Synthetic aperture radar: a new application for wave equation techniques

Fabio Rocca

ABSTRACT

The techniques of downward continuation and imaging invented for seismic waves can be applied to other types of waves. In this paper, we see how this application can be made in the case of electromagnetic surveys conducted with Synthetic Aperture Radar (SAR). The algorithms used closely follow those used for seismic waves. Differences are induced by alternate wavelengths, wave velocities, distances between sources and reflectors etc. In the case that we analyze in detail, a survey carried out using a satellite, difficulties arise from the fact that the orbit of the satellite cannot be approximated with a simple straight line if the spatial resolution of the survey is high. We determine appropriate techniques for the correction of the distortion induced by the latter and we delimit the resolution of the observed data, as seen from a satellite. Finally we show examples of the application of the technique of seismic migration to satellite data that were irradiated to earth during the short but productive life of SEASAT.

INTRODUCTION

Remote sensing of the earth's resources can be conducted using electromagnetic waves at optical frequencies and with microwaves in the 3 - 30 cm wavelength range (Elachi et al., 1986). The spatial resolution of the survey is dependent upon the bandwidth of the source, upon the width of the beams of the receiver and transmitter antennae, and upon the distance between the observation platform and the surface. The platform can be situated on an airplane or on a satellite (Harger, 1970). For reasons of continuous availability, satellites are preferable. The distances that we consider in this sequel are within the 200 - 800 km range.

Despite this very high distance, it is still possible to achieve a satisfying spatial resolution using Synthetic Aperture Radar (SAR) techniques. These methods are shown to be substantially identical to the techniques used for seismic surveying, though SAR uses different waves. The resolution achieved in the published experiments is on the order of 20 m from 800 km. However, we shall see that the resolution could improve up to 1 m or even less.

Resolution is obtained if the scattered wavefield is processed so that a wide receiving antenna is simulated. This corresponds to an extremely narrow antenna beam. In the case of SAR data, this particular processing has been carried out first optically and then digitally. It will be seen that there are no differences with respect to seismic migration for bandpass data, both in the temporal as well as the spatial domain. The same revolution experienced in seismics with the introduction of wave equation migration (Claerbout, 1972), is now possible in radar with all the consequent advantages in processing precision and in decreased costs. The digital techniques that have been used up to now can, in fact, be shown to be equivalent to either 5 degrees migration (stack along the Fresnel zone) or to a Kirchhoff diffraction stack. Therefore, the usual techniques are either too coarse to yield the resolution that might be obtained from the experiment, or too expensive to be utilized in practice.

The applications of SAR sensing are relevant to geophysics in general and to oil prospecting in particular. The radiation penetrates clouds and foliage and no sun is needed. If the terrain is arid, the radiation penetrates the upper layers of the terrain and reach either the water level that reflects the microwaves or the rocks buried below (Elachi, 1984).

Since penetration increases with wavelength, it is interesting to work toward lower frequencies. However, this approach has prohibitive computing costs if Kirchhoff techniques are used. With the introduction of wave equation, the cost of processing is virtually independent of the surveying wavelength. New opportunities are thus found for an increased use of this type of surveys in wide range of applications.

SAR DATA GATHERING: THE SEASAT CASE

An orbiting platform at an altitude of say 800 km, points to the earth a microwave beam, broadside with respect to the satellite orbit. In the sequel we will always refer to the SEASAT mission, a satellite that was launched in 1978 and that relayed useful data for ocean waves motion analysis (Beal, 1981; Vesecky, 1982). The beam of the antenna can be deflected fore or aft the satellite; in SAR terminology, this deflection is named "squint". A table to translate the seismic terminology into the SAR one will be found in the paper by Ottolini (Ottolini, 1987). Even if the antenna is pointed broadside, the relative motion between the satellite and the scatterers on the earth surface will produce a modest antenna squint (Figure 1).

During the period in which a scatterer on the earth's surface is illuminated by the beam of the satellite, radiation reflected back to the satellite incurs a progressive phase shift due to the variation of the relative moveout. This moveout is approximately hyperbolic; the approximation derives from the fact that the orbit is elliptic and that the scatterer is not in the orbital plane.

The moveout would be very close to hyperbolic if the satellite orbit were low in altitude so that the "visibility" from the scatterer is limited to a short time. During this time then the orbit could then be approximated with a straight line along which the satellite moves with a constant speed. We would then be in a situation very similar to

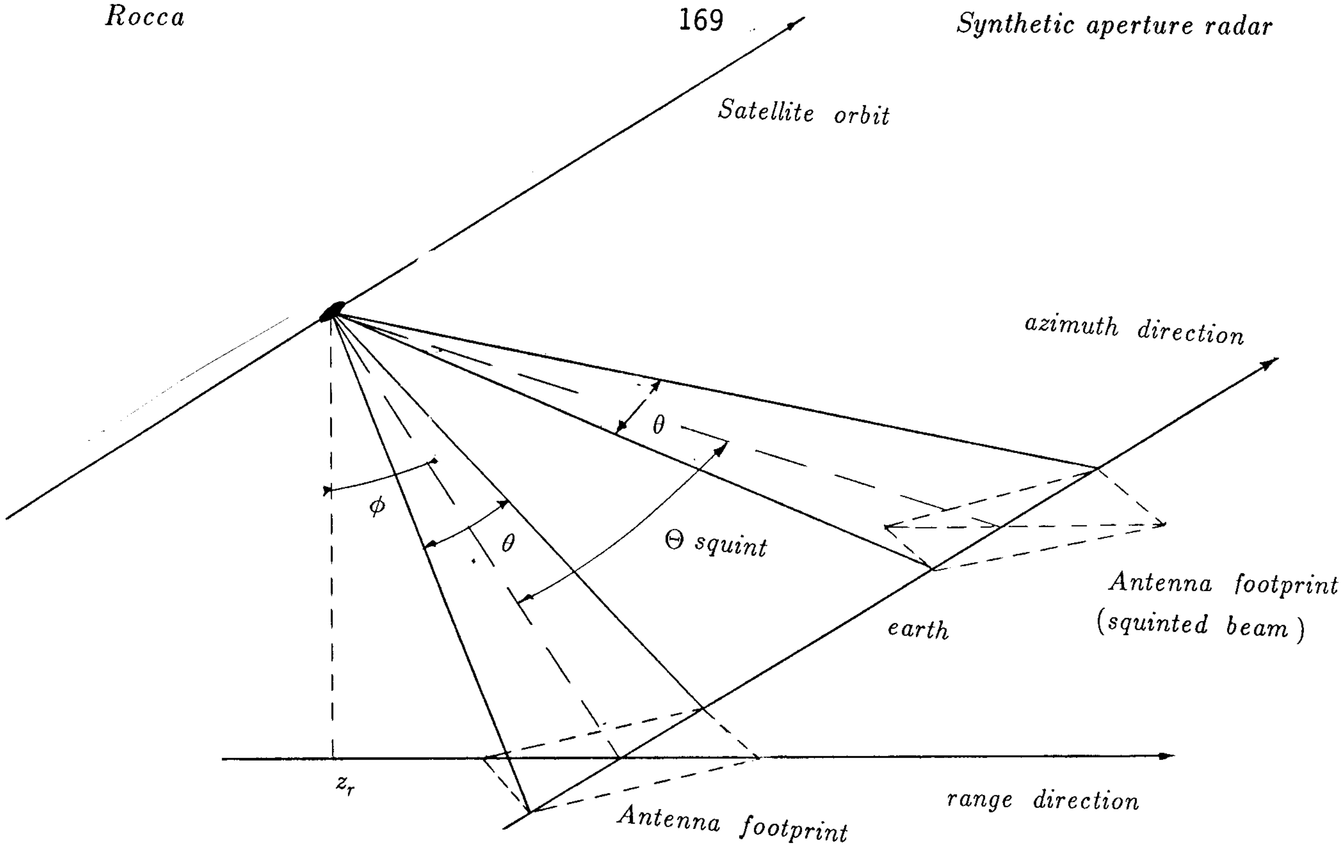

FIG. 1. Geometry of the satellite survey.

that of seismic surveys.

