

# Chapter 5

## Geo-Referencing Techniques

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The Geo-referencing procedure, referred to as *Coordinates Registration* technique, is a fundamental process in the operation of an OTHR Sky Wave system or of any other radar capable to detect targets outside the *line-of-sight*.

Exploiting a path of the radar signal that is not in a straight line, this type of apparatus requires a conversion process that transforms the measured coordinates (*group time delay* and *apparent azimuth*) in operational coordinates (*ground range* and *mph true azimuth*) [62].

Not only the phase of *revelation*, but also the subsequent *tracking* depend strongly on the accuracy of the Coordinates Registration process. In fact, usually a target is directly traced to *ground* coordinates, propagating the errors introduced during the CR procedure [25, 23].

Hence, without applying the Geo-referencing process it would be impossible to give an exact interpretation of the measured quantities, that is to place the radar detection in the right geographical context.

Many solutions to the CR problem have been proposed for the various OTHR-SW systems. Generally these solutions involve optimal dedicated signal processing techniques and the acquisition of additional data from remote devices.

The present chapter proposes some of the most common approaches, describing the basic concepts of the CR method and highlighting its advantages and limitations. In the next chapter it is presented the developed Geo-referencing procedure, referred to as “*Sea-Land Transition Identification*” (SLTI) method [39], based on the *a priori* knowledge of the geomorphological structure of the OTHR-SW’s coverage area.

## 5.1 Ionosonde Network

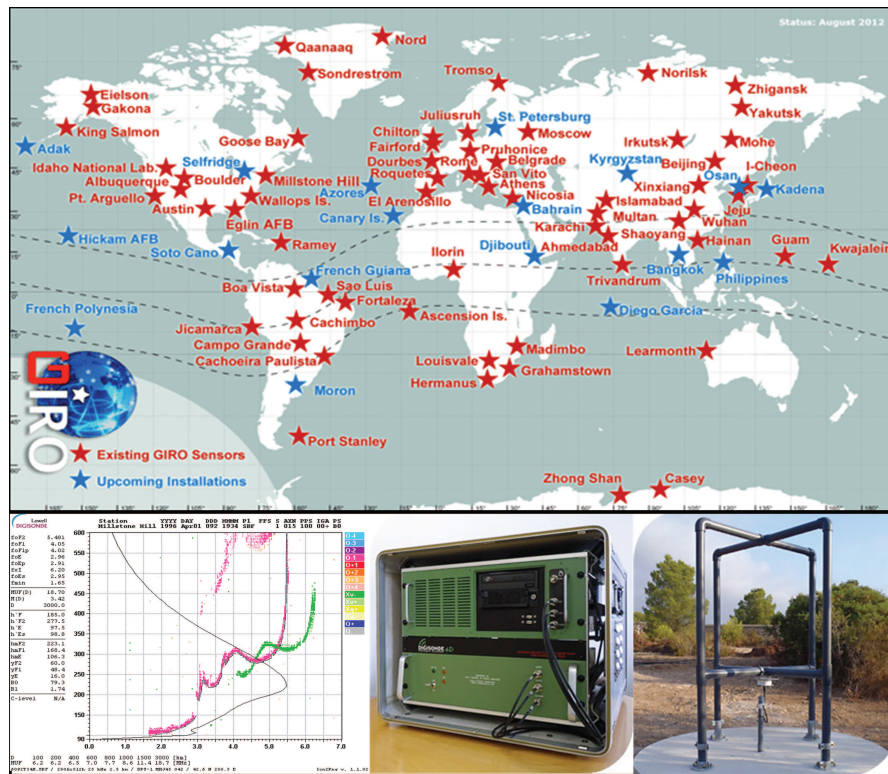


Figure 5.1. Counterclockwise from the top: Global Ionospheric Radio Observatory (GIRO) Map; An example of digital ionogram; The Lowell Ionosonde and its antenna in the four-elements configuration.

A *Ionosonde* is a radar sensor agile within the HF band whose function is to perform repeated soundings of the Ionosphere. The gathered data are processed by a dedicated software in order to generate a “*Ionogram*”.

