
Coastal meandering currents and estuarine fronts detected by JERS-1 SAR images.**Eduardo MARONE & Mauricio A. NOERNBERG****Federal University of Paraná, Brazil**
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maroneed@cem.ufpr.br, mauricio@cem.ufpr.br**KEY WORDS:** SAR, JERS-1, Coastal Processes, Estuarine Fronts.**ABSTRACT**

The Bay of Paranaguá - PR - Brazil (48° 20' W; 25° 35' S) has an area of 612 km², and it is located in the sub-tropical area of southern Brazil. The mean tidal range is 2.2 m, with a tidal prism of 1.34 km³ and a tidal intrusion of 12.6 km. It is a partially mixed estuary of the *b* type with a residence time of 3.49 days and a mean fresh water runoff up to 200 m³/s. The coastal area, adjacent to the mouth, is mainly constituted by sandy beaches, while the interior is surrounded by mangrove swamps. The coastal dynamic on the area is influenced by the action of waves, tides and meteorological forcing (winds and atmospheric pressure). Some beaches are under constant erosion processes and others show progradation behaviors.

With the objective of identifying the inundation area on the mangrove swamps, two SAR JERS-1 images (from NASDA) were acquired and studied for two different tidal stages. However, when processing and analyzing one of the images, evidences of coastal-trapped waters were observed in the two margins (N and S), off the outlet of the bay.

The tidal stage at the image time was of 150 minutes after the low sea during a semi-diurnal spring tide period. The meteorological conditions were of E wind with speed of 5,8 m/s, and without rainfall in the 10 previous days.

In the North margin of the outlet, they were formed 3 trapped water patterns with approximately 2 km of extension in direction to the sea and 3.5 km along the coastline. The total extension occupied by the patterns along the coast measures 15.2 km, approximately. In the South margin, one coastal-trapped water behavior was formed, with 4.1 km of extension toward the sea and 5.9 km along the coast.

Possibly, the formation of those patterns is due to the retention of bay waters, less saline and with different density. The concomitant action of some factors can have been producing different surface-roughness signature between the water of the trapped patterns and the coastal water, allowing the detection by the SAR sensor. The main factors that can have been influencing in the signature are the density difference among the water masses, the presence of moderate winds and the influence of currents on surface waves.

In the inner part of the estuary it is possible to observe the same meandering pattern that cross the South-North section. Due to the estuary characteristics and the tide situation this phenomenon can be associated with tidal mixing front.

The observation and the understanding of this type of coastal phenomenon of small scale can give support in the study of the coastal processes in the area, mainly those related to the transport of sediments, beaches erosion and progradation.

1. INTRODUCTION

Tides and tidal currents are modified in estuaries by friction and by the funnelling effect of the convergence of the estuary sides (Dyer, 1995). Both tides and currents are important factors for the sediment budget. The understanding of the gravitationally driven estuary circulation is complicated on these environments due to the turbulent mixing processes in stratified fluids (Griffin, 1990).

The circulation, mixture and stratification of estuarine systems are mainly driven by three forcings: fresh water input, tidal currents and the momentum transference due to wind stress over the water surface. To these forcings one could add the geometry of the estuarine system, the density distribution and the adjacent coastal circulation patterns (Kjerfve, 1990; Miranda, 1996). The estuarine circulation is a result of a complex interaction between these forcings, and their relative spatial and temporal changes, chiefly, the seasonal changes of river runoff. The great temporal variability (minutes, hours, days, years) together with the spatial changes (from cm to km) of those forcings, complicate the study of the circulation and transport patterns in estuaries.

Some of these processes can be studied by using satellite imagery, which could give a synoptic overview of the studied area. Notwithstanding the importance of this tool, there are limitations on the use of satellite image related with the sensor characteristics and the time and space scales complexity.

When the estuaries are analysed using the interaction between the microwaves and the sea-surface roughness like as in SAR images, some estuarine process could be assessed. On that case, the conditions that could be influencing the sea-surface roughness at the moment of the image acquisition are an important parameter to be considered.