Another difference is the need of reasonable signal-to-noise ratios in satellite surveys. Such ratios cannot be obtained if the small energy irradiated by the satellite is distributed on broad surfaces. The antenna beam has therefore to be kept as narrow as possible, in keeping with the satellite dimensions.

SPATIAL RESOLUTION OF SAR SURVEYS

The spatial resolution obtained without synthetic focusing with an antenna that has length L, is readily calculated. The beamwidth is approximately:

$$\theta = \lambda / L \, , \tag{1}$$

where λ is the wavelength. The ground resolution at a distance z is:

$$r = z \frac{\lambda}{L}, \tag{2}$$

If z=850 km and λ = .23 m for L=10 m, we get r=20 km. If we want a resolution of say 10 m, the antenna width has to increase two thousand fold, thus going to 2 km. This is what migration gives us. In fact, the only option that we have is first to record and then to downward continue the data so as to reduce the effective distance between sensor and scatterer. To be able to do this, the data are recorded on board and then relayed to the earth by means of a radio link.

The satellite carries out an approximately zero offset survey. The radar on board emits pulses of radio frequency energy at the rate of one each 600 microseconds (approximate figures). Since the velocity of the satellite is 7450 m/s, the spatial sampling interval is 4.41 m. The energy is emitted at the frequency of 1,331 GHz and the bandwidth is 20 MHz. The echo returns after 5.66 msec. More than eight pulses are in the ether at the same time. During that time the satellite has moved about 40 m, so that we can think that the survey is approximately carried out with zero offset, as it was said before.

So as to limit the peak power, as with Vibroseis, the radar emits a chirp waveform that is compressed digitally into the usual Klauders wavelet. The duration of the radio frequency pulse is about 33 microseconds.

The resolution in the range (time, in seismic terminology) direction r_r is related to the pulse duration τ by the equation

$$r_r = \frac{c\,\tau}{2\sin\phi}, \tag{3}$$

The sin ϕ factor derives from the fact that we are interested in the ground resolution along the direction parallel to the surface of the earth, rather than that in the scatterer satellite direction.

The angle ϕ is known as the off nadir angle. Formula (3) also shows that this angle has to be far from zero to ensure that ambiguities are avoided. In the SEASAT case, $\phi=20^0$; in this case the resolution in range is about 23 m.

The time between two successive RF pulses is partly occupied by the chirp and partly by the radar returns (about 300 microseconds). In order to avoid the interference with the echoes generated by preceding or following RF pulses, the radar antenna is properly shaped in the direction orthogonal to the direction of the orbit. In this way, the regions of the earth that could contribute to these early or late arrivals are not at all illuminated. This shape of the antenna beam thus allows the elimination of aliasing in range.

SEISMIC SURVEYS VERSUS SAR

In the previous section we have seen the that electromagnetic data are gathered on board an aircraft or a satellite and then retransmitted to an earth station. We now note the similarities and the differences between the seismic and the electromagnetic experiment.

Since we will limit ourselves to the problem of image focusing, there is no real difference between the mathematics involved in the processing of the two fields. This simple fact has been obscured by different terminology, however.

Who would say, straight away, that dipping events are equivalent to Doppler shifts and vice versa?

The main differences are due to the huge variations of the physical parameters involved. However, we will see that even if there are several order of magnitude between the velocities and frequencies involved, the resolution is still man sized in both cases, so that we will be able to find a lot of common ground.

In the electromagnetic case, the central frequency of investigation is 40 millions times higher than the usual seismic frequencies but, on the other hand, the velocity of propagation is about 100,000 times higher too. Thus, being the central wavelength 23 cm, the ratio with respect to the seismic case is now a more reasonable factor of 400.

The horizontal sampling interval is smaller than that usual for seismics (4.41m) but the difference is not really relevant. The range resolution is also similar to what is being obtained in seismics, so that we can discount big variations from this viewpoint.

The major difference derives from the fact that the signal is band - pass rather that substantially low - pass as for seismics. Thus, the wavelength that is used for the investigation is much shorter than the resolution cell. This induces two new disturbing effects: speckle noise and spatial alias, both practically absent in the seismic case (Figure 2).

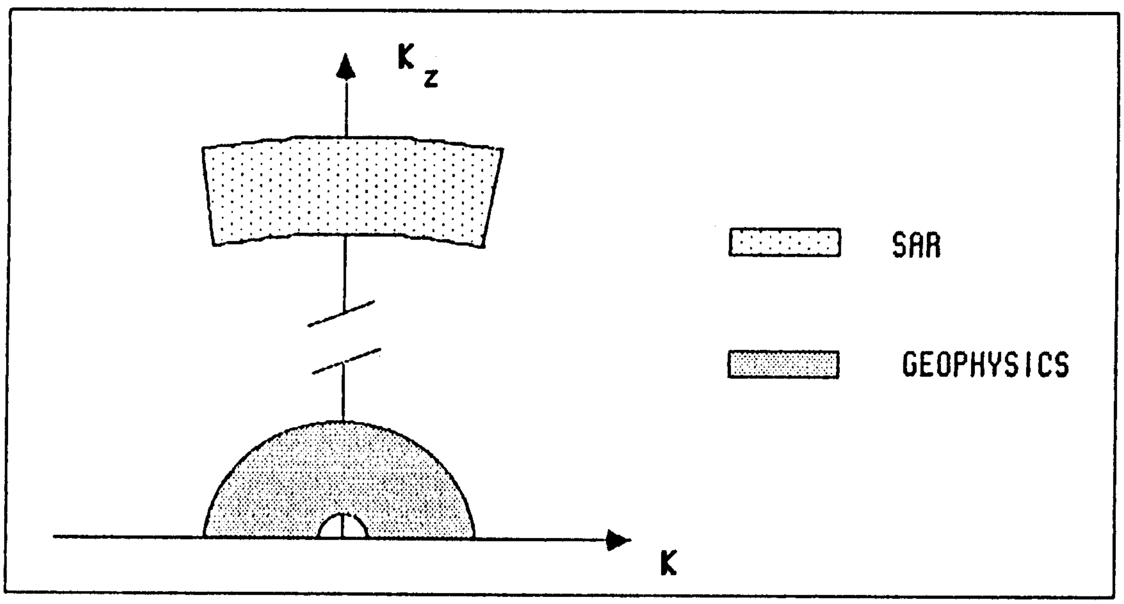

FIG. 2. SAR and seismic images in the transform domain.

Spatial Aliasing

Let us first briefly calculate the resolution that we can obtain from the SAR survey, using the classical seismic arguments. If the on board antenna has width L in the in line direction, (azimuth direction in SAR terminology), then we know that the beamwidth is

$$\theta = \frac{\lambda}{L}, \tag{4}$$

The maximum angle of arrival of the waves to be recorded is $\theta/2$; therefore, the maximum wavenumber that has to be recorded is:

$$k_{\max} = \frac{4\ \pi \sin\frac{\theta}{2}}{\lambda_{\min}}, \tag{5}$$

Thus, the spatial sampling rate should be

$$\delta = \frac{\lambda_{\min}}{4\ \sin\theta/2}, \tag{6}$$

and the spatial resolution is one half of the antenna length. Up to now, no alias problems appeared, that were not present in the seismic case. In fact, we defined the sampling interval just in order to avoid alias. However, if the antenna beam is squinted of the angle θ_s fore or aft of the spacecraft, the maximum angle of arrival is now $\theta_s + \theta/2$. This angle is no more dependent on the antenna beamwidth only, but is determined by the squint too. Then, the sampling rate should decrease in proportion. However, the antenna has still the same, small, beamwidth so that even if the data are aliased, we can recover them, unwrapping the alias (Figure 3). The unique information we need to be able to focus the image is the approximate direction of pointing of the antenna, so that we can tell which alias replica we are actually looking at (Cafforio, 1987b).

