# Chapter
# 7

## Coordinate Registration

As described in chapter 4 the ionospheric plasma is characterized by two non-zero gradients (spatial and temporal) that prevent us from making accurate predictions on the trajectory of the signals that pass through it.

Even in the simplifying assumptions of a stratify Ionosphere, specular reflection of the radar beam, absence of multiple paths and stable propagation mode it is impossible (without knowing the actual electron density profile in the ionospheric area interested by the radar beam) to exactly estimate the path taken by the HF signal to reach the target and by the echo to go back to the radar. Hence, the data gathered and processed by an OTHR-SW system are useless if we are not able to univocally associate it to a given position on the Earth's surface. This is the basic reason why we decided to develop an algorithm, to be run on a real-time basis on each radar sweep, capable to correct the data-position association evaluated by the employed raytracing technique. The developed algorithm, referred to as "Sea-Land Transition Identification" (SLTI) procedure is basically based on the identification of coastline profiles within the received OTHR-SW' echo and it is largely described in the previous chapter. In this chapter we present the implemented model of the OTHR-SW's scenario and we give an example of the application of the SLTI algorithm for the Coordinate Registration of the radar footprint.

In OTHR-SW applications the idea of employ the geographical features as a known references in order to make up for the lack knowledge about the ionospheric condition was already introduced in the mid 90s [62] with the name of *"Coastline Matching"*. The author of the paper mentions this method only as

the possible development of a different CR procedure.

Although an accurate bibliographic research was made, we did not succeed in tracking down any other paper concerning an analogous subject. The reason of this lack in a further investigation of the method could be mainly due to the lack of information about the surface clutter in the HF band for high angles of incidence. In fact the few available real data relative to HF back-scattering coefficients are referred to measurements made with an HF sensor located on a small cliff or on a beach, hence they only account for incidence angles that are shorter than that typical of OTHR-SW systems (where the incident signal comes from an height of about 300 km, after the ionospheric reflection).

It is only known that while the HF back-scattering coefficient for sea surfaces presents a dependency on the local state of the sea during the observation period, hence it can show different values within the same geographic area, the HF back-scattering coefficient for terrestrial regions does not have time-varying characteristics, but it is strongly influenced by the slope and the soil type and by the possible presence of conformations of comparable size to half the wavelength of the considered HF signals. Moreover, due to the continuous presence of sea waves (responsible for the Bragg's components of the sea spectrum), the bandwidth of maritime HF surface clutter results larger than that of terrestrial HF surface clutter. Hence the clutter process results quite stationary for a given land region, while its magnitude and bandwidth change in function of the Sea State for a given water region. Nevertheless what is fundamental for the proposed method is that the values of the backscattering coefficients for sea and land areas are known to be really different from each other, so that it is in principle possible to identify a discontinuity in the echo from a radar footprint that include a land area and a sea area. This particular characteristic allows us to perform a real-time analysis of the received instantaneous power, detecting, with a resolution depending upon many factors (*in primis* the length of the radar pulse, the frequency of the signal and the antenna's take-off angle), any eventual sea/land transition present within the radar footprint. So, once known the geographic location of the coastline profiles within the OTHR-SW's surveillance area we can exploit that information to Geo-reference each footprint that includes at least a sea/land transition, providing a CR tool for the radar system.