In this paper, we examine some features in a SAR JERS-1 image from the Paranaguá bay – Brazil, including some simultaneous meteorological and oceanographic conditions.

2. ESTUARY DYNAMICS

Paranaguá Bay, at the coast of Paraná State in southeastern Brazil ($48^{\circ} 25' W$, $25^{\circ} 30' S$), is part of a large interconnected subtropical estuarine system that includes the Iguape-Cananéia Bay system at the southern coast of São Paulo State. Rather than being an estuary, Paranaguá Bay (612 km^2) is best defined as an estuarine system comprised of two main water bodies, the Paranaguá and Antonina bays (260 km^2) and the Laranjeiras and Pinheiros bays (200 km^2). The system connects to the open sea by three tidal channels, the main entrance area around Mel Island of about 152 km^2 (Figure 1). The structural properties of the Bay are typical for a marine ingression environment. An extensive coastal plain surrounds Paranaguá Bay and the upper reaches of the bay originate about 50-km inland at the piedmont of the Serra do Mar mountain range. Mangrove swamps and marshes mainly fringed the interior of the system, while Ocean exposed areas adjacent to the mouth are composed of extensive sand beaches and some rocky shores (Angulo 1992).

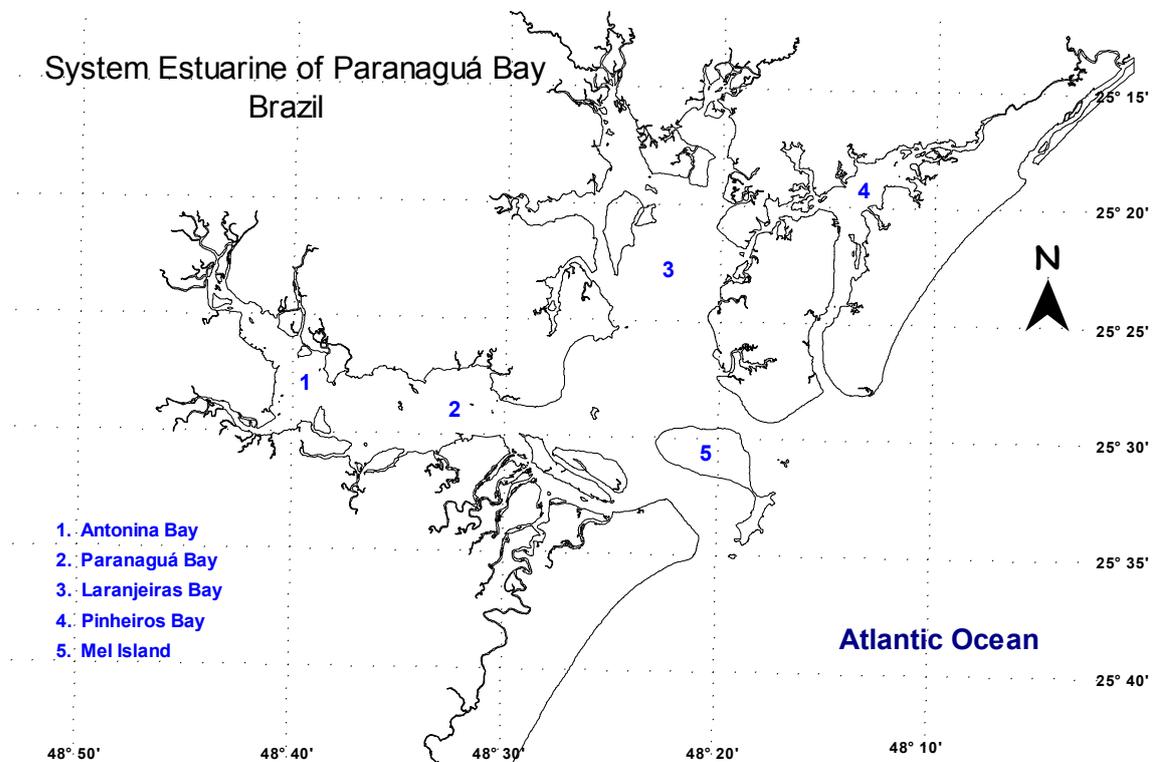


Figure 1. Bays location in system estuarine of Paranaguá Bay

The Paranaguá Bay estuarine complex has been classified as a partially mixed estuary (type B), with lateral heterogeneity (Knoppers *et al.*, 1987), mean depth of 5.4 m, total water volume of $14 \cdot 10^9 \text{ m}^3$ and a residence time of 3.49 days (FUNPAR, 1997). As circulation patterns and stratification vary between seasons, mean salinity and water temperature in summer and in winter are 12-29 ups and 30°C and 20-34 ups and $18\text{-}25^{\circ}\text{C}$, respectively. The structure and function of the estuarine system is influenced by different gradients. A salinity-energy gradient from freshwater to marine conditions, a lateral gradient originated from the freshwater input of rivers and tidal creeks, which creates several 'micro-estuaries', and a temporal gradient, with daily, seasonal and inter-annual components super-imposed on the above gradients.