Speckle Noise

The return (echo, in seismic terminology) from each resolution cell is the superposition of several returns from the scatterers inside the cell. If the scatterers are statistically homogeneous, their radar echoes will have identical amplitude distribution. The phases of the arrivals will be completely random, though, due to the random spatial distribution of the scatterers within the cell. If the wavelength is longer than the cell, no significant changes will be due to this effect. However, in the SAR case, a cell is about 100 wavelengths.

Hence, if the angle of incidence of the radiations changes, the phase of the superposed returns will change too. This implies that only the modulus of the received bandpass signal will be of interest for imaging purposes; the phase will carry almost no information even if it is necessary to achieve focusing.

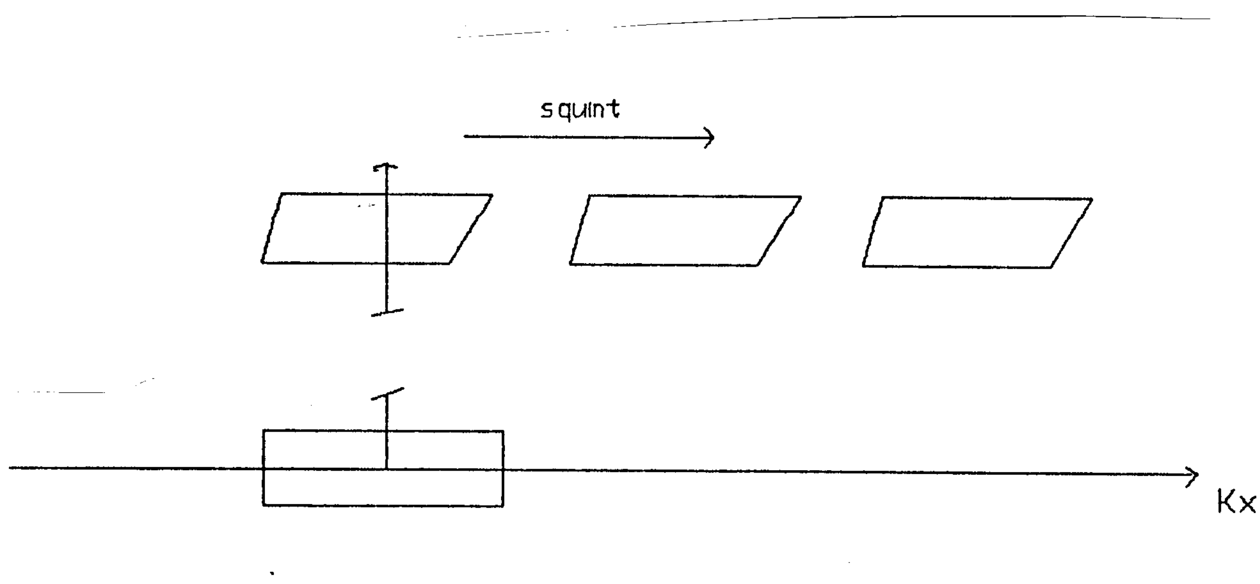

FIG. 3. Effects of the alias on a squinted beam.

To be more specific, the phase of the radar return carries a single piece of information relative to the location of all scatterers within the resolution cell. This phase will change, depending on the direction of incidence of the rays. If we had many incidence angles, and thus more phases, we could use them to tell the positions of the scatterers within the cell, but this would just correspond to an increase of the resolution. In conclusion, for a given resolution, the phase of the radar return has no clear meaning, whenever the single scatterer is smaller than the cell.

Therefore, all the processing will be carried out on complex numbers, that is taking into account both amplitude and phase of the echoes. Only the modulus will be displayed.

Since the investigating wavelength is much shorter than the resolution cell, the images are disturbed by the so called speckle noise. This type of noise can be interpreted as deriving from the random appearance, at given angles of observation, of strong reflections in random locations. Changing the observation angle, this glittering effect also changes. Thus, it can be attenuated by incoherent averaging of the images over observation angles (looks) (Raney, 1985), as seen in the next section.

Look summation

The maximum resolution that can be obtained is L/2, where L is the length of the antenna, as we have seen. In this case, the antenna beamwidth corresponds to the coherence band of the received radiation. In other words, in the case of maximum resolution for a given antenna beam, the relative moveouts of the scatterers that are contained in the same resolution cell can be neglected.

If we wish to decrease the resolution with respect to this limit, we have two options:

- lowpass the data in the image domain. Obviously we have to average the moduli, since, as we have seen, the phases of neighbouring pixels will be random and the data would rapidly average to zero.
- proceed to the focusing, and then divide the wavenumber domain in smaller regions, each correspondent to the desired resolution along the two axes. Then antitransform and sum the moduli (incoherent averaging) that correspond to the data in each region of the spatial domain.

Actually, it is the second procedure, i.e. that of the incoherent summation, that should be followed. Operating in this way, in fact, we sum different "looks" of the data. Different regions of the frequency wavenumber domain correspond to different angles of view.

Combining different looks, we are able to average out the speckle noise that would otherwise be overwhelming as seen in Figures 4 and 5 (Bonanomi, 1987).

The simple low pass of the high resolution images would not do; if we just cut the high spatial frequencies, we would eliminate signal that could still be used. However, to use this signal, we have to average it after the removal of the phase, i.e. averaging the moduli.

MORE DISPARITIES BETWEEN SAR AND SEISMICS

Up to now we have seen no reason not to use the usual seismic data processing techniques to focus SAR data. Indeed, the region occupied by the signal in the frequency wavenumber domain is not usual; moreover, the final presentation of the data should somehow remove the speckle noise. It should be pointed out that the speckle is really more "signal" then noise, since it corresponds to "bona fide" diffractors that we do not wish to see. They are too small to be resolved, and therefore clutter the overall picture.

We can summarize now two subtler differences that have to be considered before rushing to the conclusion that the two types of processing are identical.

- The 2 D survey carried out by the radar is not related to a medium that is uniform in the orthogonal direction, as it is generally accepted for 2D seismics, but to a distribution of scatterers on the surface of the earth. This surface is not transparent to the radiations and then it cannot be contained in the

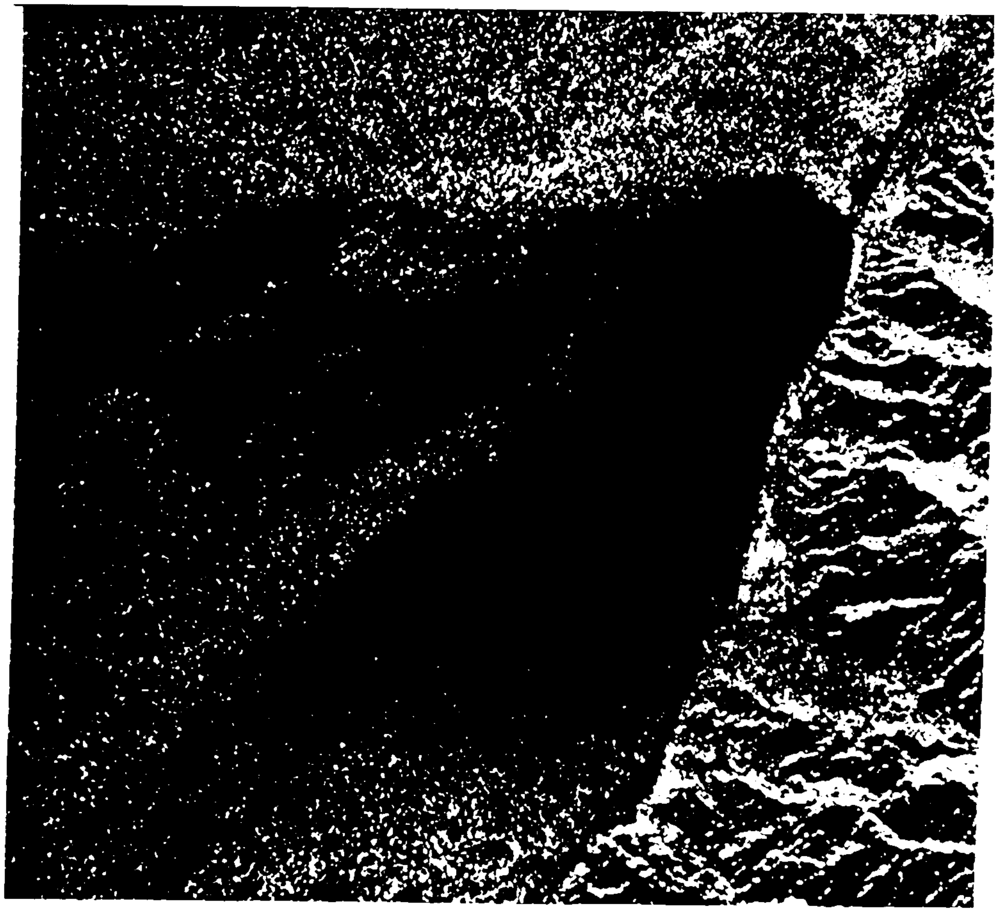

FIG. 4. Image obtained from a single look. The speckle noise is quite visible.

plane of the orbit.