In its basic form a *Ionogram* consists in the representation of the group delay as a function of the operative frequency. The web site <http://ulcar.uml.edu/DIDBase/> is the homepage of a really interesting portal that gives access to the *Global Ionospheric Radio Observatory* (GIRO): a network of digital Ionosondes located all around the World that periodically gather Ionospheric data. Differently from the basic analogic Ionosondes, the modern Digital Ionosondes are equipped with a quite-complex processing software that allows the data interpolation with a Ionospheric Model in order to estimate its characteristic parameters (e.g., height, thickness and critical frequency of each of the layer considered by the ionospheric model).

In [63] Dyson and Bennett explain how the data provided by two vertical incidence ionosonde to be included in a *Multiple Quasi-parabolic Ionospheric Model* (MQPIM) to be used to run a raytracing procedure (see the previous chapter) in order to estimate the actual path of the OTHR-SW signal.

The need to maintain reduced overall dimensions of the device, to be dislocated in remote sites and to operate continuously in time, generally imply low values of the transmitted power (less than one kW). There are various types of ionosonde: VIS, QVIS, OIS, etc. ... which differ in the orientation of the radar beam with respect to the Ionospheric layers.

Fig. 5.1 shows: the map of Global Ionospheric Radio Observatory (GIRO) updated at August 2012; An example of a digital Ionogram generated by a Lowell Digisonde; a picture of the Lowell Ionosonde and its antenna in the four-elements configuration (it is possible to alternatively employ an 8-elements antenna). We propose the “Lowell Digisonde International” (LDI) network because it is one of the largest and most of the gathered data are freely available online. The company is based in Lowell (MA,USA) and it has been active in the Ionospheric investigation for many years. Besides the US, another country that invested a lot in the deployment of Ionosondes and in the development of processing techniques for Ionograms is the Australia: KEL Aerospace, in cooperation with DSTO, has developed devices (as the *IPS-71 Advanced Digital Ionosonde System*) and software tools (as the *SONNET Real-Time Frequency management Software*) for the characterization of the Ionosphere over the country and above the surveillance area of its OTHR-SW system *JORN*.

Anyway, it is possible to find in the web the link to several Ionosonde Networks all around the World. Here it is just a short list of theme:

- GIRO (Global Ionospheric Radio Observatory);
- CHAIN (Canadian High Arctic Ionospheric Network);
- BIZON (Advanced Russian Digital Ionosonde);
- IPS (Australian Ionosonde Network);
- SEALION (SouthEast Asia Low-latitude Ionospheric Network);
- Digisonde (Global Ionosonde Network);
- Dynasonde Network (Swedish Ionosonde Network).

The operative limit to the employment of these devices lies mostly in their need for relatively-long periods of ionospheric observation in order to derive information on the composition of the plasma, with an update times generally ranging between 5 and 10 minutes, but that can exceed 20 minutes for a detailed digital

Ionogram. This makes it impossible to monitor what actually occurs to the Ionosphere in “Real-Time”. In addition a Ionosonde typically operates on a limited area (in case the ionosonde is at oblique incidence this area is wider), so, due to the spatial inhomogeneity of the Ionosphere, it would require a network composed of many sensors to obtain comprehensive data on the entire surveillance area of an OTHR-SW system [25, 62, 23, 76, 42].

## 5.2 HF Beacons and Transponders

As an alternative solution to the Coordinate Registration problem in OTHR-SW applications it has been suggested to employ HF devices as *beacons* and/or *transponders* to be located within the radar’s surveillance area for various azimuthal pointing directions. In fact these devices represent indeed powerful tools for the real-time Geo-referencing of the HF received echo. The basic operating principle is analogous to the one exploited by the SLTI method introduced by this paper: whenever one or more of these devices (whose geographical position is *a priori known*) is present within the radar footprint of the Over The Horizon sensor, its return appears really evident in the received echo that is hence easily Geo-referenced.

The *beacon* is an active device that transmits, in a pulsed or continuous mode, a unique HF ID signal, providing a known geographical reference to all the mobile units that are able to receive it [59]. Also the *transponder* is an active device, but, differently from the beacon, it does not transmit any ID signal, but it just amplifies and broadcast again any received HF signal, by rapidly switching the mode of the antenna from the receiver to the transmitter.