The hydrodynamics are driven by tidal forcing and river runoff (Knoppers *et al.*, 1987; Brandini *et al.*, 1988; Rebello & Brandini, 1990; Marone *et al.*, 1997; Machado *et al.*, in press). Waves, mainly from the southeast, are only important in the bay mouth where they range from a mean height of about 0.5-m (periods 3-7 s) to a maximum height of 2-3 m during storm events. The coastal region around the bay mouth is mainly constituted of sandy beaches, which presents a highly erosive and depositional environment. The coastal slope

has a smooth gradient, reaching the 50-m depth only at 66 km from the coast. Tides are semidiurnal with diurnal inequalities. Tidal amplitudes increase towards the head of the bay, being amplified less than twice. The tidal phase and amplitudes indicate that the tidal wave propagates in a mixed form, with a progressive form at the outer region and a standing wave form in the upper bay. During neap cycles, strong non-linear interactions allow for the formation of up to 6 high and low tides per day. Spring tides range from 1.7 m at the mouth to 2.7 m in the upper bay. The mean tidal range is 2.2 m, with a tidal prism of 1.34 km³ and a tidal intrusion of 12.6 km. Following cold front forcing, storm surges elevate water levels up to 80 cm above astronomical tides (Marone & Camargo, 1994). Current velocities increase upstream, with maxima of 0.8-0.85 m s⁻¹ at ebb and 1-1.4 m s⁻¹ at flood (FUNPAR, 1997).

The average annual freshwater input from the coastal plain catchment area (about 1918 km²) and from the small and steep drainage basins of the Serra do Mar is up to 200 m³ s⁻¹. Groundwater contribution may contribute up to 10% of the total surface freshwater runoff (FUNPAR, 1997; Marone *et al.*, 1997). Seasonal variations of freshwater input correspond to around 30% of mean annual values during the dry period (May/October) and 170% during the rainy period (November/April). Runoff to the coastal zone ranges from approximately 7 to 28 x 10⁶ m³ day⁻¹ during the dry and rainy season, respectively.

3. DYNAMIC CONDITIONS DURING THE IMAGE SPOT

The SAR image was obtained on May 22, 1994 around 10:00 AM in a spring tide condition and after 150 minutes of low tide (Figure 2). Meteorological conditions indicated E winds with a speed of 5,8 m/s, at dry period (no rain) during the previous 10 days.