- The relative motion between satellite and scatterers, that we need to compute the moveouts, is made more complex by the ellipticity of the trajectory and by the relative motion of satellite and earth.

2D surveys in 3D space

The scatterers in the SAR situation are 3D scatterers located on a non-planar surface. It is rather simple to show that this effect does not imply relevant changes with respect to the seismic case.

Using the exploding reflector approach, approximation well justified by the small aperture angle of the survey, the constant velocity c, and the very small offset, we have that the field measured by the satellite is:

$$P(x, y, z, \omega) = \frac{1}{4\pi} \times \tag{7}$$

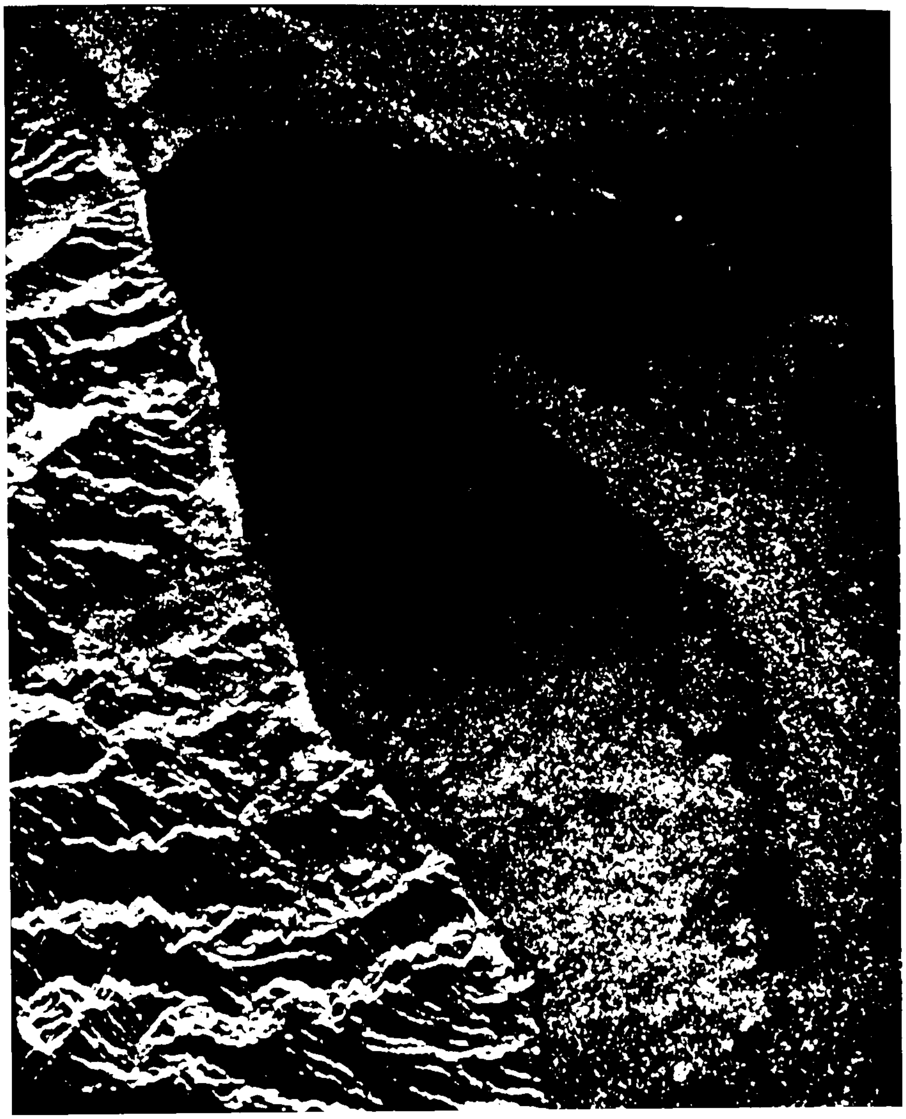

FIG. 5. Image obtained from the summation of four looks. Smaller amounts of speckle noise are visible. On the right, it is possible to see a long ship wake; there is an unwanted horizontal flip with respect to Figure 4.

$$\int\int\int s(x',z',\omega)\,\delta(y')\,\frac{e^{-j\frac{2\omega}{c}\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}}}{\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}}\,dx'dy'dz',$$

where x, z are the axes in the plane defined by the orbit. In this section we will take that as a straight line. The scatterer is defined as $s(x,y=0,z)$. The third coordinate y, is orthogonal to this plane.

If we could measure the data for all y's, we could Fourier transform, and for $k_y=0$ we would get:

$$P(x, k_y, z, \omega) = -\frac{\pi}{2} \times \tag{8}$$

$$\int\int s(x', z', \omega) H_o^{(2)}\left(\sqrt{\frac{4\omega^2}{c^2} - k_y^2} \sqrt{(x-x')^2 + (z-z')^2}\right) dx'dz',$$

$$P(x, k_y = 0, z = 0, \omega) = -\frac{\pi}{2} \times \tag{9}$$

$$\int\int s(x', z', \omega) H_o^{(2)}\left(\frac{2\omega}{c} \sqrt{(x-x')^2 + z'^2}\right) dx'dz',$$

$$P(k_x, k_y = 0, z = 0, \omega) = -\frac{j}{2} \times \tag{10}$$

$$\int\int s(x', z', \omega) \frac{e^{-jz'\sqrt{4\frac{\omega^2}{c^2} - k_x^2}}}{\sqrt{4\frac{\omega^2}{c^2} - k_x^2}} e^{-jk_x x'} dx'dz'.$$

Using the Stolt change of variables (Stolt, 1978) we would then get the migrated data. However, we only measure $P(x, y = 0, z = 0, \omega)$ and we need $P(x, y, z = 0, \omega)$. We also have that:

$$P(k_x, y = 0, z = 0, \omega) = -\frac{\pi}{2} \times \tag{11}$$

$$\int\int s(x', z', \omega) H_0^{(2)}\left(z' \sqrt{4\frac{\omega^2}{c^2} - k_x^2}\right) e^{-jk_x x'} dx'dz'.$$

If we approximate the Hankel function with its expansion for high values of the argument (and they are high indeed, since they might be of the order of several billions), we get:

$$\approx -\sqrt{\frac{\pi}{2}} \int\int s(x', z', \omega) \frac{e^{-jz'\sqrt{4\frac{\omega^2}{c^2} - k_x^2}}}{z'^{\frac{1}{2}} \sqrt{4\frac{\omega^2}{c^2} - k_x^2}^{\frac{1}{2}}} e^{-j\left(\frac{\pi}{2} + k_x x'\right)} dx'dz'. \tag{12}$$

The denominator under the integral is a slowly varying function of ω, k, z. For the range of values of interest, the denominator is practically a constant since its amplitude varies a few percent over the whole range. Then, the denominator can be taken as a multiplicative factor and be neglected completely. We get again an equation similar to (10), that we can invert in the usual way.

In practice, rho filters are irrelevant for bandpass data, and more so if we observe the moduli of the scatterers only.

