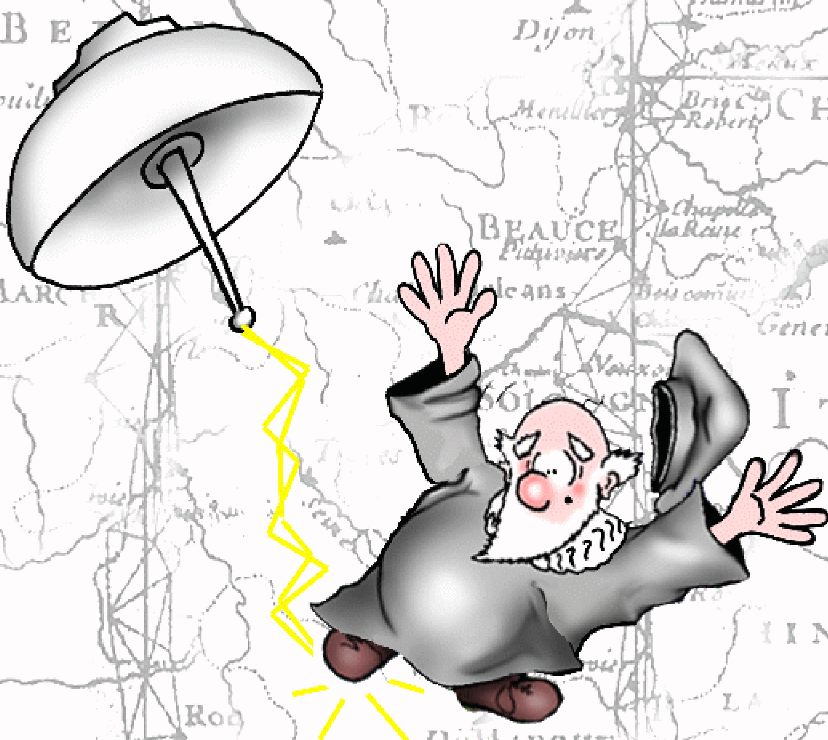
RADAR INTERPRET

Introduction to

Interpreting Digital RADAR Images



with

TNTmips®

Before Getting Started

Airborne and satellite radar systems are versatile imagery sources with day-night, all-weather capability. Radar imagery will likely increase in importance in the future as new multiwavelength, multipolarization radar systems are deployed that allow interpreters to better discriminate between different surface materials. However, radar images have unique characteristics that require specialized tools for proper processing and interpretation. This booklet introduces the concepts of radar image interpretation and gives you an overview of the processes in TNTmips® that enable you to process and interpret radar imagery.

Prerequisite Skills This booklet assumes that you have completed the exercises in the tutorial booklets *Displaying Geospatial Data* and *TNT Product Concepts*. Those exercises introduce essential skills and basic techniques that are not covered again here. You will also find important background information in the booklet *Introduction to Remote Sensing of Environment*. Please consult those booklets for any review you need.

Sample Data This booklet does not use exercises with specific sample data to develop the topics presented. Rather, it provides guidelines for using TNTmips® to work with your own digital radar imagery.

More Documentation This booklet is intended only as an introduction to radar interpretation techniques. Details of the processes discussed here can be found in a variety of tutorial booklets, Technical Guides, and Quick Guides, which are all available from MicroImages' web site (go to http://www.microimages.com/search to quickly search all available materials, or you can narrow your search to include only tutorials or plates).

TNTmips® Pro and TNTmips Free TNTmips (the Map and Image Processing System) comes in three versions: the professional version of TNTmips (TNTmips Pro), the low-cost TNTmips Basic version, and the TNTmips Free version. All versions run exactly the same code from the TNT products DVD and have nearly the same features. If you did not purchase the professional version (which requires a software license key) or TNTmips Basic, then TNTmips operates in TNTmips Free mode.

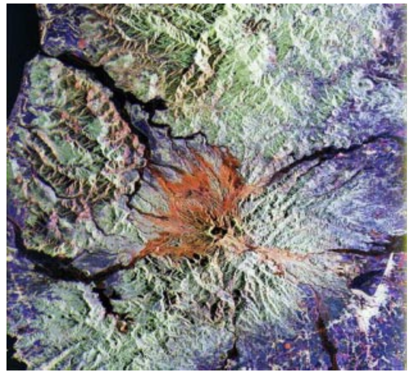
Randall B. Smith, Ph.D., 4 January 2012

You can print or read this booklet in color from MicroImages' Web site. The Web site is also your source for the newest tutorial booklets on other topics. You can download an installation guide, sample data, and the latest version of TNTmips.

http://www.microimages.com

Interpreting Digital Radar Images

Aircraft-mounted imaging radar systems have been in use for several decades. Early systems processed the recorded data to create an image on film, but modern systems record and process radar image data in digital form. With the launch of commercial radar imaging satellites during the past two decades (Canada's RADARSAT and the European Space Agency's ERS-1 and ERS-2), digital radar images are becoming more widely available.