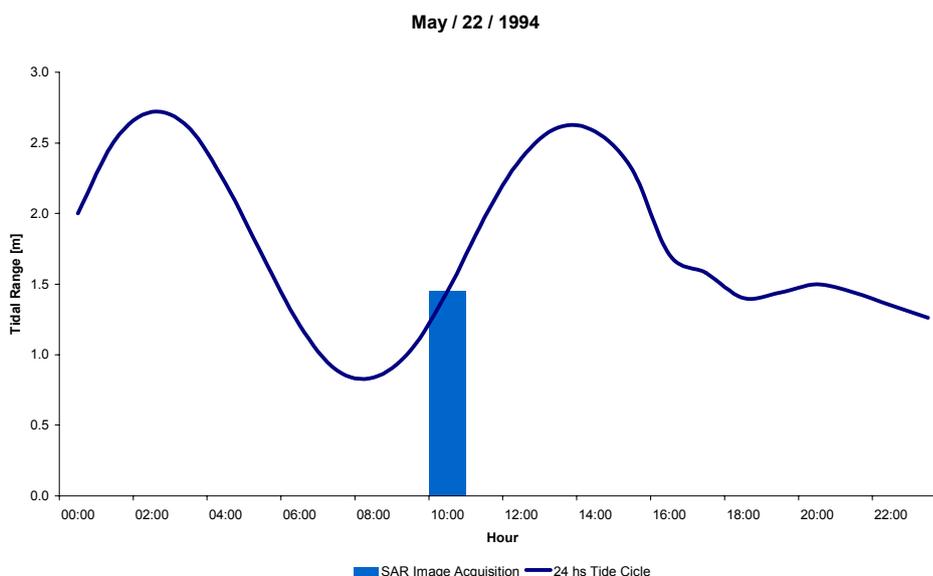


Figure 2. Tide of the day and hour of the image acquisition

4. THE SAR JERS-1 IMAGE

The SAR JERS-1 image for 22/05/94 presented the bellow characteristics:

Ground Station:	HEOC
Logical Format:	CEOS-BSQ
Processing Level:	2.1
Multi Look:	3
Pixel Spacing:	12.5m

The MITI (Ministry of International Trade and Industry)/ NASDA (National Space Development Agency of Japan) retains ownership of the data. NASDA supported the acquisition of the satellite data.

The spot was processed using a routine developed by INPE (National Institute for Space Research – Brazil), and transformed in an 8 bits image.

The image's histogram was bimodal (Figure 3), with first of them related to signal response to the roughness of the continental area, with higher backscatter. The signal portion corresponding to the water surface presented a lower backscatter due to the higher specular reflection. A linear stretch was applied to the water portion in order to analyse the coastal features. This procedure saturated, also, the continental area.

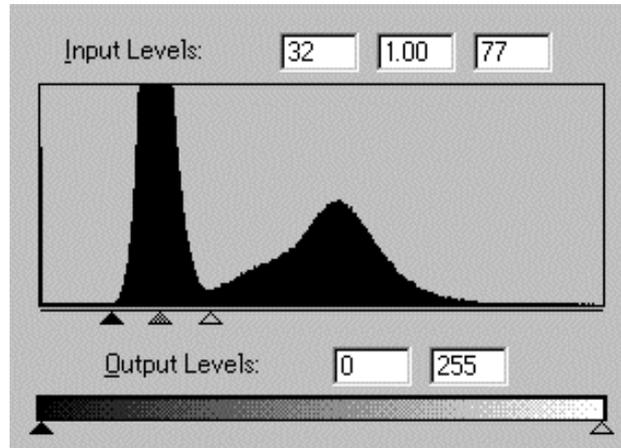


Figure 3. Histogram of full image

After this stretch, it was possible to observe two different patterns at the spectral response. One of them, covering most of the image, and a second one, at the coastal area as well as the estuarine one, which corresponds, probably, to tidal currents and meandering features.

Estuarine, coastal and meander waters were analysed. Estuarine and coastal waters presented similar histograms (Figure 4), but meandering waters shown lower values for the backscatter and standard deviation (Figure 5).

The image was georeferencing to the SAD-1969 datum. No automatic classification was performed due to the non-conformity of the backscatter data to the normality assumption of some conventional classifiers, which indicates that it is not accurate to use this kind of classification (Ulaby and Dobson, 1989). The features were drawn manually at the Figure 6.