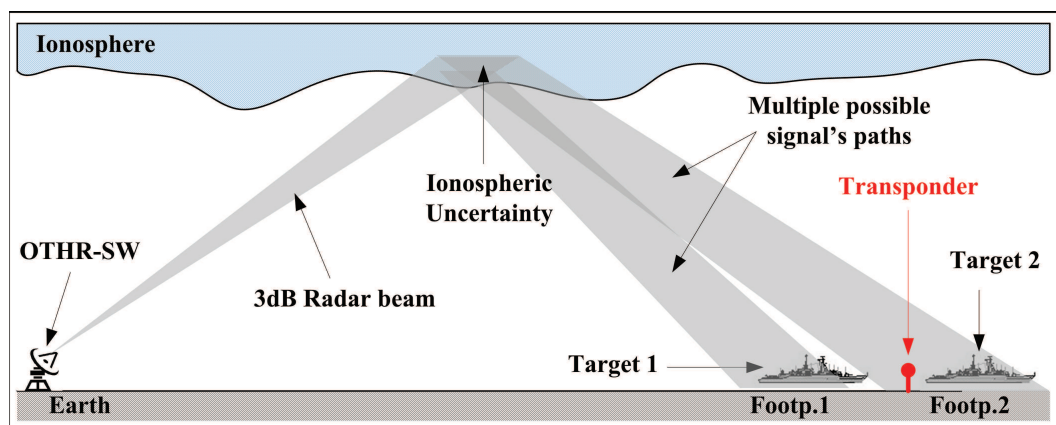


Figure 5.2. OTHR-SW scenario in case of employment of HF transponder.

In both cases the signal transmitted again toward the radar follows the same path of the echo generated by the targets present in the same radar footprint and it is therefore subject to the same propagation effects due to the temporal variations and spatial inhomogeneity of the ionospheric plasma. This makes the devices an ideal reference for the real-time calibration of the radar range and azimuth.

If we also consider the relative structural simplicity, the easiness of the installation (unfortunately the calibration is not so trivial) and the relatively low cost if compared to that of the entire OTHR-SW apparatus, than beacons and transponders seem to be a viable solution to the CR problem.

For example the US OTHR-SW system ROTHr has the ability to correct the position of the target on the basis of the error committed in the estimated position of geographically known beacons deployed within its surveillance area [77].



Figure 5.3. Map of HF beacon stations around the World and picture of the *VK6RBP* HF beacon located near Perth, Australia.

Nevertheless, how we would see for other different methods, it remains a reserve about the feasibility of a temporary or permanent installation of these devices within the OTHR-SW coverage area, which usually extends well outside the national territory. Moreover, given the limited range of action, the positioning of these devices should follow an appropriate geographical criteria <sup>1</sup> and it would require a high number of devices. [62, 14, 45, 77].

### 5.3 Targets of Opportunity

With the label “*Target of Opportunity*” we generally intend all possible cooperative (in the sense that their position and their HF RCS are *a priori* known)

<sup>1</sup>From a work of J. Bucknam on “*Beacon Assisted Coordinates Registration*” it emerges that the positional corrections evaluated via the employment of a beacon can be considered valid for any target up to 200 nautical miles (about 370 km) from the device [77]

targets that can be present within the surveillance area also for limited amounts of time. Note that, how suggests by their name, the Targets of Opportunity are a sporadic resource that can be exploited only when they are actually present within the OTHR-SW's surveillance area. A peculiar subset of these element is represented by the “*Sources of Opportunity*” that can be identified as “*active*” targets of opportunity, that is units capable to transmit in HF band (i.e. CBs, HF transmitting stations, etc.).

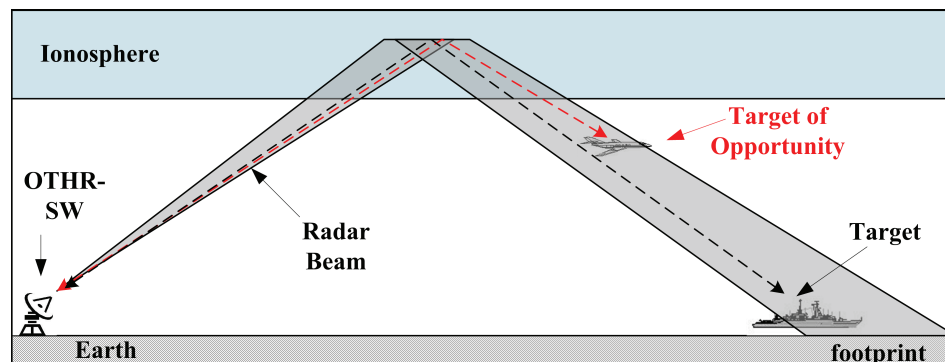


Figure 5.4. *Coordinate Registration with target of opportunity.*

Fig. 5.4 presents a sketch of the OTHR-SW scenario in the case of Coordinate Registration with a target of opportunity. Note that the known target is an airliner whose actual position (latitude, longitude and elevation) is provided to the OTHR system by the interfaced GPS-PNAV device.