Color composite radar image of Mount Pinatubo volcano and surroundings in the Philippines, acquired by the Spaceborne Imaging Radar-C instrument carried by the NASA space Shuttle Endeavour in April 1994. The image was created from different radar wavelength and polarization bands. Red areas show rough ash deposits, and the black areas are smooth volcanic mudflow deposits along rivers.

Unlike most remote sensing systems, which rely on the sun as an energy source, imaging radar systems are active sensors that "illuminate" surface features with broadcast microwave energy and record a returned signal. Most imaging radar systems produce microwaves with wavelengths between 1 cm and 1 meter, longer than the wavelengths used in weather radar to detect rain and snow. These longer wavelength microwave signals propagate through the atmosphere and clouds with almost no interaction or weakening. As a result imaging radar systems can be used to map surface features day or night and in almost any weather conditions. These characteristics make radar imaging especially useful in tropical and polar regions where persistent cloud cover hampers optical remote sensing efforts.

Radar images can reveal information about the shape of the surface terrain as well as its physical and biophysical properties. Radar images have long been used in geological studies to map structural features that are revealed by the shape of the landscape. Satellite radar images are now routinely used to monitor arctic sea ice conditions and to detect oil slicks on the ocean surface. Radar imagery also has applications in vegetation and crop type mapping, landscape ecology, hydrology, and volcanology.

Acquisition and import of radar images are discussed on pages 4-5. Pages 5-9 cover controls on radar image brightness and methods of contrast enhancement. The role of wavelength and polarization mode in determining radar image characteristics is introduced on pages 10-13. Pages 14-16 discuss radar image noise and its reduction, while pages 17-18 explain geometric distortions in radar images. Common sources of radar images are listed on page 19.

Importing Radar Images

STEPS
- ☑ choose Main / Import from the TNTmips menu
- ☑ press the Raster icon button on the Import Format panel of the Import window
- ☑ select the format appropriate for your radar image
- ☑ press [Select Files] and select your image file
- ☑ set any additional required parameters on the Import Raster window
- ☑ press [Import], then specifiy a destination and name for the new raster object

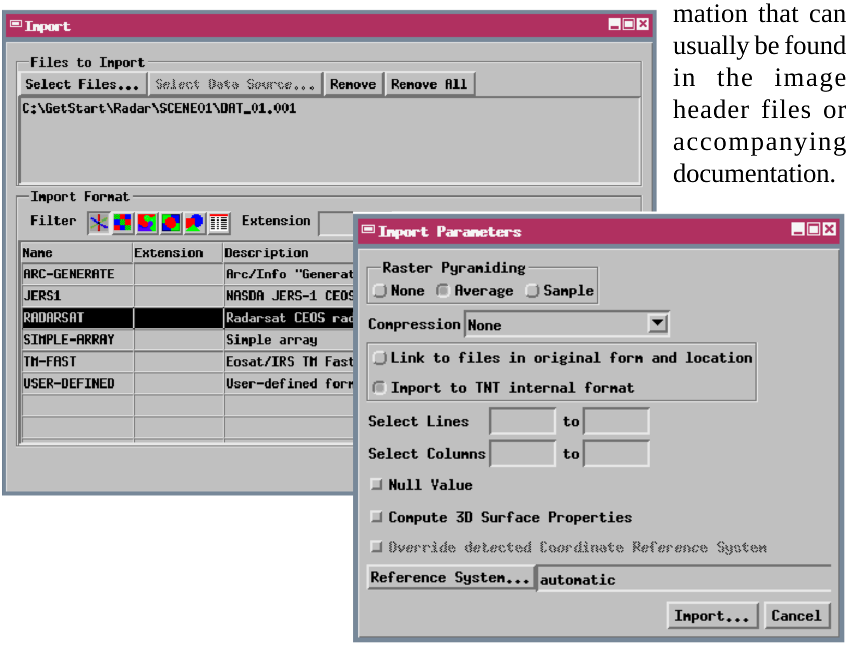
Before you can begin interpreting a digital radar image, you must first import the image into a TNTmips Project File by using the Import process. TNTmips provides direct import of radar data from the following sensor formats:

ERS-SAR: European Space Agency ERS-1 and ERS-2 satellites

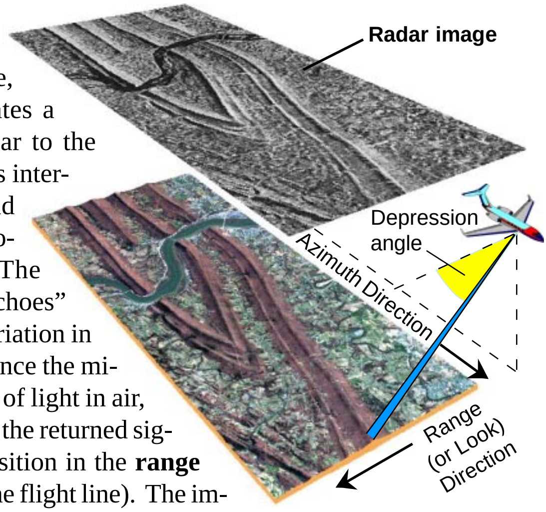
RADARSAT: Canada RADARSAT satellite

In some of these formats the main image file is accompanied by a separate header or leader file that is also required by the import process. Be sure to keep all supplied files together when importing radar imagery.