## 7.1   Implemented Model of the OTHR-SW Scenario

In order to prove the feasibility of the proposed CR approach and to define some boundary values, especially in terms of Clutter-to-Noise Ratio $CNR$ and difference between land and sea backscattering coefficients $\Delta\sigma$, we needed to develop a model for the considered OTHR-SW scenario. Figure 7.1 shows a simplified side-view scheme of the OTHR-SW propagation channel with the relative geometric parameters and the three main blocks of the developed scenario model.
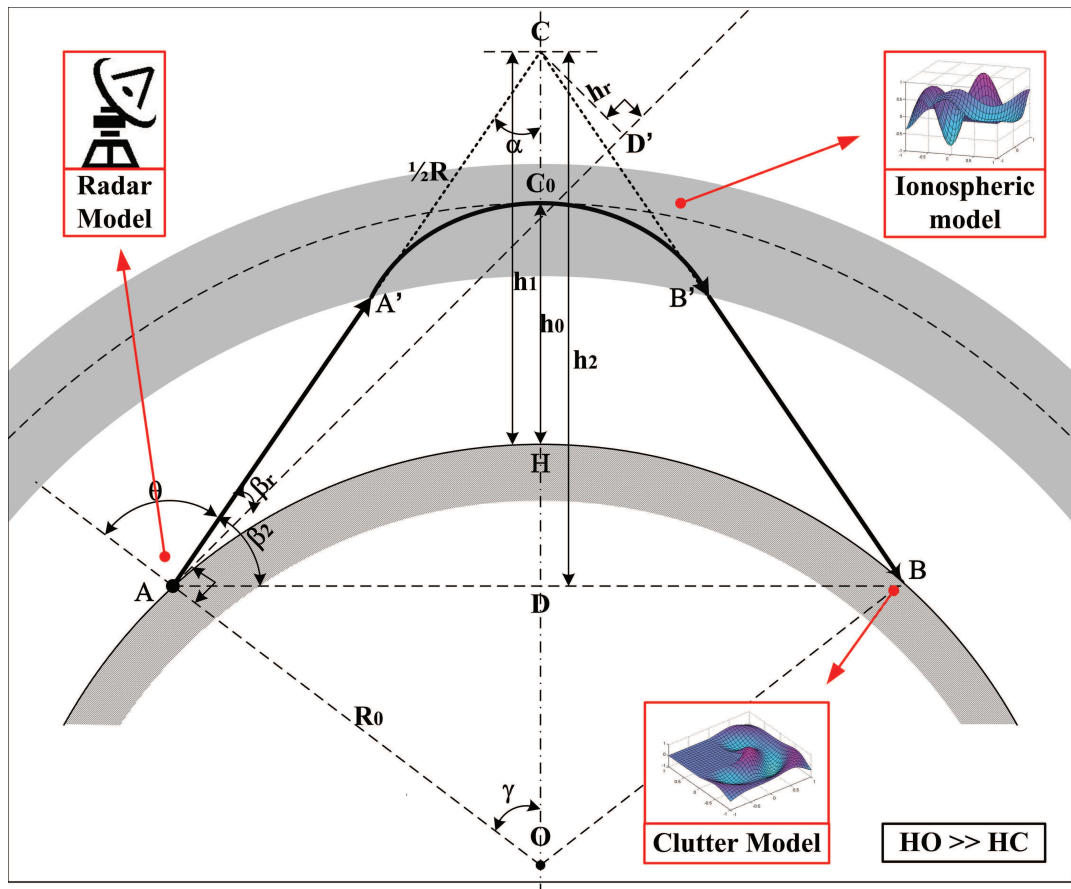
Figure 7.1. *Scheme of the OTHR-SW simulated scenario with repartition in three main model blocks and presentation of the geometric parameters.*

The block-structure of the model was originally imposed in order to be free to independently upgrade each block any time a simulation hypothesis is updated. As it appears evident from the figure, the developed model adopts these three main blocks:

– *The Radar System*:

– *The Ionospheric Propagation Channel*

– *The Surface Clutter Process*

The diagram presented in figure 7.2 resumes the main hypotheses initially formulated for the characterization of the simulated OTHR-SW scenario. The latest update of the scenario model considers the following four main improvements:

– The model of the ionospheric signal's path still considers a single hop, but the mirror reflection of the ray is replaced by a more complex algorithm that
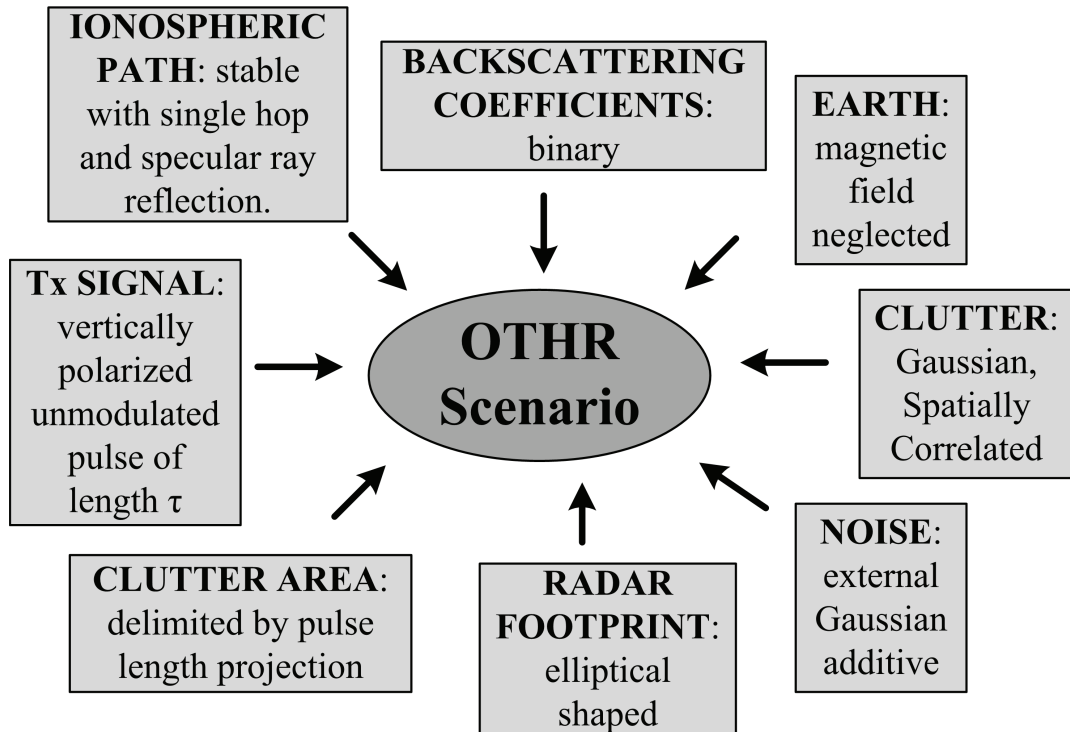
Figure 7.2. *Main hypotheses initially formulated to implement a model of the OTHR-SW scenario.*

simulates the progressive refraction of the signal through the Ionosphere, supported by a stratified model of the medium (see MQPIM in section 4.4).

– On the basis of the Ionospheric analysis proposed in chapter 4 which points out that above the Mediterranean area, in quite Ionospheric condition, the coherence time of the Ionosphere ranges between 23 and 100 seconds, we assume a maximum value of the Coherence Integration Time (CIT) equal to 30 seconds.

– The Gaussian clutter model is replaced by a Rayleigh model of the surface clutter process, with different spatial and temporal correlation factors for sea and land regions. The hypothesis on the backscattering coefficients remains valid: two different coefficient values are assumed for land and sea areas; those values are changed for the various simulations, in order to assert basic method requirements.

– The radar footprint is still consider as elliptical, but in the last scenario's model its image in Rx is reconstructed taking into account of the different incidence angle that characterizes each pulse projection on the ground,

determining a potentially different path for the echo contributions corresponding to the various position of the pulse that scans in range the radar footprint.

