \mathbf{u})_{\mathrm{amb}}$
LP	19.7 m	99 ms	1.2 m/s
LC	9.8 m	49 ms	2.4 m/s
LS	25 cm	1.3 ms	92 m/s
CP	1.9 m	9.5 ms	3.0 m/s
CC	95 cm	4.8 ms	5.9 m/s
CS	25 cm	1.3 ms	22 m/s

Table 1: The AIRSAR ATI systems. In the mode name, the first letter represents the frequency band and the second, the type of along-track baseline. b is the "effective" baseline, which is the same as the physical baseline for the "ping-pong" modes, LP and CP, and approximately half of the physical baseline for the "common-transmitter" modes (LC and CC) where only one antenna is used for transmit. LS and CS are the "single-pulse" ATI modes, where an interferogram is formed two images, each obtained by a signal transmitted from one antenna and received by the other, i.e., transmit aft, receive forward for the first image and transmit forward, receive aft for the second. Δt is the time interval corresponding to each effective baseline for a platform moving at a nominal speed of 200 m/s. A nominal PRF of 800 Hz is assumed.

trajectory [*Slide 6*] is formed to facilitate image formation. This trajectory is the synthetic antenna aperture. Thus, the signals from each interferometric antenna must be propagated to this reference trajectory. This propagation is carefully accomplished by using an average platform attitude (and therefore, imaging plane) at each point along the reference trajectory. This imaging plane determines from where along the individual phase center trajectories the signals must be propagated to the reference trajectory.

2.2 Range Compression

The raw signal data (proportional to the voltage digitized at the analog-to-digital converters after being mixed down to video from microwave frequencies) [*Slide 7*] is compressed against the reference chirp to localize the time of the return of each scattered signal within a given pulse. The information determined by the previous motion alignment step is then used to interpolate [*Slide 8*] the pulses from both interferometric channels to a constant spacing along the reference trajectory to prepare for image formation.

2.3 Motion Compensation

The motion compensation of the data relies on the accuracy of the elevation reference, as well as the position information from the embedded GPS/inertial navigation system. In particular, any error in the elevation reference will introduce a phase bias into the data for each channel. In a system with antennas displaced solely along track, this presents no difficulty, because the same phase bias is introduced into each channel and is cancelled in the interferogram. However, where there is a cross-track baseline component as well (as is the case in both AIRSAR ATI radars, but especially the C-band system) this phase bias will be different for each channel, leading to what appears to be a togographic phase signature. This only occurs when the scatterer is at a significantly different elevation than the reference. The motion-compensation correction used to propagate the signal from the antenna phase center to the synthetic array is:

$$\rho_m = \mathbf{l} \cdot \mathbf{n} \tag{7}$$

where $\mathbf{l}$ is the lever arm to an antenna phase center and $\mathbf{n}$ is the look direction unit-vector. The propagation is accomplished by an interpolation followed by a phase-correction of $\phi_m = -(4\pi/\lambda)\rho_m$. The baseline vector, $\mathbf{b}$, is the difference between the two lever-arm vectors, and the difference in the motion-compensation phase distortion between the two interferometric channels introduced by an error in the elevation reference is:

$$\delta\phi_m = -\frac{4\pi}{\lambda}\mathbf{b} \cdot \frac{\partial \mathbf{n}}{\partial h}\Delta h = -\frac{4\pi \Delta h}{\lambda \rho}\mathbf{b} \cdot [\mathbf{z} + \mathbf{y}\cot\theta] \tag{8}$$

where $\mathbf{z}$ and $\mathbf{y}$ are unit vectors in the vertical and cross-track directions, respectively, and θ is the look angle. For typical AIRSAR imaging geometries, at C-band, this works out to

$$\left|\frac{\delta\phi_m}{2\pi}\right| \sim \frac{\Delta h}{250\text{m}}, \tag{9}$$

i.e., one cycle for every 250 meters of elevation reference error.

This phase does not affect sea-level ATI processing, and could be eliminated for all scenes by introducing a digital elevation model to the motion-compensation algorithm.

2.4 Image Formation

The AIRSAR ATI processor uses the standard (squinted) range-doppler algorithm [*Slide 9*] for image formation, but employs the exact range for the range-migration and azimuth compression steps:

$$\frac{\delta\rho}{\rho} = 1 - \left(\frac{\cos^2\theta}{\cos^2\theta_c}\right)^{\frac{1}{2}} \tag{10}$$

where $\delta\rho$ is the range migration correction, ρ is the squinted, motion-compensated range to the target. The correction is applied in the frequency domain, so θ is the azimuth angle at a given doppler frequency:

$$\sin\theta = \frac{\lambda}{2v}f \tag{11}$$

where f is the Doppler frequency, v is the along-track speed of the platform, and λ is the wavelength of the radar. θ_c is the azimuth angle at the Doppler centroid.