If you have radar images in other file formats, you can import them using the User-Defined format option. When you pick this option, you must create a format file specifying the structure of the image file, the numerical data type, byte order, and other information that can usually be found in the image header files or accompanying documentation.



Radar Image Acquisition



An imaging radar system emits discrete radar pulses that are directed to one side, so that each pulse illuminates a strip of terrain perpendicular to the flight path. The microwaves interact with surface objects and some portion of them return toward the radar antenna. The system records the pulse "echoes" from the terrain and their variation in strength with travel time. Since the microwaves travel at the speed of light in air, the timing of each portion of the returned signal establishes its image position in the **range** direction (perpendicular to the flight line). The image is built up from the returns of successive pulses as the aircraft or spacecraft moves forward (in the **azimuth** direction).

An important element of the radar imaging geometry is the **depression angle**, defined as the vertical angle between a horizontal plane and a straight line connecting the radar antenna and a particular terrain feature. (This line represents the two-way travel path of the energy returned from that feature.) The depression angle is steepest for the portion of the image nearest the flight path (near range), and decreases toward the far range.

Different factors control the spatial resolution of a radar image in the range and azimuth directions. The range resolution depends primarily on the brief duration of the microwave pulse (measured in microseconds). Range resolution also improves toward the far range as the depression angle becomes smaller. Resolution in the azimuth direction depends fundamentally on the width of the beam produced by a single microwave pulse; the narrower the beam, the better the resolution. In early airborne radar systems the beam was narrowed by increasing the physical length of the radar antenna, but there are obvious practical limits to antenna size. Modern Synthetic Aperture Radar (SAR) systems use a short physical antenna, but complex processing of multiple radar returns creates the effect of a much longer "synthetic" antenna. A particular surface feature is "imaged" by pulses at a number of successive antenna positions. The relative motion between the antenna and each target modifies the returning signal in such a way that the data from the various pulses can be resolved to place each feature in its correct position with good azimuth resolution.

Roughness and Radar Image Brightness

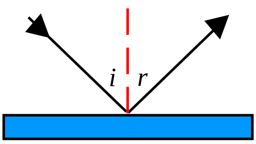
Radar image (left) and reflected light satellite image (right) of the same terrain. Arrow shows radar look direction. Radar image has been projected to ground range (see page 17).

Areas with stronger radar returns are shown as brighter areas in a radar image. Because of the side-looking geometry of imaging radar systems, only a small portion of the broadcast energy returns back in the direction of the antenna and is detected by it. The strength of the radar return depends on a number of factors, including the orientation of the surface, its roughness and electrical properties, and the polarization direction of the returning radar wave.

For areas that are relatively flat, surface roughness is the primary characteristic that determines the radar signature. A smooth horizontal surface, such as a calm water body, acts like a mirror to produce a specular reflection (see illustration at left). Almost all of the radar energy is reflected at an angle equal to the angle of incidence, which means that the reflection is directed away from the radar antenna. Since little energy returns toward the radar antenna, smooth areas appear very dark, like the river in the illustration above.

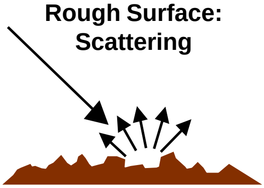
When the broadcast radar signal encounters a rougher surface, the irregularities on the surface act to scatter the radar energy in many directions. A small portion of the scattered energy is directed toward the radar antenna, where it is detected and produces a bright signature in the image. Brightness therefore increases with the degree of surface roughness.

Smooth Surface:
Specular Reflection
(no radar return)

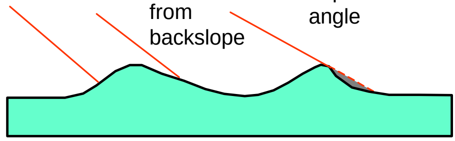


Angle *i* = Angle *r*

Rough Surface:
Scattering



Other Controls on Radar Brightness

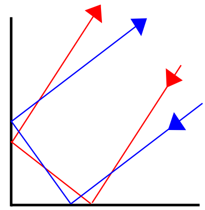


Terrain shape also produces significant brightness differences due to the varying orientation of the local surface relative to the radar travel path. If other factors are equal, the strongest returns will come from surfaces that are perpendicular to the travel path, or directly facing the sensor. Slopes that face away from the sensor will produce weaker returns. If the back slopes of hills and ridges are steeper than the local depression angle, they are not illuminated by the radar pulse, and are completely shadowed. The shadow effect increases toward the far range as the depression angle becomes smaller, causing more gentle backslopes to become shadowed. The long mountain ridges in the images shown on the previous page are very evident in the radar image due to the combination of bright foreslopes and darker backslopes.

Buildings in populated areas usually look bright in radar images because of their shape. The planar building sides intersect the surrounding ground at a right angle, creating a **corner reflector**. As shown in the illustration to the right, the radar signal bounces off of both planar surfaces and is reflected directly back toward the antenna, regardless of the depression angle. Corner reflectors are sometimes constructed in areas to be imaged by radar as a means of calibrating the strength of the returning signal.