The ellipticity of the orbit

The actual moveouts can be determined by looking at Figure 6. It is easy to see that, if R is the earth's radius, we have:

$$\xi = (R + h)\sin\frac{x}{R+h}, \tag{13}$$

$$\eta = (R + h)\cos\frac{x}{R+h} + R\cos\frac{z}{R}, \tag{14}$$

$$\varsigma = R\sin\frac{z}{R}. \tag{15}$$

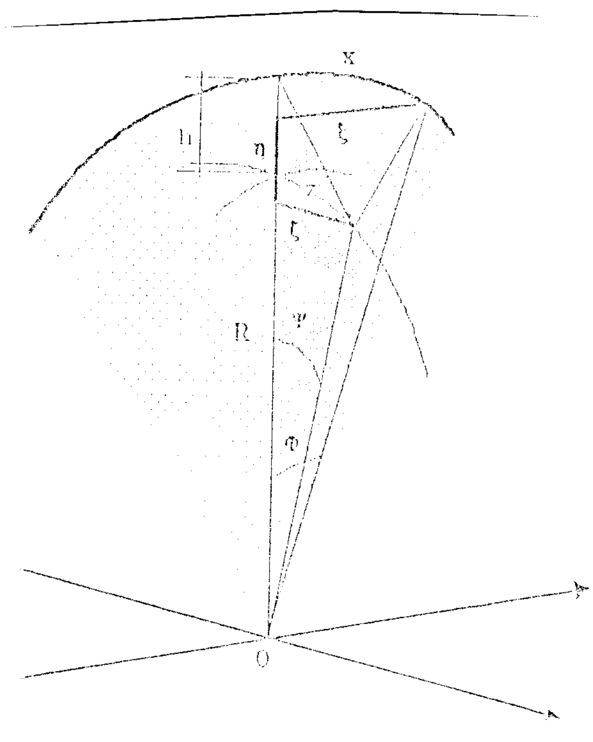

FIG. 6. Geometry of the satellite survey for a circular orbit.

Moreover :

$$\frac{c^2t^2}{4} = \sqrt{\xi^2 + \eta^2 + \varsigma^2}, \tag{16}$$

and then :

$$\frac{c^2t^2}{4} = h^2 + x^2\frac{R}{R+h} + z^2\frac{R+h}{R} + \ldots, \tag{17}$$

$$\frac{c^2t^2}{4} = \frac{c^2t_o^{\ 2}}{4} + x^2\frac{R}{R+h} + \dots\dots$$

Thus, in a first approximation, the circularity of the orbit implies that the only correction that we need to apply is to correct the velocity of light by a factor greater than 1. This has nothing to do with relativity, though; it is only an effect of the circularity of the orbit. If the scatterer were at the center of the earth, there would be no moveout and the velocity would be infinite.

IMAGING OBJECTS IN MOTION

The analysis that we carried out in the previous section considered the earth motionless; however, we have to take into account that during the time in which the object is illuminated by the radar, it can move and the earth moves too. Making a comparison in seismics, if we had a scatterer moving along the seismic line with the same speed of the ship, it would migrate with infinite velocity. Therefore, we have to take into account the change in the moveouts induced by earth motion first, and then by object motion. The time of observation from a satellite in quasi polar orbit, within the viewing angle correspondent to the antenna beamwidth mentioned previously, is about 2 seconds. In this time the moveout of a scatterer, that is the variation of the say 850 km distance, is just about 37 m, with a motionless earth. The component of the velocity of the earth in the direction of the satellite depends on the latitude and upon the angle between the orbit and the north.

In the case of SEASAT, the orbit (ascending) is inclined 13^0 NNW. At the latitude of the region imaged in the figures of this report (the southern tip of the Italian boot), the component of the earth motion along the satellite orbit is about 76.4 m/s. compared to that of 7450 m/s of the satellite. There is also a component orthogonal to the orbit (about 330 m/s). Taking into account both components, the antenna of the satellite results aimed about 1^0 from broadside, even if it is broadside for the satellite. As we have seen, this implies noticeable aliasing, since the aperture of the antenna is 1.3^0 only. This alias can be easily taken into account as previously observed, since all the parameters are known.

Ships move updip

Suppose that a ship that has some motion in the range direction is imaged. In the "seismic section" it will then appear as a dipping event and will migrate updip. Thus, in SAR pictures, the ships are not positioned at the tip af their wake, if they move at all in the direction orthogonal to the orbital plane. They are displaced along the inline direction.

This inline displacement depends on their radial velocity (the dip). With the usual migration arguments, it can be seen that the displacement is equal to:

$$d = \frac{v_r}{v_s} z_r \,, \tag{18}$$

where v_r is the radial component of the velocity, v_s is the velocity of the satellite and, finally, z_r is the distance of the ship from the projection of the orbit onto the earth's surface. In the case of the SEASAT data, r is about 250 km, due to the off nadir angle ϕ used. Thus, a radial velocity of 1 m/s implies a displacement of 35m along the line. There will also be some very slight defocusing.

Autofocusing

Let us now consider a plane that cruises with a velocity component of 300 m/s in the direction orthogonal to the orbit of the satellite (radial direction). It would be imaged as if it were displaced horizontally by more then 10 km but then would be aliased back, defocused.

It is also evident that SAR techniques are very interesting for imaging airplanes too. In that case, some autofocusing techniques or some data deriving from other radar information (namely, the velocity or the direction of flight or both), should help in this process. However, to discuss this very crucial topic would take us too far from seismic data processing, even if quite a few common elements could be found.

Another application of autofocus is determining the actual curvature of the hyperbola, either by maximizing the Kurtosis of the data or using some other minimum entropy approaches. Obviously, we are not proposing an experiment to measure the velocity of light; the result of the autofocus is a more precise measurement of the velocity of the satellite or of its small orbital oscillations. In fact, since the wavelength is small, even small orbit variations induce noticeable phase shifts. However, these shifts are "slowly varying" and can be easily parametrized and compensated as it can be seen in other applications (Cafforio, 1987a).

A great quantity of data is available to make these minimum entropy estimates. This makes it reasonable to study how far the techniques developed for seismics can go at evaluating and compensating the small satellite motions. In turn, it will be possible to achieve the ultimate goal, i.e. wavelength resolution.

WIDE LINE SURVEYS FROM SPACE

In the SAR survey there is a very small offset between source and receiver. As a matter of fact, it is the same antenna that acts as source and receiver in different time intervals. So, there is just one receiver, but it need not to be that way. One can think of a satellite trailing a cable along which other receivers are located so as to achieve a multiple coverage experiment as in seismics.

However, one of the main purposes of that, namely velocity estimation, is irrelevant for SAR applications where the speed of light is rather constant in the zone of interest, even if its variations in the troposphere are not to be neglected at all.

However, the other advantages of multiple coverage can be obtained like improvement of the signal - to - noise ratio and reduction of alias noise using dip moveout.

The most interesting application of non zero offset surveys appears to be the measurement of the elevation of the terrain. This can be obtained by comparing the phases (or, if incoherent comparison is used, the times of arrival) of the reflection of the same scatterer to receivers that have different positions in space.

3D surveys can indeed be carried out by using multiple passes of the satellite, but then the identity of the scatterer has to be established by crosscorrelating the incoherent images. Therefore, the resolution is reduced and the vertical resolution even more so. A new solution proposed for this problem is the use of tethered satellites from the space shuttle. Two receivers are simultaneously active, so that they will are able to record and compare the phases of the arrivals from the same scatterer.
In this case, the direction of the cable that links the second receiver to the main unit should have a noticeable component along the vertical, in order to have a parallax with respect to the vertical features of the earth (Vetrella, 1987).

In seismic terminology, these features correspond to cross dips. They are lumped together in a zero offset section, but they can be sorted out using a wide-line survey. In space, the nice thing is that the cable can have the feathering we wish without much effort, and no favorable currents are needed.