The azimuth reference function is first computed in the time domain:

$$g(t)e^{-4\pi\rho(t)/\lambda} \tag{12}$$

and then Fourier-transformed to do the convolution as a conjugate-multiply in the doppler-domain. $g(t)$ is a windowing function to used to reduce azimuth ambiguity noise and limit the reference function to the desired synthetic aperture length. In the examples presented here, the full synthetic aperture is used for $g(t)$. A further refinement will be to limit $g(t)$ to the time specified by (5).

The interferogram is formed from the single-look imagery in the slant range, and the correlation map is formed by averaging the single-look imagery over several looks:

$$\gamma = \frac{\langle C_1 C_2^* \rangle_N}{\sqrt{\langle C_1 C_1^* \rangle_N}\sqrt{\langle C_2 C_2^* \rangle_N}} \tag{13}$$

The magnitude of each element in this map is a number between 0 and 1 and the argument is the interferogram, averaged over N looks.

Once the image (and interferogram) formation process is complete, the data are projected [*Slide 11*] onto the reference elevation surface at sea level and converted from phase to velocity.

2.5 Calibration

Table 2.5 describes the parameters used to calibrate AIRSAR ATI data. The following is the calibration procedure [*Slide 10*] for AIRSAR ATI data:

1. The Doppler centroid of the data set is estimated as a function of range from the radar signal data. This is compared to the Doppler centroid predicted by the INU-measured attitude, and used to determine biases for pitch, Δp, and yaw, Δy.

   The latter Doppler centroid (phase change per pulse) is calculated from the motion data:

$$\begin{aligned}\phi_D = \frac{4\pi t_{\text{prf}}}{\lambda}\Bigg\{ \quad & v_s \left(\sin y \sin \left[\cos^{-1} \frac{h \sec p}{\rho} \right] + \frac{h \cos y \tan p}{\rho} \right) + \\ & v_c \left(\cos y \sin \left[\cos^{-1} \frac{h \sec p}{\rho} \right] - \frac{h \sin y \tan p}{\rho} \right) - v_h \frac{h}{\rho} \Bigg\}\end{aligned} \tag{14}$$

   where ϕ_D is the Doppler, t_{prf} is the time between pulses from a given antenna (either forward or rear), λ is the wavelength, p is pitch, y is yaw, h is the height of the platform above the terrain, v_s, v_c and v_h are the along-track, cross-track and height components of the platform velocity, and ρ is the slant range.

   In order to estimate the bias in yaw and pitch we solve a set of linear equations:

$$\phi_D^{\text{Est}}(\rho_i) = \phi_D^{\text{IMU}}(\rho_i) + \frac{\mathrm{d}\phi_D}{\mathrm{d}y}(\rho_i)\Delta y + \frac{\mathrm{d}\phi_D}{\mathrm{d}p}(\rho_i)\Delta p \tag{15}$$

for Δy and Δp, the yaw and pitch biases, respectively; where $\phi_D^{\mathrm{Est}}(\rho_i)$ are the Doppler centroid estimates from the radar phase history at ranges ρ_i and similarly, $\phi_D^{\mathrm{IMU}}(\rho_i)$ are the Doppler centroid calculations from the motion data. (Note that the Doppler centroid may only be estimated from the radar phase history modulo an even number of π's. These are added back in to make the comparison to the Doppler centroid calculated from the motion data.) $\frac{\mathrm{d}\phi_D}{\mathrm{d}y}(\rho_i)$ are the derivatives of the Doppler centroid with respect to yaw evaluated at ranges ρ_i and similarly, $\frac{\mathrm{d}\phi_D}{\mathrm{d}p}(\rho_i)$ are the derivatives of the Doppler centroid with respect to pitch. These derivatives are:

$$\frac{d\phi_D}{dp} = \frac{4\pi t_{\mathrm{prf}}}{\lambda}\Bigg\{ \quad v_s\left(\frac{h\cos y\sec^2 p}{\rho} - \frac{h^2\sec^2 p\sin y\tan p}{r^2(1-(\frac{h\sec p}{\rho})^2)^{\frac{1}{2}}}\right) + v_c\left(\frac{-h\sec^2 p\sin y}{\rho} - \frac{h^2\cos y\sec^2 p\tan p}{r^2(1-(\frac{h\sec p}{\rho})^2)^{\frac{1}{2}}}\right)\Bigg\} \tag{16}$$

$$\frac{d\phi_D}{dy} = \frac{4\pi t_{\mathrm{prf}}}{\lambda}\Bigg\{ \quad v_s\left(\cos y\sin\left[\cos^{-1}\frac{h\sec p}{\rho}\right] - \frac{h\sin y\tan p}{\rho}\right) + v_c\left(-\sin y\sin\left[\cos^{-1}\frac{h\sec p}{\rho}\right] - \frac{h\cos y\tan p}{\rho}\right)\Bigg\} \tag{17}$$

2. An initial image and interferogram is formed for a standard calibration set with corner reflectors in the scene.

3. The ranges to surveyed corner reflectors located in the calibration data set are computed using the platform position information and compared to the ranges at which the corner reflectors appear in the slant-range imagery. The difference between the actual and observed range is the common-range delay, r_c.