Metal objects such as powerline towers and bridges appear very bright in radar images because they have high values of a property called the dielectric constant. Most dry natural materials have low dielectric constants, but the presence of moisture in soil, snow, or vegetation increases this value and their radar reflectivity. Radar imagery can thus play a role in assessing moisture content of surface materials.

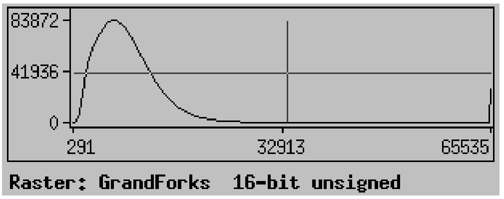
Buildings are very bright in a radar image of a town because the building sides act as corner reflectors.

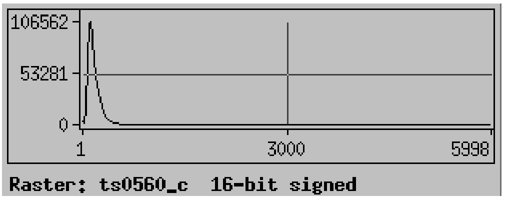


Corner Reflector
(side view)

A stong signal is directed back toward the radar antenna regardless of the depression angle.

Enhancing Radar Image Contrast





Sample histograms from typical radar images of land surfaces. Above, an early Spring RADARSAT image from North Dakota, USA, an agricultural area. Below, an AIRSAR image from western Nebraska, USA, an area with both cropland and grassland.

The strength of the microwave energy scattered back from the ground to a radar sensor varies greatly. While the signal received from the majority of the ground surface is typically weak, there are often a few objects in the scene that, because of their geometry or electrical properties, return an extremely strong backscattered signal. As a result, the numerical values in a digital radar image may range over several orders of magnitude, but the majority of the values are at the low end of the range. The illustration to the left shows several examples of radar image histograms.

AIRSAR image of a town and surrounding agricultural fields shown with linear contrast enhancement and the upper input range limit greatly lowered. Image is from the Salinas Valley, California USA. Buildings in the town and a few fields are at or near maximum brightness, while most fields are dark and show poor contrast.

Because of this distribution of brightness values, a radar image displayed with no contrast enhancement or with Auto-Linear enhancement typically looks mostly black with only a few bright features. You can improve the linear contrast using the TNTmips Contrast Enhancement procedure by lowering the upper input range limit, as shown in the image to the left. Contrast for the areas with lower cell values is enhanced, but all of the cell values above the input limit are shown at maximum screen brightness. You can obtain even better contrast for radar images by using one of the nonlinear enhancement methods, as discussed on the following page.

Nonlinear Contrast Enhancements

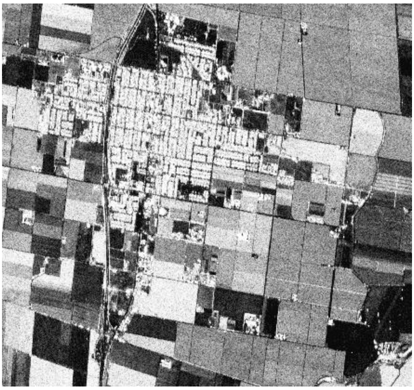
TNTmips offers several nonlinear contrast enhancement methods, including normalized, equalized, logarithmic, and exponential. You can use these methods either as auto-contrast options from the Contrast menu in the Raster Layer Controls window, or select and manipulate them in the Raster Contrast Enhancement window.

Although these nonlinear enhancement methods are available for any type of image, they are ideally suited to the unique brightness distribution of radar images. The normalized method determines output brightness values by fitting input values to a normal (gaussian) curve. The equalized method attempts to assign equal numbers of cells to each output brightness level. The logarithmic method computes output values using a logarithmic translation function. The exponential method is more flexible than the logarithmic because you can modify the power of the exponential function by dragging the translation curve. A power value less than 1 is usually appropriate for radar images. For more information on using these enhancement methods, see the tutorial booklet *Getting Good Color*, or the TNTmips Reference Manual.

Which contrast enhancement method is "best" will vary from image to image depending on the particular distribution of raster values and the portion of the data range that is relevant to your interpretation objectives.

Exponential Contrast Enhancement

Auto-Normalize Contrast Enhancement



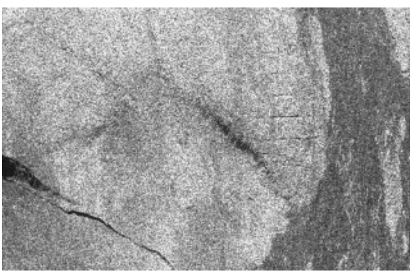
Auto-Equalize Contrast Enhancement

Roughness and Radar Wavelength

Wavelength bands commonly used in imaging radar systems. Band designators are former military code letters.