AN EXAMPLE OF DOWNWARD CONTINUATION OF SAR DATA

A detailed analysis of SAR processing using the seismic approach is given in (Ottolini, 1987); an example of SAR data downward continued to the closest range (upper part of the picture) is shown in Figure 7 (Bonanomi, 1987). Actually, the data have been downward continued for 850 km; the phase shift would amount to about 23 million radians.

These data are equivalent to a seismic section, 60 km deep and 60 km wide. The bottom of the picture shows data that are still to be migrated to take into account the differential phase shift between the two range levels. It is possible to notice the small hyperbola chunks that characterize the migration that still has to be carried out. Even if this migration corresponds to a very small angular aperture, still the defocusing after 60 km is quite evident.

It interesting to look at the wakes of the ships; they can be very long and indeed wakes up to 100 km have been reported (Peltzer, 1987). In this case we see a wake about 20 km long, on the left. In the central part of the figure and even better in Figure 8, mountains appear that seem very distorted since their side that looks toward the satellite (up) appears compressed whereas the other side is expanded. This derives from the fact that the off-nadir angle is 20 degrees.

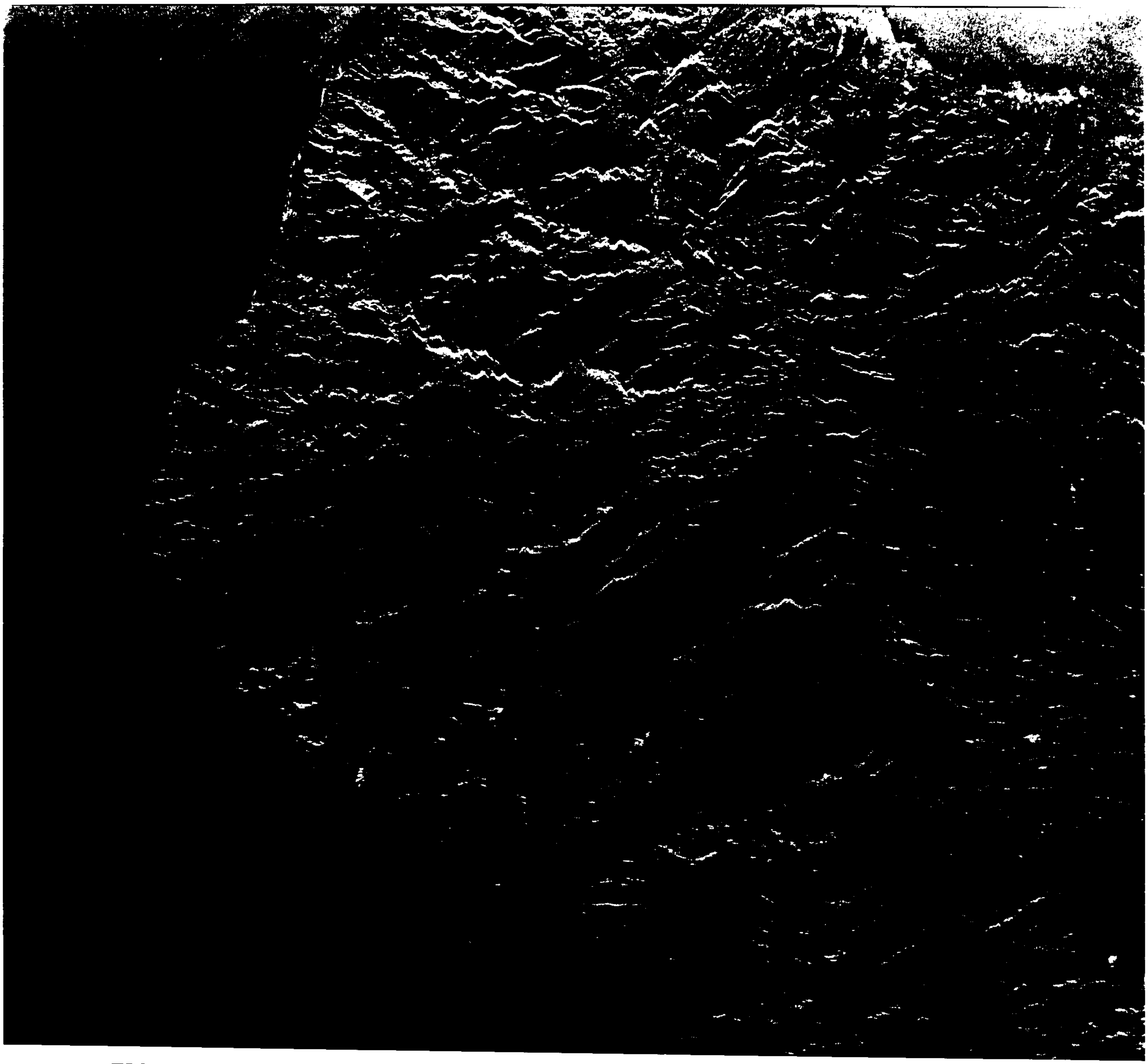

FIG. 7. An example of SAR data taken by the SEASAT mission in 1978 is shown, after downward continuation (850 km of it) carried out using wave equation techniques. The phase shift applied to the data would amount to about 23 million radians! The image represents the southern end of the Italian peninsula and the town of Reggio di Calabria can be seen at the top; the spatial resolution is about 20 m. A long ship wake can be seen on the left of the picture.

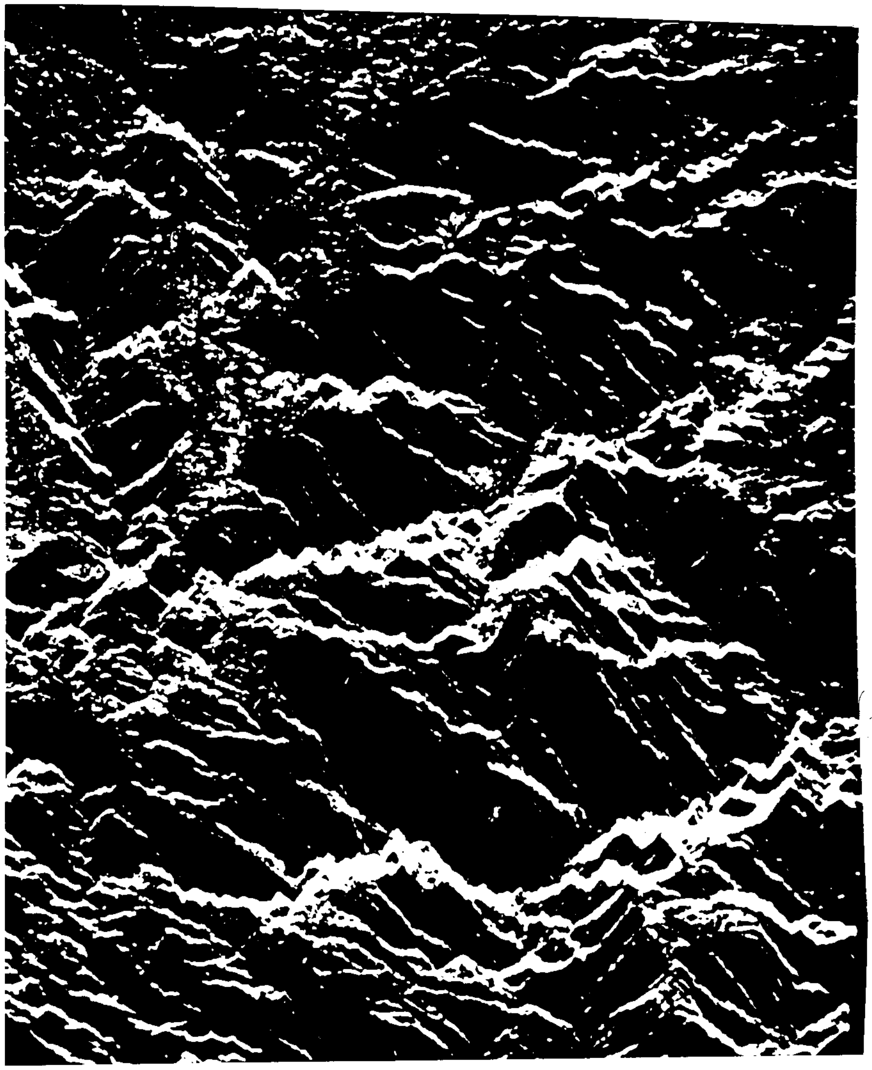

FIG. 8. A close up of the central part of Figure 7. The side of the mountains that looks toward the satellite is compressed, whereas the other side appears expanded. The vertical axis corresponds to the distance from the satellite and not to a terrestrial coordinate.