The mechanism illustrated by the last point of the previous list can initially appear quite complicated to understand. In order to better understand the illustrated concept let us refer to figure 7.4 that shows a scheme of the top and the side view of the area where the radar beam intercepts the ground. In both pictures the projection to the ground $\delta I$ of the radar pulse of time-length $\tau$ is also proposed ($c$ represents the speed of light and $\beta$ the incidence angle that, in the assumed geometry, has the same value of the take-off angle). According to one of the hypotheses resumed by the diagram in picture 7.2 the *"Clutter Area"*, that is the region labelled as $A_C$ in the lower part of figure 7.4, is limited in range by the pulse and not by the footprint. In geometrical terms this means that the pulse projection to the ground $\delta I$ is smaller than the range amplitude of the radar footprint. Under this assumptions we can simplify the *echo generation mechanism* by imagining that on a radar sweep basis the pulse scans the radar footprint, generating, for every range-position within the footprint, a return (a single contribution to the entire echo) that goes back to the radar according to its actual take-off angle and frequency. Now, by assuming that in the time-scale of the described mechanism we can neglect any eventual Doppler shift introduced by the surface clutter to the echo contribution, we can assert that the geometry of the path covered by that single return (and consequently also the delay-time that characterizes that contribution at the receiver) is dependent upon the averaged incidence angle of the pulse projected to the ground. Hence the singular echo contributions reach the receiving antenna with theoretically different delay-times and the image of the radar footprint as reconstructed at the receiver appears altered. By employing a rigorous raytracing algorithm, supported by the proposed CR technique, it is possible to correctly recreate the image of the radar footprint and detect eventual targets without mistaking their number or position due to multiple returns.

### 7.1.1 Radar System Model

Figure 7.3 illustrates another simplified sketch of the basic OTHR-SW geometry showing the ability of the radar system to overcome the horizon line. The sketch is supplied by the scheme of the radar footprint and the pulse projection to the ground proposed by figure 7.4.

The expected power contribution at the radar receiver, associated to the surface element $\Delta S$, is given by the famous radar range equation:

$$\Delta P_{rx} = \frac{P_{tx} \cdot G^2 \cdot \lambda^2}{(4\pi)^3 \cdot R^4} \cdot \sigma_0 \cdot \Delta S$$
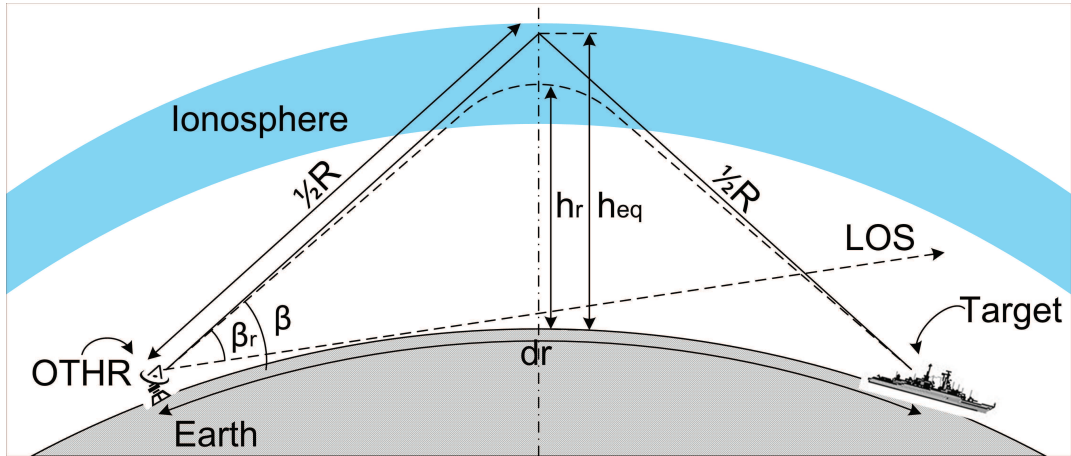
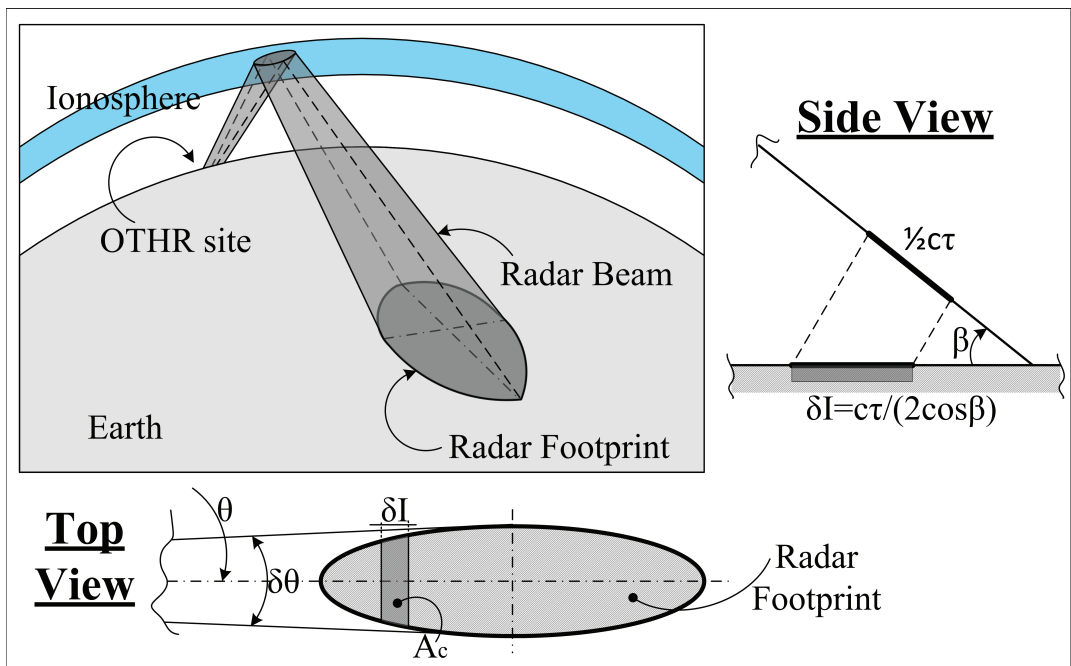Figure 7.3. *Simplified sketch of the OTHR-SW geometry.*