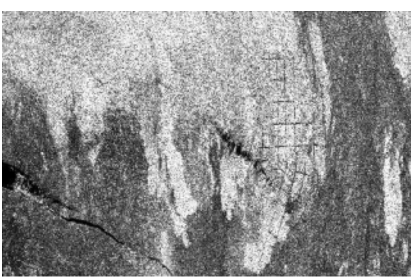
Band	**Usual Wavelength**	**Wavelength Range**
K		0.8 to 2.4 cm
X	3 cm	2.4 to 3.8 cm
C	6 cm	3.8 to 7.5 cm
S	8 cm, 12.6 cm	7.5 to 15 cm
L	23.5 cm	15 to 30 cm
P	68 cm	30 to 100 cm

Surface roughness differences are responsible for much of the brightness variation seen in radar images. Roughness refers to the degree of irregularity and vertical relief of surfaces, at scales measured in centimeters. Whether a surface appears rough (bright) in a radar image depends to a large extent on the radar wavelength. A particular surface may be rough for a short-wavelength radar but smooth for longer wavelengths, as illustrated by the example below.

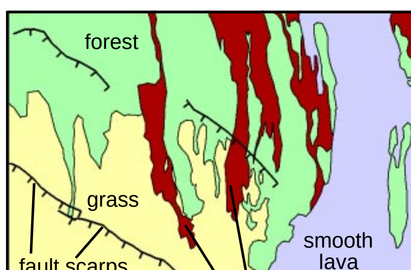


C-Band VV (wavelength = 6 cm)

L-Band VV (wavelength = 23.5 cm)



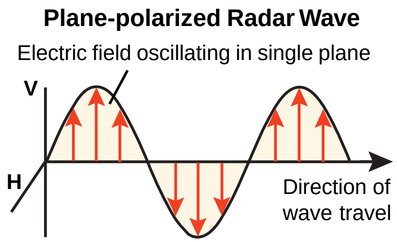
P-Band VV (wavelength = 68 cm)



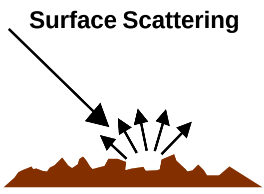
Interpretation

AIRSAR images at three wavelengths from a small area on the south flank of Kilauea volcano, Hawaii, USA. The look direction is toward the bottom of the images, which coincides with the downward slope direction. Land cover was interpreted from maps and other imagery. Ancient lava surfaces are vegetated, with forest at higher elevations and grass and shrubs at lower elevations. Two types of recent, unvegetated lava flows are present: fluid, smooth-surfaced flows and more viscous flows with a rough blocky surface. In the C-Band image, only the smooth recent lavas appear dark; the other surfaces are rough at this wavelength. At the longer wavelengths the grassland area becomes smooth and thus dark as well. The rough lavas and forest have similar brightness at all three of these radar wavelengths.

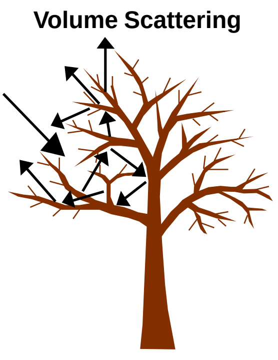
Radar Polarization and Scattering Types



Imaging radar systems typically transmit a plane-polarized radar pulse. The electric field associated with such a pulse oscillates in a single plane perpendicular to the direction the wave is traveling. The most common polarization mode is to both transmit and receive horizontally polarized signals (designated HH mode, with the first letter indicating the transmitted polarization). Some systems transmit and receive vertically polarized waves (VV mode); the radar images of Kilauea shown on the previous page were acquired in this mode. Both HH and VV modes can be called **like-polarized** radar modes.

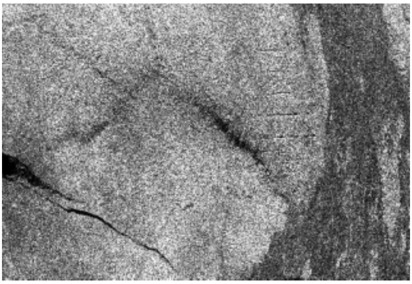


When a polarized radar pulse is scattered by the rough surface of a material such as soil or rock (**surface scattering**), most of the scattered energy that returns to the antenna has the same polarization as the transmitted pulse. But when the pulse strikes vegetation, it penetrates to varying degrees (depending on wavelength) and has numerous encounters with leaves, twigs, and branches that produce many scattering events. Although the physical mechanism is not well understood, this **volume scattering** causes partial depolarization of the radar signal, so that some of the scattered waves vibrate in various directions. Depolarization somewhat reduces the strength of the like-polarized signal returned to the radar antenna, but vegetation still produces strong like-polarized signals at appropriate wavelengths, as shown by the images on the previous page.

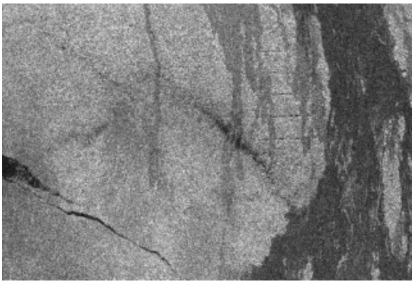


Short-wavelength radar signals (X and C bands) interact primarily with the uppermost leaf canopy, and do not penetrate beyond it. Longer-wavelength radars (L and P bands) penetrate deeper to interact with stems of smaller plants and twigs and branches of trees.