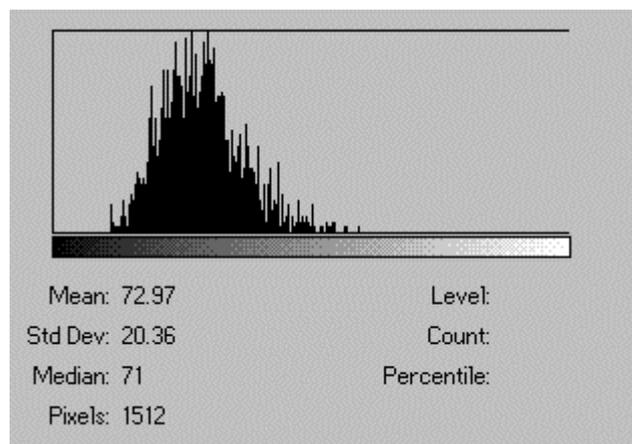


Figure 4. Meander waters histogram

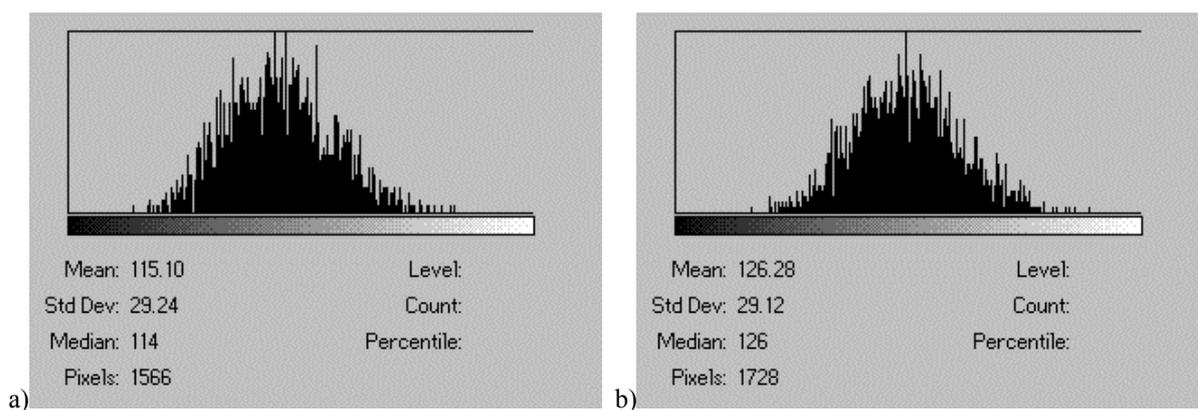


Figure 5. Histograms of a) marine waters e b) estuarine waters

5. RESULTS AND DISCUSSION

In the North margin of the outlet, they were formed 3 trapped water features, presenting meandering patterns with approximately 2 km of extension seaward and 3.5 km along the coastline. The total extension occupied by the patterns along the coast was 15.2 km, approximately. In the South margin, one coastal-trapped water behaviour was formed, with 4.1 km of extension toward the sea and 5.9 km along the coast.