The HF band ( $[3 - 30]$  MHz) corresponds to wavelengths in the range of  $[10 - 100]$  meters, and, as is known, the targets which fall into the *Mie Region* (aka *Resonance Region*) are those with overall dimensions comparable to half of the wavelength. Hence we are interested in targets with dimensions in the order of  $[5 - 50]$  meters.

In order to be able to employ those targets in the Geo-referencing process of the OTHR-SW echo, we must be able to distinguish their echo-contribution from the more powerful Clutter component and to locate the origin of this contribution with a better resolution of that of the OTH radar.

Hence we can assume to profitably employ:

- localized and stationary targets that are able to generate a powerful return in the HF band: radio transmitters or repeaters, industrial clusters, military equipment, power plants, etc.
- mobile targets that are moving at high speed (trains and air-planes), so that they are easily detectable in Doppler, and equipped with a real-time

positioning device (for example GPS or Galileo, etc.) directly interfaced with the OTHR system.

Particular relevance in the Geo-referencing process is given to the second category of targets, referred to as “*Moving Targets of Opportunity*”. This category includes airliners whose route across the coverage area is known *a priori*, together with the unique identifier and the timetables [14], or cargo ships that generally follow predefined trade routes and, differently from airliners, remain longer within the surveillance area [29].

Although the presence of these “co-operating” targets is not guaranteed in a continuous way in the area of interest, size and cruise speed make them an ideal reference for ionospheric HF-band radars [22].

The two ROTHr devices placed in Texas and Virginia, employed in an anti-drug mission in Gulf of Mexico and Caribbean Sea, used to employ a procedure called “*Ground Coordinates Correction*” (GCC) that exploits reference sources located at known positions in order to correct eventual errors in the CR process. A study on experimental data collected by the two ROTHr in 1993 indicates a significant improvement of the results by firstly applying correction factors to the radar tracks directly in *slant-coordinates*, then carrying out a *Track-Associations* procedure and finally performing the conversion to *ground-coordinates*. This process, described in [34] is referred to as “*Slant Tracks Referencing*”.

## 5.4 OTHR-SW Superposition and Fusion

This CR technique requires the employment of at least two OTHR-SW sensors with superimposed, or partially-superimposed, surveillance areas (fig. 5.5). We locate the OTH radar systems in order to provide a triangulation on the area of interest. Hence, unfortunately, the overall surveillance area results smaller than the smaller coverage-area provided by the considered radar system, but, disposing of redundant information from independent sensors, we are able to overcome the uncertainties introduced by the Ionosphere. In order to do this, the involved OTHR-SW systems need to work together, so a stable and reliable communication link between the involved sensors must be established.

The procedure of CR considered by this approach consists of three main points:

- Track Association : identification of the radar track relative to the given target;
- Mode Assignment : assignment to the echoes selected in the previous step of the respective propagation-modes (in respect to the considered Ionospheric model);