Polarimetric Radar Images



C-Band HH



C-Band HV

AIRSAR images of different polarization from Kilauea; compare to the C-Band VV image and interpretive map on page 9. The grass and forest areas are bright in the HV image because volume scattering caused significant depolarization of the returning signal. Surface scattering by the rougher lava-flows caused much less depolarization, so these flow areas are darker in the HV image, though not as dark as the smooth lava flows. Note that the rough lavas and vegation have nearly the same brightness signatures in the like-polarized images.

Some experimental radar systems can transmit and receive signals with either vertical or horizontal polarization planes. This capability enables them to simulaneously acquire images with different send-receive polarization combinations. In addition to the conventional HH and VV like-polarization images, such systems can also produce **cross-polarized** radar images by pairing transmission at one polarization with recording at the other polarization (HV and VH modes).

Cross-polarized radar images can discriminate between areas of surface scattering and volume scattering because of the differing depolarization effects associated with these mechanisms. Surface scattering does not cause significant change in polarization, so the cross-polarized receiving antenna receives little energy from areas of bare soil and rock. These areas appear relatively dark in a cross-polarized radar image, though brighter than radar-smooth surfaces. For vegetated areas, significant depolarization of the radar signal occurs because of volume scattering. The cross-polarized receiving antenna detects the small fraction of the depolarized radar energy that has had its polarization direction changed by exactly 90 degrees. The strength of this received signal is much smaller than that recorded in either of the like-polarized modes, but still significantly larger than the signal from areas of surface scattering. Vegetated areas thus appear brighter than nonvegetated areas in a cross-polarized radar image.

Viewing Color Band Combinations

In the future more radar systems will likely acquire images at several wavelengths with multiple polarization modes in order to better discriminate different types of surface materials. As with multispectral optical images, these multiband radar images can be used as components of an RGB raster (color) display. By carefully choosing wavelength/polarization components you can create color images that emphasize various surface properties and enhance your ability to interpret surface materials, as shown by the examples on this page.

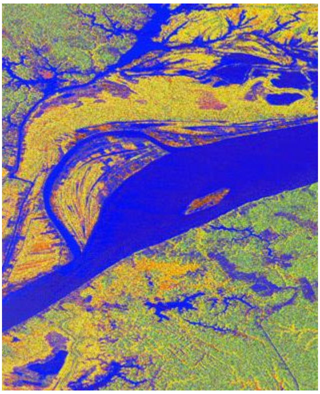
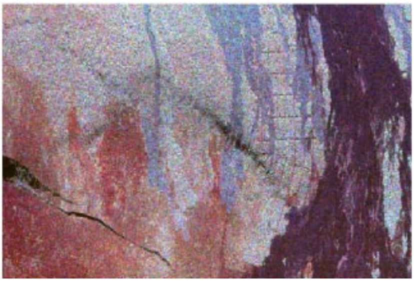


Image of the Manaus region of Brazil from the Spaceborne Imaging Radar-C sensor operated on the NASA space shuttle in 1994, courtesy of NASA-JPL. Three L-band polarization channels were used to create the color image: HH as red, HV as green, and VV as blue. Green areas are heavily forested, smooth river surfaces are blue, and flooded forest areas are yellow and red.



AIRSAR Image of the area of Kilauea shown on previous pages. C-band HV is used as the red channel, L-band HV as green, and L-band VV as blue. Forest appears in the bright blue-green colors, grassland reddish-brown, rough lava flows dark blue, and smooth lava flows black.

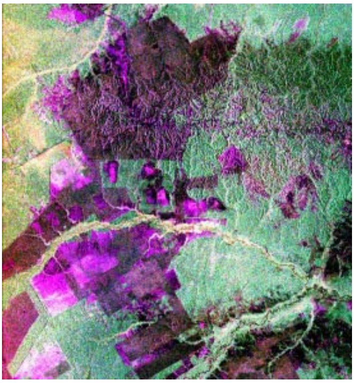


Image of central Sumatra from the SIR-C sensor, courtesy of NASA-JPL. Forest appears green in the image, while the dark to bright pink areas have been cleared for palm oil plantations. L-band polarization channel color assignments are the same as in the Manaus image above.