4. The cross-correlation between the two interferometric channels is used to obtain the differential delay, r_d, (from the range offset) and a first estimate of a correction to the along-track baseline $(\mathbf{s}\cdot\mathbf{\Delta b})$ (where $\mathbf{s}$ is a unit vector along the direction of platform motion).

5. Image and interferogram formation is repeated using the updated calibration parameters. The phase variation as a function of range (assuming a stationary calibration scene) is used to fit, and remove, cross-track baseline components: $(\mathbf{c}\cdot\mathbf{\Delta b})$ and $(\mathbf{h}\cdot\mathbf{\Delta b})$, where $\mathbf{c}$ and $\mathbf{h}$ are unit vectors in the cross-track and height direction, respectively. These are estimated by solving the set of linear simultaneous equations:

$$A\mathbf{\Delta b}\cdot\mathbf{n} = \eta \tag{18}$$

for $\mathbf{\Delta b}$ where $\mathbf{\Delta b}$ is the vector of baseline components errors, η is the vector of interferometric phase observations over the stationary terrain (will be zero when the

Parameter	Description
r_c	common range delay
r_d	differential range delay
$\mathbf{\Delta b}$	baseline correction $(\Delta(\mathbf{l_1} - \mathbf{l_2}))$
Δp	INU pitch bias
Δy	INU yaw bias
$\Delta\phi$	phase offset

Table 2: Each of these parameters is a single constant (Δb has three constant components) which should hold for a given instrumental configuration. In other words, these eight parameters may be determined at the beginning of a data collection campaign over a calibration site and then applied to correct every subsequent data set without re-measurement of the calibration parameters.

baseline components are correct), the line-of-sight vector is:

$$\mathbf{n} = \begin{pmatrix} \sin y \sin\gamma + \cos y \sin p \cos\gamma \\ \cos y \sin\gamma - \sin y \sin p \cos\gamma \\ -\cos p \cos\gamma \end{pmatrix}; \qquad \gamma \equiv \cos^{-1} \frac{h}{\rho \cos p} \tag{19}$$

and the rotation matrix A is given by the yaw, pitch, roll Euler angle sequence for the INU.

6. A scene with land at a known elevation reference is used to determine the phase offset between the two interferometric channels. This calibration signal phase is used to track phase changes in the receiver chain during the mission.

To date, we have accomplished the baseline and differential delay calibration steps. Still remaining is the INU-bias estimation and the phase offset between the two channels. The effect of an uncorrected INU-bias is to introduce phase "bars" reflecting the motion of the platform along the data take. The uncorrected phase bias leads to a non-zero phase for stationary targets, and can usually be corrected by land near the elevation reference in the scene for the data sets shown in this paper.

3 Example ATI Data Sets

In this section we present several data sets [*Slides 12–20*] used to validate the AIRSAR ATI processor and evaluate the measurement accuracy of the AIRSAR ATI system.

ATI Data Collection Site
South Pacific Ocean
South China Sea
Philippine Sea
New Zealand Transit
Kohala Coast (Four lines over ground truth)
East Australian Current (Four lines, one long transit)
East China Sea
Gulf of Thailand
Tasman Sea (Two lines)
Baringhead, New Zealand

Table 3: ATI data sets collected by AIRSAR during the 1996 Pacific Rim campaign.

3.1 Pacific Rim Mission

In the 1996 PacRim campaign AIRSAR collected several ATI data sets during ocean transits between other data collection sites for the purpose of developing and validating an operational ATI processor. Table 3.1 lists these data sets.

The Eastern-Australian Coast L-band data set [*Slide 13*] shows evidence of outflow from Brisbane harbor and mixing in the open ocean. Also in evidence in this data set, as well as others shown in this paper, is the incomplete calibration of the AIRSAR data, as mentioned above, and the error in the motion-compensation phase induced by topography. The C-band data acquired simultaneously for this scene [*Slide 14*] show the shoaling and breaking waves coming into the shore.