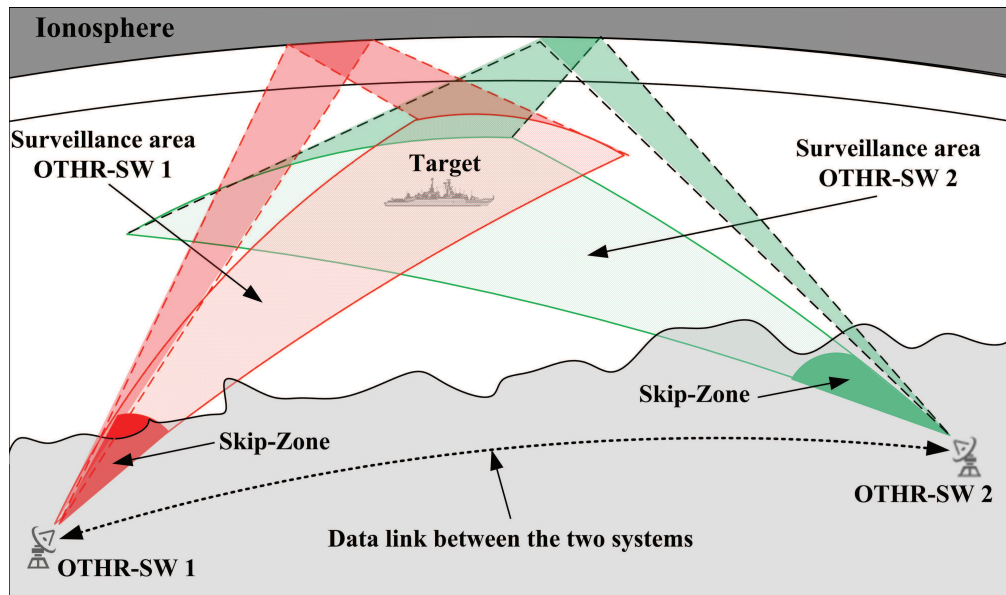


Figure 5.5. Sketch of two OTHR-SW with partially-superimposed surveillance areas.

**Ground Position Determination** : conversion of the radar tracks to ground coordinates, followed by the calculation of a weighted mean of this latter.

The “*Radar Fusion*” concept is not a subject that involves an exclusively OTHR-SW systems: in the literature can be traced numerous articles about the the joint employment of an OTHR and some  $\mu$ -waves radar [77, 78, 79].

After all the “*fusion*” of multiple devices is a process that generally brings benefits not only limited to the context of Geo-referencing. For example, the combined employment of two radar that are not aligned with the target allows to estimate also the radial component of velocity, increasing also the efficiency of the process of recognition and classification.

The main limitations to the application of the fusion method consists in the well known synchronization problems that always arises whenever two complex sensor work in a joint mode. We also need to notice that in order to employ this method in OTHR-SW applications it is necessary to install a secondary radar system with a remarkable impact on the cost of construction: the building of a second OTHR apparatus means nearly doubling the budget.

Instead, for what concerns the “*LOTHAR-FATT*” project, in which much of the research here presented was carried out, it seems highly desirable a sort of “*integration*” of the OTHR system with the existing Italian National Network of Surveillance Coastal Radars.



## 5.5 Forward-Based Receiver Augmentation

Another method to overcome the Ionospheric uncertainty proposed by Australian researcher is the “*Forward-Based Receiver Augmentation for OTHR*” (FBRA), also known as “*Skywave Line-Of-Sight*” (SkyLOS).

The method consists in using one or more HF band receivers of reduced size (about 10 elements each) placed in the advanced position within the coverage area of the main OTHR-SW system, so as to ensure a direct view (in the line-of-sight) of the targets (Fig. 5.6).

This system configuration seems to be able to make the OTHR-SW independent of the space-time variability of the Ionosphere, entailing also minimal additional costs (realization and maintenance of the advanced receiving sites) compared to those of a secondary OTHR-SW apparatus [40].

The major limitations of this approach are usually the non-sovereignty of the surveillance area and the localized nature of the supply brought by the advanced receivers which is limited to their line-of-sight. Moreover, as in the case of the fusion method, the various problems related to the synchronization of apparatuses separated by hundreds of kilometers from each other must be taken into account.