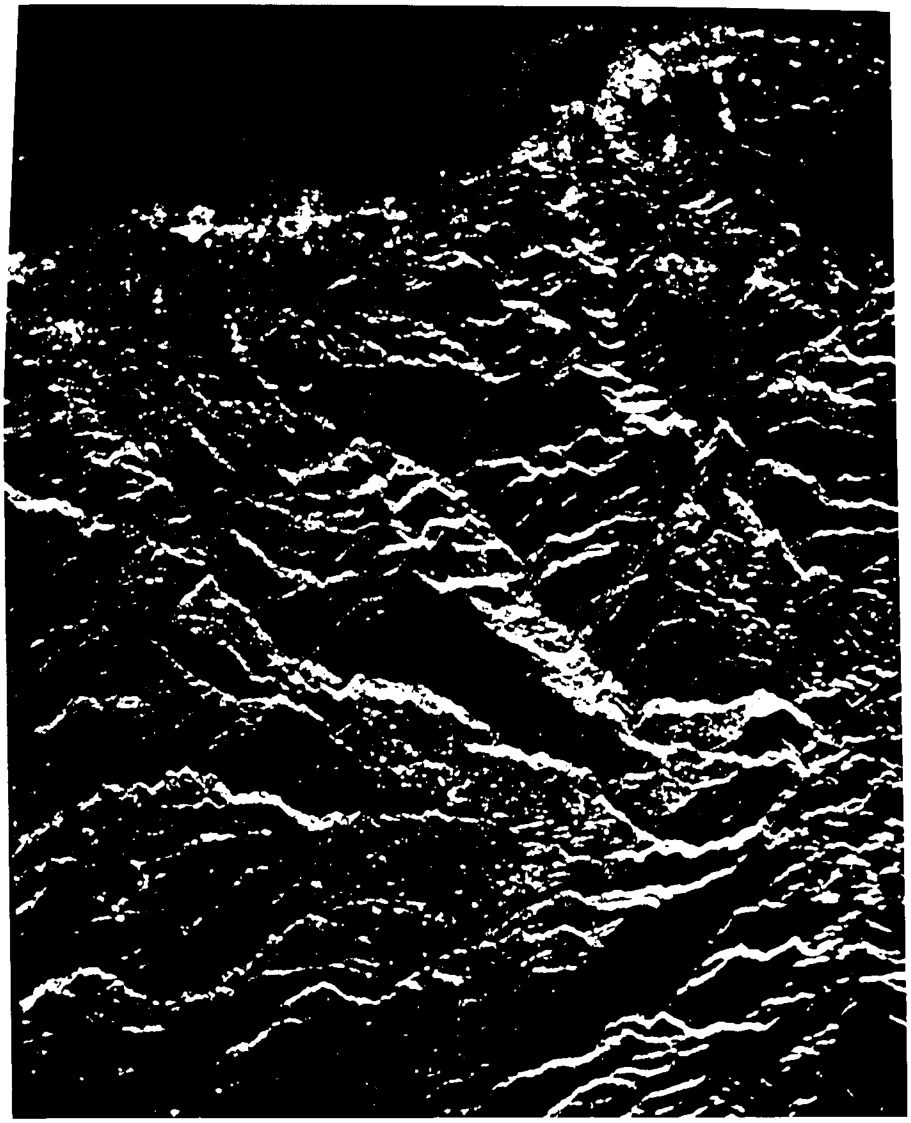

FIG. 9. A close up of the town Reggio di Calabria, in the upper right side of Figure 7; there is an unwanted horizontal flip of the image.

Mountains sloping 20 degrees when facing the satellite are compressed into single range lines and higher slopes result in "catastrophes" i.e. the top of the mountain is imaged at smaller "depth" than the bottom. On the other hand, the other versant appears rather flat and uniform. These effects have to be compensated using a proper digital model of the terrain or by making multiple surveys.

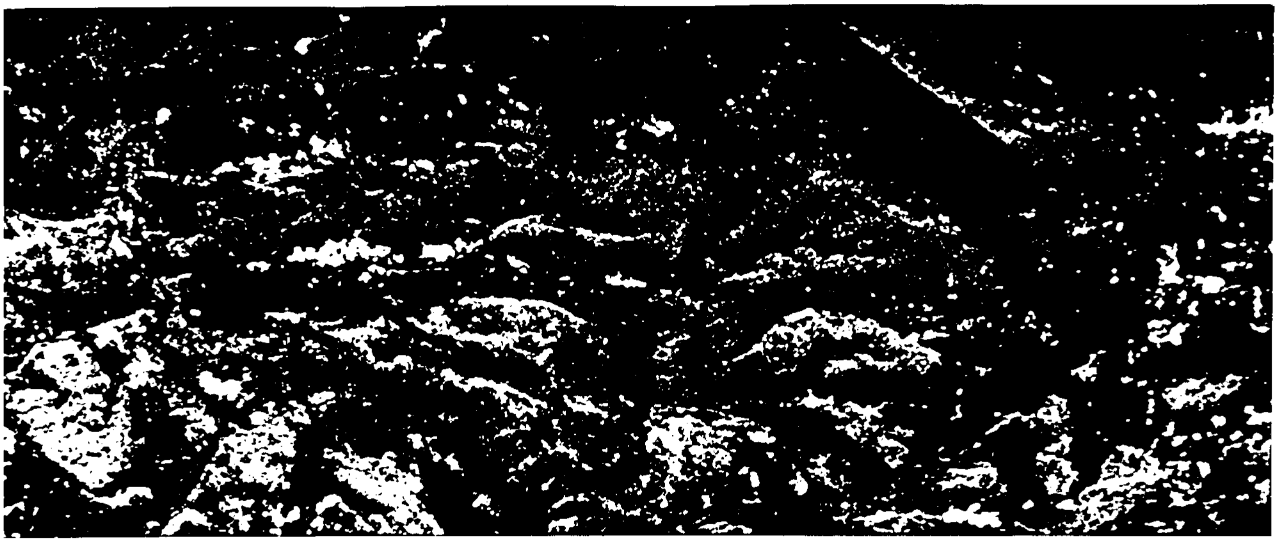

FIG. 10. An image taken from the NASA space shuttle Challenger during the experiment SIR - B (Shuttle Imaging Radar B). The image represents roads and houses, as seen from a distance of about 200 km, in the region of Freiburg, Federal Republic of Germany.

PROCESSING WITH THE WAVE EQUATION

All the considerations presented above could just be another, maybe futile, exercise in transposition of a concept from the field where it was invented into another field where it perhaps was not needed. However, the vast size of the data set that have to be processed in the SAR surveys make it very relevant to study techniques that can reduce the computational burden. Moreover, the added precision of the wave equation processing will allow to increase the resolution with respect to current achievements.

Another interesting question derives from the possibility of synergy between the two fields. It is easy to understand that real-time surveys using SAR are very useful for several applications and therefore parallel machine capable of achieving the computation rate necessary for that purpose will be studied. If these machines turn out to be the same that we need for migration (Bolondi, 1977), it would be helpful for the exploration industry too.

As an example of a real-time survey, we can consider a satellite that analyzes earth resources and therefore needs to process data (maybe onboard to take rapid decisions) at the speed of say 10 millions pixels per second, to achieve a resolution of 10mx10m.

Another example corresponds to that of an airplane flying high along a coastal line which can explore inland for more than 100 km, with the resolution of say 10 cm. In this case, the processing needs go up to about 3 billion pixels per second. These processing tasks imply about 100 multiplies per pixel so that the total number of multiplies per second required maybe of the order of several billion or more.