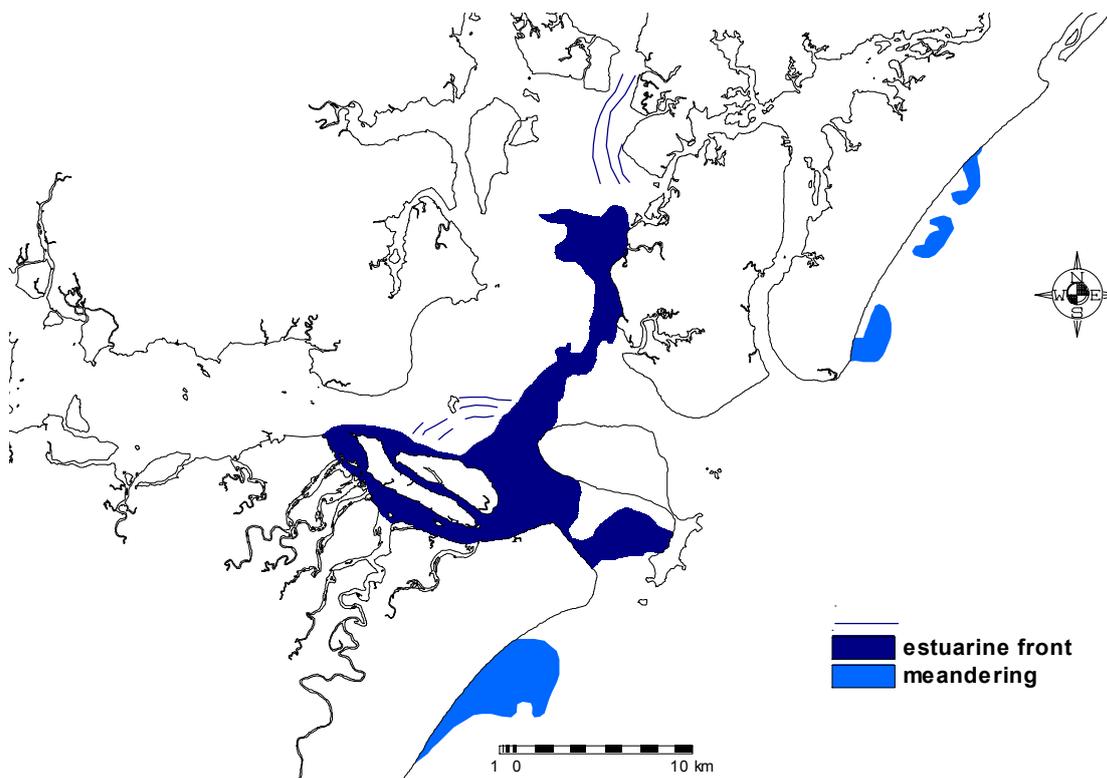


Figure 6. Map showing areas with different pattern of backscatter from JERS-1 SAR image

Possibly, the formation of those patterns is due to the retention of estuarine water, less saline and with different density. The concomitant action of some factors can have been producing different surface-roughness signature between the water of the trapped patterns and the coastal water, allowing the detection by the SAR sensor. The main factors that can have been influencing in the signature are the density difference among the water masses, the presence of moderate winds and the influence of currents on surface waves.

In the inner part of the estuary it is possible to observe the same meandering pattern that cross the South-North section, with 21 km of length. Due to the estuary characteristics and the tide situation this phenomenon can be associated with tidal mixing front. These fronts usually occur in moderately stratified estuaries, formed in shoaling regions where tidally generated turbulent stirring is just sufficient to mix away the

buoyancy in the surrounding deeper, stratified water. This kind of front usually occurs during periods of low river discharge (Kjerfve, 1988).

The near surface velocity field could also reflect deeper process, which enables the surface roughness to be modulated. There are several ways in which the surface roughness can be influenced, and when ocean features other than surface-wave patterns have been imaged by active satellite radar it is not always clear which of these modulation processes is occurring. One way in which currents can influence surface roughness is affecting the actual wave-generation process. Waves are generated when there is a relative shear between the water surface and the wind. When a tidal current is running against the wind, even if it is only a relatively light breeze, the sea can become quite rough. This mechanism could potentially provides energy for defining the distribution of the tidal currents, provided that the wind is not so strong that the whole sea becomes uniformly rough (Robinson, 1985). Possibly the bigger wavelength of L band (21 cm), in relation with C band (5.6 cm), must be less affected by little roughness variation caused by wind gust.

At the image time, we have an estuarine flow seaward and a flooding spring tide landwards. The meteorological condition also create good conditions to highlight the front because there were no precipitation in the previous day, and the wind was from East, then, perpendicular to the frontal system.

The observation and the understanding of this type of coastal phenomenon of small scale can give support in the study of the coastal processes in the area, mainly those related to the transport of sediments, beaches erosion and progradation.

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