Figure 7.4. *Another scheme of the simulated OTHR-SW scenario with emphasis on the radar footprint model and on the projection of the pulse to the ground.*

where:

1. $P_{tx}$ represents the transmitted power;

2. $G$ the antenna gain (the same gain is assumed in transmission and reception for sake of simplicity);

3. $\lambda$ the wavelength;

4. $R$ the one-way signal path;

5. $\sigma_0$ the normalized backscattering coefficient associated to the radar footprint element $\Delta S$.

Parameters 1 to 3 are relative to the Radar System Model: they can be modified for each simulation according to the given task. Parameter 4 is a result of the OTHR-SW geometry and depends upon the pointing direction of the antenna and upon the electronic composition of the Ionosphere in the region interested by the radar beam. Parameter 5, relatively to a given surface element $\Delta S$ is evaluated as described in the following.

## 7.1.2   Ionospheric Propagation Channel Model

The adopted raytracing algorithm is that proposed by the Department of Information Engineering of the University of Pisa [6]. The code obtains statistical ionospheric data from the IRI 2007 (International Reference Ionosphere) database [2], [28], considers a stratified Ionosphere that effects the HF signal according to the Snell's refraction law and applies the *Breit and Tuve* theorem to perform the last passage of CR, i.e. to convert group time delay into ground-range distance. In order to extract $e^-$ density profiles from the IRI database we need to define the following entries: location, date, time and Sun Spot Number (SSN). Note that we suppose the electron density profile to be constant during the pulse transmission and the reception of the echo, and to be homogeneous for the area interested by the radar beam.

## 7.1.3   HF Surface Clutter Model

With the term "clutter" it is generally denoted the backscattered return from a patch of the Earth surface illuminated by a radar beam or pulse [70], [51]. The development of statistical models that properly characterize radar clutter processes is critical for designing optimum algorithms for detecting targets and, as in our case, to Geo-reference the received signal. In HF OTHR-SW applications the clutter component is the dominant feature of the echo [18]: hence, the proposed CR method, based on clutter discrimination, does not require high power in transmission.