With these kind of figures, the added precision of frequency domain migration is a necessity. Up to now, SAR data have been focused with different techniques that correspond to Kirchhoff diffraction stacks (Curlander, 1986). When these stacking operations are carried out in the frequency domain, the operation is carried out range line by range line, with a sort of 5 degrees migration.

When the antenna beam is squinted, then the data are first interpolated along the slant line corresponding to the "average dip of the beds" and then 5 degrees migrated. Obviously, the dechirping is always carried out in the frequency domain. The problems with this type of processing start when the curvature of the hyperbola cannot be neglected. Then, some sort of frequency dependent interpolation in the time-wavenumber domain has been attempted but with limited results at least from the viewpoint of precision (Wu, 1985).

If high resolution was considered necessary, then it has been mandatory to work in the space domain with the enormous resulting costs. In fact, the diffraction stack may well be more than 1000 points long, and each point corresponds to a complex multiplication. The problems increase still when the aperture angle gets larger and larger.

Summarizing, with the classical focusing techniques that have been used up to now for SAR data processing, the hyperbolic traveltime has been approximated with a parabolic phase shift, without really serious attempts to follow precisely the actual time shifts.

Wave equation focusing will allow practically perfect results with minimum cost, i.e. just that of the Stolt interpolation in the 2D Fourier domain. Moreover, it is possible to lump the operations of dechirping and focusing. Finally, no variations in propagation velocity, either vertical or lateral, limit the Fourier technique.

THE TECHNIQUE FOR HIGH RESOLUTION: SPOT SAR

Another added feature of frequency domain focusing is logarithmic dependence upon the wavelength of the computing costs. In fact, increasing the wavelength for a given resolution, the hyperbola occupies more pixels and the data windows should increase. This increases the number of operations logarithmically, and therefore does not involve real difficulty.

In the case of diffraction stacks, on the contrary, the cost of computing is proportional to the length of the diffractor response. This decoupling allows the use of lower frequencies, say in the 5-600 MHz range rather than in the GHz range. This in turn means better penetration of the foliage, atmosphere and even earth surface. Moreover, one might use the same concept to extend the resolution for a given wavelength, rather then extending the wavelength for a given resolution. This again implies a wider antenna beamwidth and more pixels in the diffraction stack.

This extended resolution case is named SPOT SAR (Di Cenzo, 1986; Munson, 1983). The antenna beam cannot be widened too much without reducing the signal-to-noise ratio by spreading the irradiated energy on too large a surface. On the contrary, in seismics, the principal rationale for source and geophone patterns, that is the antennas beamwidths, is the removal of directional noise rather than the increment of signal gain.

Therefore, to increase signal gain, an antenna that is steered so that it points continuously towards the region to be imaged has been proposed. This is equivalent to a broader beam, but there is no possibility of a continuous survey. Hence, the name of SPOT SAR.

If the platform that hosts the sensor flies in a circle around the object to be imaged, we get back to the classical tomographical case. If frequency domain focusing is used, no big problems appear. However, the alias is now time varying, and should be kept under close control. In fact, the alias depends on the mutual angles between scatterer and satellite, and it will increase with increased squint of the antenna beam. The limited beamwidth of the antenna, always the same and dependent on the spatial sampling rate, allows avoiding of confusion, provided that the direction of the antenna is known approximately at all times.

We see that these problems are complicate; in the case of diffraction stacking they would become more so. It is important to notice that SPOT SAR may allow spatial resolutions of the order of magnitude of the wavelength, as happens with seismic data. This shows the enormous promise of wave equation techniques for SAR data processing. Without these, SPOT SAR would be impossible or, at least, unfeasible.

CONCLUSIONS

The transposition of wave equation techniques from seismics to SAR data processing is a valid example of crossbreeding made possible by the advent of new technologies. These allow experimenters to operate in real time on very large data sets. Many techniques used for seismics can be exported to SAR. In contrast it is reasonable to expect that some computers that will be designed for SAR data processing will also be useful for other geophysical applications.

ACKNOWLEDGMENTS

The author thanks Prof. C. Cafforio, Dr. C. Prati, Dr. Ing. V. Bonanomi, and M. Guzzi for their cooperation in this project and their help in understanding the numerous problems under study.

REFERENCES

Beal, R. C., DeLeonibus, P. S., and Katz, I., 1981, Spaceborne synthetic aperture radar for oceanography, The John Hopkins University Press, Baltimore.

Bolondi, G., Rocca, F., and Savelli, S., 1977, A frequency domain approach to two - dimensional migration, presented at the 39th Meeting of the European Association of Exploration Geophysicists, Zagreb, 1977; Geoph. Prosp., Vol. 26, No. 4, Dec. 1978, pp. 750 - 772.

Bonanomi, V., and Guzzi, M., 1987, Migrazione di Stolt generalizzata con onde elettromagnetiche; implementazione su array processor. Politecnico di Milano, Thesis for the Dr. Ing. degree.

Cafforio, C., Piacentini, M., and Rocca, F., 1987a, Algorithms for image reconstruction after non uniform sampling, IEEE Trans. ASSP, No. 8, pp. 1185 - 1189.

Cafforio, C., Prati, C., and Rocca, F., 1987b, SAR real time on board processing: the polyphase algorithm. Proc. Int. Conference on Supercomputing, Santa Clara, 1987.

Claerbout, J. F. and Doherty, S. M., 1972, Downward continuation of moveout corrected seismograms, Geophysics, Vol. 37, pp. 741 - 768.

Curlander, J. C., 1986, Performances of the SIR - B digital image processing subsystem, IEEE Trans. GE - 24, Vol. 4, pp. 649 - 652.

Di Cenzo, A., 1986, Comparison of resolution for spotlight - mode synthetic aperture radar and computer aided tomography, Proc. IEEE, Vol. 74, No. 8, Aug. 1986, pp. 1165 - 1166.

Elachi, C., Roth, L. E., and Scaber, G. G., 1984, Spaceborne radar subsurface imaging in hyperarid regions. IEEE Trans. GE - 22, pp. 382 - 387.

Elachi, C. et al., 1986, SIR - B The second shuttle imaging radar experiment, IEEE Trans. GE - 24, Vol. 4, No. 4, pp. 445 - 452.

Harger, R. O. , 1970, Synthetic aperture radar systems : theory and design, New York, Academic Press.

Li, F., Held, D., Curlander J. C., and Wu, C., 1984, Doppler parameter estimation from spaceborne synthetic aperture radar, IEEE Trans. GE - 22, Vol. 2.

Munson, D. C., and O' Brien, J. D., 1983, A tomographic formulation of spotlight - mode synthetic aperture radar, Proc. IEEE, Vol. 71, pp. 917 - 925, August 1983.

Ottolini, Rick , 1987, SAR Imaging from a processing point of view, SEP Reports, SEP - 56 (this issue), pp.

Peltzer, R. D. , et al. , 1987, A remote sensing study of a surface ship wake, Int. Journ. on Remote Sensing, Vol .8, No 3, pp. 687 - 704.

Raney, R. K. , 1985, Theory and measure of certain image norms in SAR, IEEE Trans. GE - 23, No. 3, May 1985, pp. 343 - 348.

Stolt, R., 1978, Migration by Fourier transform, Geophysics, Vol. 43, No. 1, pp. 23 - 48.

Vesecky, J. F. and Stewart, R. H., 1982, The Observation of ocean surface phenomena using imagery from the SEASAT synthetic aperture radar: an assessment, JGR, Vol. 87, No. C5, pp. 3397 - 3450.

Vetrella, S., and Moccia, A. , 1987, The tethered satellite system as a new remote sensing platform, Int. Journal on Remote Sensing, 1987, Vol. 8, No. 3., pp. 309 - 323.

Wu, K. H., 1985, Extensions to the Step Transform to accommodate nonlinear range migration and high squint angle, IEEE Trans. AES, May 85, pp. 338 - 344.