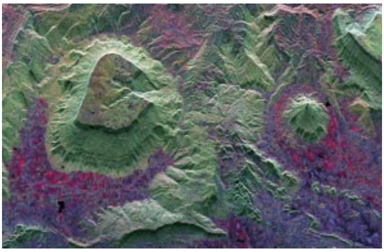
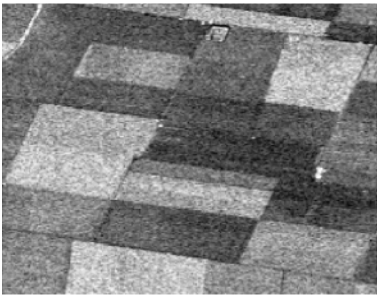
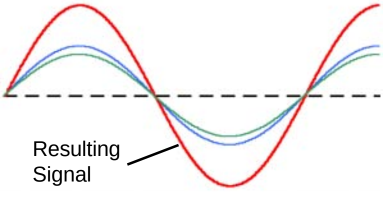


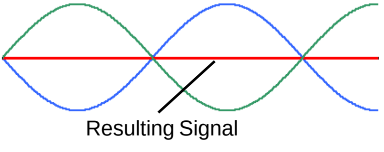
Image of north central Thailand from the SIR-C sensor, courtesy of NASA-JPL. This is a deeply dissected area of plateaus and hills. Forest areas appear green and agricultural areas and settlements appear blue. (L-band HH = red, L-band HV = green, and C-band HV = blue.)

Radar Speckle Noise

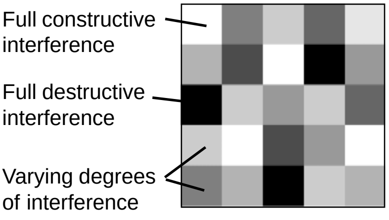


Radar image (C band HH) of relatively homogeneous agricultural fields with varying brightness, illustrating characteristic radar speckle noise.





Schematic Sample of a Radar Image of a Homogeneous Area to Illustrate Speckle



Radar images have an inherently grainy appearance due to random brightness variations that are most apparent in otherwise uniform areas of an image. The cause of this characteristic image noise, called **speckle**, can be traced to the nature of the radar signal and its interactions with surface objects.

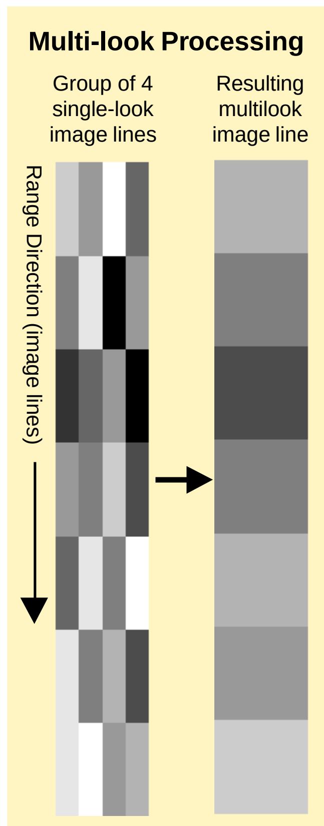
A radar imager emits pulses of energy with a single wavelength and frequency, which remain constant during subsequent interactions. The return signal that creates an image cell comes from an area large enough to contain numerous individual features that scatter the radar energy. The signal recorded from each of these areas represents the aggregate of all of the signals from the individual scattering elements. Because those scattering elements differ in position and height, the travel paths of their component return signals may vary in length by fractions of a wavelength or more. The strength of the overall recorded signal then depends upon how well the peaks in all of the sinusoidal wave forms are aligned. If the peaks are exactly aligned, constructive interference occurs, producing a strong signal and a bright image cell. If the peaks in one wave line up with the troughs of another, the two waves effectively cancel each other out in the process called destructive interference. These interference effects are random, and can vary dramatically with slight differences in direction and angle of view. As a result, the brightness of adjacent radar image cells fluctuates randomly relative to the average brightness for that surface and viewing geometry.

Multi-look Processing and Speckle

Speckle can be treated mathematically as a separate random noise factor superimposed on the "true" return radar signal. Fortunately this noise does not significantly alter the average signal strength in homogenous areas represented by many adjacent image cells. This means that speckle can be reduced by averaging the values of cells in local neighborhoods, at the expense of degraded spatial resolution.

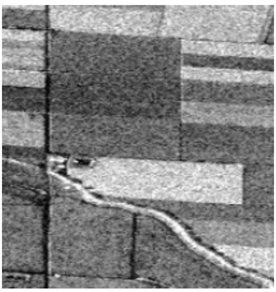
Speckle reduction by averaging occurs as part of a standard radar processing step that produces a **multi-look image**. In a raw Synthetic Aperture Radar (SAR) image, each line of cells in the range direction represents the image of one radar "look", corresponding to a single transmitted radar pulse. (Each look is actually produced by sophisticated processing of a number of consecutive pulses, however). The dimensions of these single-look image cells are not the same in the range and azimuth directions, because range and azimuth resolution are controlled by different system characteristics. Resolution in the azimuth direction in SAR systems is the same regardless of range, and is typically several times better than the range resolution. A single-look image cell is therefore several times larger in the range direction than in the azimuth direction. Multi-look processing aggregates small groups of adjacent range lines (usually three or four) into wider multi-look range lines to produce cells that are more nearly square. The new cell values are computed by averaging in the azimuth direction (averaging cells with the same range position). The resulting multi-look image has reduced speckle and better image geometry. Because of these benefits, suppliers of radar images routinely apply multi-look processing, and raw single-look images are only used for specialized purposes. Most digital radar images that you encounter therefore will be multi-look images.