Referring to the last equation, in order to estimate the clutter term relative the expected power contribution at the radar receiver $\Delta P_{rx}$ we need to evaluate the product $\sigma_0 \cdot \Delta S$.

Whenever the consider footprint element $\Delta S$ includes a sea/land patch, $\sigma_0$ is evaluated proportionally to the percentage of sea/land area within the element
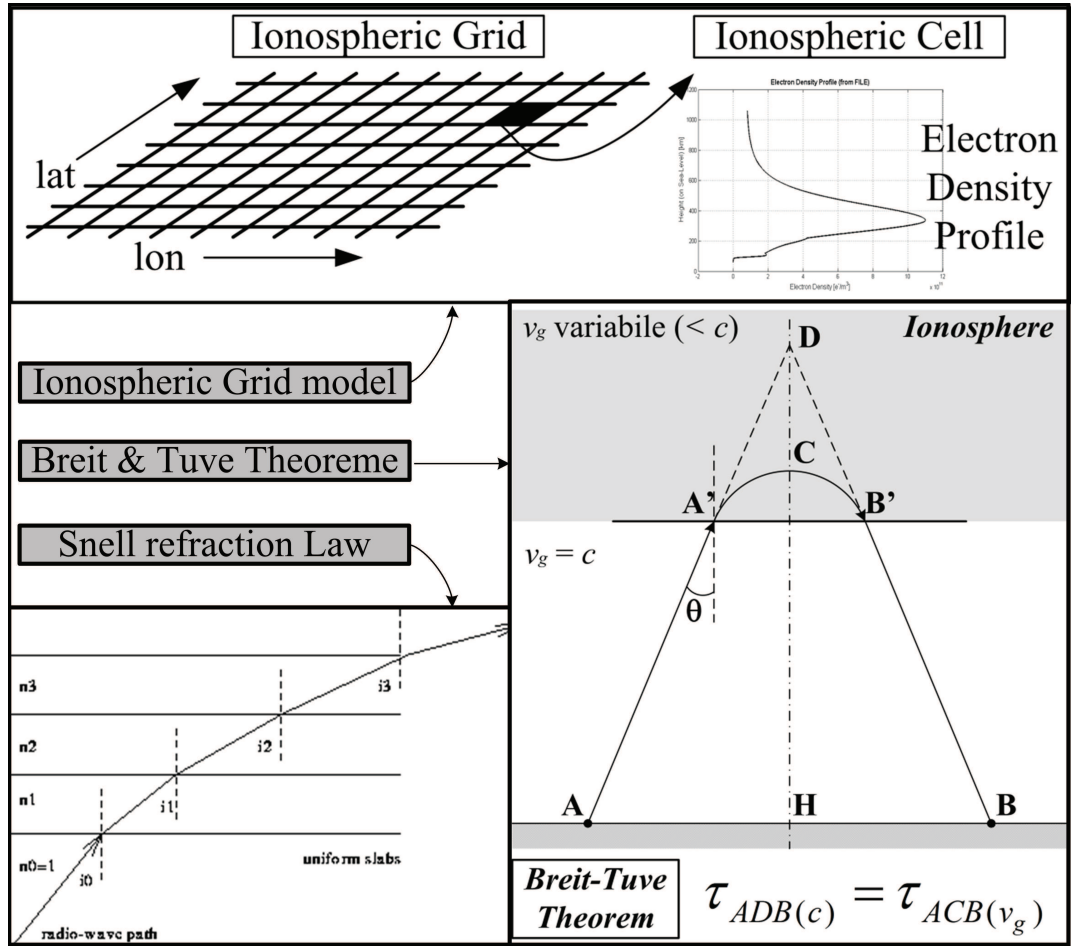
Figure 7.5. *Three of the main assumptions to model the ionospheric propagation channel.*

and the respective backscattering coefficients, as shown in Fig. 7.6. Besides the differences in the value of $\sigma_0$, sea and land clutter exhibit other characteristic features [69], [53]. Both clutter processes are geographically non homogeneous (and depend on the radar grazing angle $\beta$ and operating frequency $f$), but they have different spatial distributions. The sea clutter is highly non-stationary in time, while the land clutter should present a much more stationary behaviour in time.