Several data sets were collected at the Hawaii site, near the Kohala coast. We have only begun to look at these data sets, but there is clearly some sort of shear zone which can be seen in the correlation map [*Slide 17*] where the brightness of the pixel corresponds to the magnitude of the correlation (13). This shear zone is even more evident in the ATI phase [*Slide 18*] where the sharp discontinuity amounts to about 60 cm/s in velocity. Waves fields propagating across this scene are also in evidence.

3.2 EOCAP '98

In Fall 1998 AIRSAR conducted the EOCAP data collection, including an experimental ATI collection for one investigator in the Gulf of Mexico [*Slide 12*] looking at a mesoscale eddy, and an ATI calibration/validation experiment over Monterey Bay. Unfortunately for the cal/val experiment, which was conducted with several other participating ground-based radars, the winds were very low during the data collection. Nevertheless, the ATI data do show a good ocean wave field [*Slide 19*] in both C-band and L-band data sets. These data also show that we have not quite finished our calibration: platform motion effects are in evidence [*Slide 20*] as vertical bars of phase along lines of constant position along-track.

We also collected data over one of our standard engineering checkout sites, San Francisco Bay. The correlation time in the bay is somewhat longer than in the open ocean, and the swift currents through the bay are in evidence [*Slide 23*], as well as the wave field [*Slide 25*] diffracting off of Point Bonita. We used this site to investigate acquiring data at different baselines (Δt): as expected the longer baseline shows more velocity sensitivity [*Slide 23*]. One surprise was the observation of traffic [*Slide 24*] with the "one-pulse" baseline.

3.3 Performance

The phase accuracy of an ATI product is related to the signal-to-noise ratio (SNR) through the interferometric correlation:

$$\gamma_n = \frac{1}{1 + \mathrm{SNR}^{-1}} \tag{20}$$

and

$$\gamma = \gamma_n \gamma_t \tag{21}$$

where γ_t is the temporal decorrelation of the scene, and is actually a quantity of physical interest, as mentioned in section 1.1:

$$\gamma_t = e^{-t^2/\tau_c^2} \tag{22}$$

where τ_c is the coherence time [*Slide 26*] for the scattering scene. (Note that some authors define $\tau_c' = \tau_c/\sqrt{2}$.)

The correlation then determines the root-mean squared phase noise:

$$\sigma_\phi = \frac{1}{\sqrt{2N}} \frac{\sqrt{1-\gamma^2}}{\gamma} \tag{23}$$

where N is the number of looks. The phase noise determines the minimum detectable velocity component, as well as the accuracy with which a velocity component can be measured:

$$\text{Velocity Component Uncertainty} = \frac{\lambda}{4\pi\Delta t}\sigma_\phi. \tag{24}$$

Alternately, the ambiguous velocities from Table 1 can be used to obtain the same quantity for each AIRSAR ATI mode:

$$\text{Velocity Component Uncertainty} = \frac{(\mathbf{n}\cdot\mathbf{u})_{\mathrm{amb}}}{2\pi}\sigma_\phi. \tag{25}$$

Phase noise estimates for C-band [*Slide 21*] and L-band [*Slide 22*] show that the AIRSAR instrument is sensitive to velocities as small as a few cm/s, depending on the spatial resolution.

3.4 Example Application

One application of ATI data is to map coastal surf zones. The breaking surf will relatively bright in a SAR image, but the correlation will be relatively poor due to the rapid motion of the scatterers. This is in contrast to other poorly correlated areas due to low signal strength, such as polluted regions or regions with surfactants. One may exploit this contrast by highlighting areas which are dark in the correlation map but bright in the scatter cross-section to map the regions of active surf. [*Slide 27*]

4 Future Capabilities

The standard AIRSAR ATI (VV) data product will be available to investigators for the Pacific Rim 2000 campaign.

4.1 Test Data Set

We are currently packaging an example ATI data set for investigators who may wish to experiment with this mode of AIRSAR data. The data set will have imagery, interferograms, correlation maps, incidence angle maps and velocity-component maps for both L-band and C-band and will provide these for both the "ping-pong" and "common-transmitter" baselines, allowing the estimation of correlation times from the data. This data set should become available by Christmas 1999.

4.2 Experimental ATI Modes

In addition to the standard vertically polarized ATI product, there are other polarization channels available to AIRSAR for ATI data collection: at L-band, ATI data can be collected in either HH polarization (transmit horizontally polarized, receive horizontally polarized) or VV polarization. At C-band, in addition to the VV channel VH and HV (i.e., cross-polarized) channels are available.

In the new experimental AIRSAR configuration, with fully polarized C-band TOPSAR antennas and a fast high-power switching network, AIRSAR can also collect fully-polarimetric along-track interferometric data. AIRSAR can also collect VV polarized simultaneous along-track and across-track interferometric data. An engineering test data set has been collected for each of these modes to evaluate their utility.

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