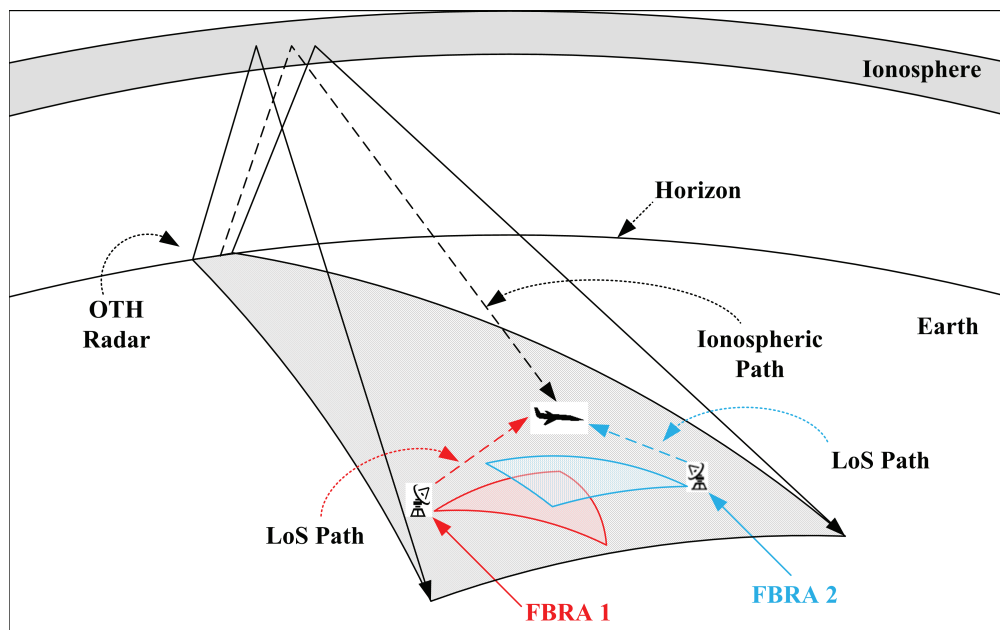


Figure 5.6. Simplified scheme of the Forward-Based Receiver Augmentation (FBRA) for OTHR-SW systems.

In fig. 5.6 a scheme of the basic principle of the FBRA method is proposed. The target, illuminated by the remote OTHR-SW, generates echoes received by

three system: the OTHR-SW, FBRA1 and FBRA2. The two FBRA's are passive devices that operate in the line-of-sight of the target (hence they are immune from the deleterious effects introduced by the Ionosphere on the radar echo), processing the received echo and forwarding the information to the OTHR-SW system. Once the three systems are interfaced and synchronized, they allow a triangulation that reasonably enhances the performance of the Geo-referencing procedure.

## 5.6 Ionospheric Sounding with the OTHR-SW

The French OTHR-SW system “*NOSTRADAMUS*” supports an operative mode to perform an Ionospheric sounding in the circular region that surrounds the radar. This functionality is articulated in two different types of sounding:

- Backscatter Sounding by Frequency Sweep (BSS);
- Backscatter Sounding by Scanning Elevation (ELS).

These two radar-routines allow to estimate ionospheric parameters to be inserted in a Multi Quasi-Parabolic Ionospheric Model (MQPIM) in order to characterize the Ionosphere (in terms of electron density profile) in the geographic region that surrounds the radar site. Note that the peculiar configuration of the single element and that of the antenna array (see fig. 3.9) allow the system to obtain a radar coverage area with circular symmetry and to produce an ionospheric model of the ring-shaped region around the radar site.

The major drawback to this method is the cost, in terms of dedicated time, of the scanning procedure which strongly depends on the ionospheric geographical location of the radar and that, according to the radar mission and deployment plan, may be totally unacceptable [75].

## 5.7 Different CR methods

Here we presented a list of the most common approaches to the Coordinate Registration problem for OTHR-SW systems. Certainly there are other different approaches and often they consist in the joint application of two, or more, methods that we just described. This is for instance the case of the approach proposed in [63], where the technique of *raytracing* is applied in accordance with a *Multiple Quasi-Parabolic Model* of the Ionosphere periodically updated with data from two *Vertical Incidence ionoSondes* (VISs) located in the surveillance area. In other cases the proposed CR method assumes the semblance of a *change of coordinates* that accounts for the error due to the Ionospheric uncertainty. This

is the case of [50], where it is described an algorithm for the transformation of *apparent azimuth* and *slant-range distance* in *real-azimuth* and *ground-range distance*. The method is based on a *spherical geometry model* of the scenario where a bistatic OTHR-SW operates and, by performing the coordinate transformation, it also introduce a correcting factor that accounts for eventual errors in the positioning of the radar footprint.

However the objective of the work presented in this thesis is not limited to the mere analysis of the available approaches to the CR problem, but it is mainly the development of an alternative Geo-referencing procedure for OTHR-SW systems to be employed be employed independently or in conjunction with any other of the listed methods.

In the following chapter we present the basic principle of the SLTI method with its mathematical formulation and with a brief analysis of its strengths and weaknesses. Then in chapters 7 and 8 we describe the application of the method respectively for Coordinate Registration and for Ionospheric Probing purposes.