Under the hypothesis that a low-resolution radar is used (i.e. that a resolution cell contains a large number of independent scattering structures), we can represent the EM field backscattered from a given surface patch as the superposition of the contributions from many discrete scatterers:
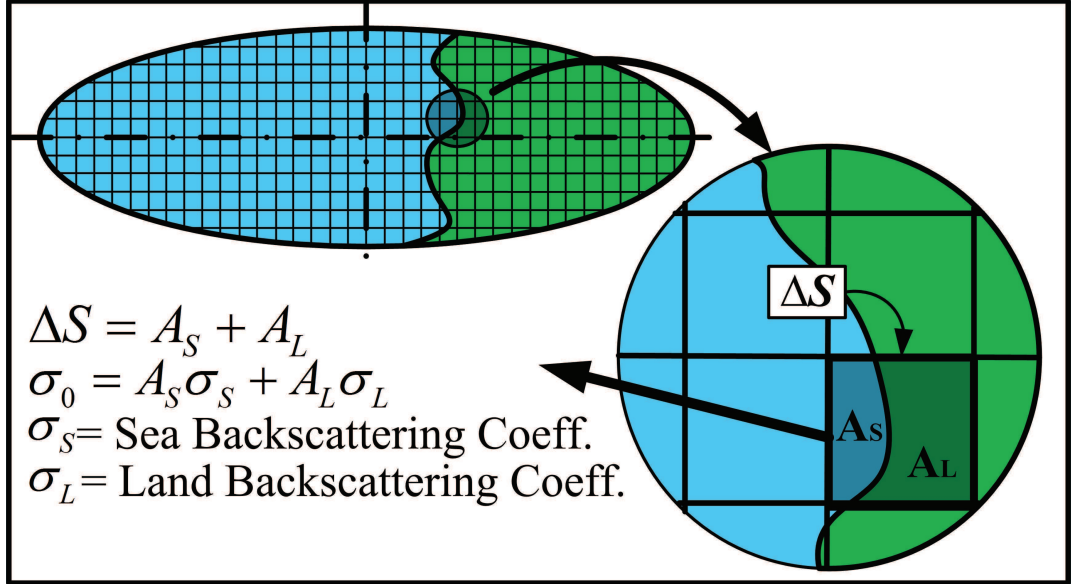
Figure 7.6. Evaluation of the normalized backscattering coefficient $\sigma_0$ for a general surface element $\Delta S$.

$$E = \sum_{n=1}^{N} a_n$$

$$a_n = I_n + jQ_n$$

$$I_n = \sqrt{\sigma_{0n}} cos\phi_n$$

$$Q_n = \sqrt{\sigma_{0n}} sin\phi_n$$

Each contribution is characterized by its in-phase $I_n$ and quadrature $Q_n$ components that, in turn, are functions of the normalized backscattering coefficients $\sigma_{0n}$ and the phases $\phi_n$. Assuming a Gaussian clutter model, the probability density function (pdf) of the backscattered clutter envelope $E$ is [51]:

$$P(E) = \frac{2E}{x} \cdot e^{-\left(E^2/x\right)} 0 \leq E \leq \infty$$

where $x$ represents the mean clutter power. Hence the *pdf* of the clutter power is expressed by:

$$P(P_{\sigma_0}) = \frac{1}{x} \cdot e^{-\left(P_{\sigma_0}/x\right)} 0 \leq P_{\sigma_0} \leq \infty$$