Speckle obscures edges and other image details and makes it difficult to determine the typical radar response from uniform areas of a radar image. Processing radar images to reduce speckle can significantly improve their interpretive value.

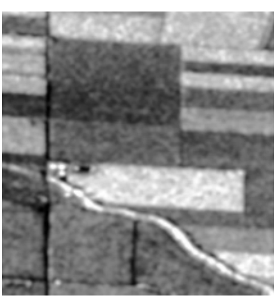


Reducing Speckle Using Radar Filters

STEPS
- ☑ choose Image/ Filter / Spatial Filter from the TNTmips menu
- ☑ choose Radar from the Class menu on the Raster Spatial Filtering window
- ☑ examine the options on the Type menu


Original radar image


After applying 3x3 Frost filter


After second application of 3x3 Frost filter

Although multi-look processing reduces radar speckle, it does not eliminate it. The remaining speckle noise can be further reduced by applying a spatial filter to the image. The TNTmips Spatial Filter process includes several radar filters tailored to the particular characterisitics of radar speckle.

Unlike the additive noise found in many images, radar speckle is approximately multiplicative. In other words, the range of the random brightness deviations increases with the average gray level of a local area. Using this mathematical model, a measure of the noise range (standard deviation) can be estimated from the actual brightness variations in the image, using either the local neighborhood of the filter window or the entire image. The radar filters (Sigma, Frost, Lee, and Kuan) use these noise estimates in various ways to control the filter process. The objective is to reduce the speckle noise in uniform regions by some type of averaging while preserving the brightness variations that occur at the boundaries between areas of differing overall brightness. The radar filters come closer to meeting this objective than simple low-pass or median filters. Several of these radar filters have parameters that you can adjust to optimize the results.

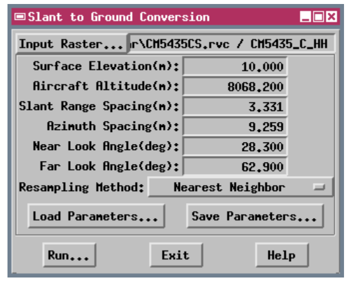
Application of the radar filters can reduce but not eliminate speckle noise. Several applications of one or more filters may be required to reduce speckle to an acceptable level. However, each application of a filter results in some blurring, or loss of spatial detail. You will need to determine the balance between noise reduction and loss of spatial resolution that is appropriate for your radar images and interpretation objectives.

Because the radar filters utilize image statistics, you should apply them prior to resampling operations, including the slant range to ground range transformation discussed next.

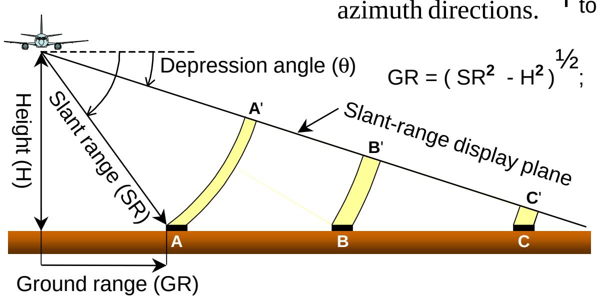
Converting Slant Range to Ground Range

Radar images are initially acquired as **slant range** images that distort the relative positions of ground features. Objects in a slant range image are positioned in the range direction (along image lines) according to their direct-line distance from the antenna (slant range). As shown in the cross-section below, this is geometrically equivalent to projecting all ground positions along spherical wavefronts to a display plane extending from the antenna to the farthest range position. The scale of a slant range image varies in the range direction, with objects in the near range being compressed relative to those in the far range (see equal-sized objects A, B, and C in the figure). A slant range image can be converted to a **ground range** presentation using the platform height (sensor altitude minus surface elevation), the slant range value for each cell, and the cell size in range and azimuth directions.

STEPS
☑ choose Image / Resample and Reproject / Radar Slant to Ground from the TNTmips menu



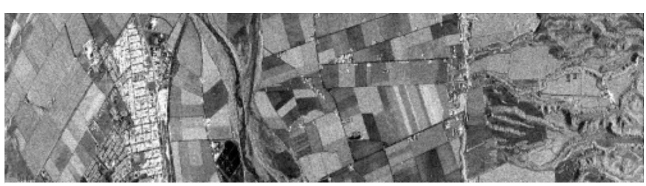
The transformation to ground range assumes a horizontal ground surface and constant platform height, and does not remove spatial distortions related to topographic relief.



$GR = (SR^2 - H^2)^{1/2}$; $GR = H\left(\left(1/\sin^2\theta\right) - 1\right)^{1/2}$

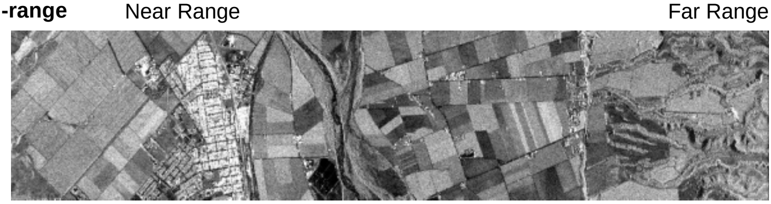
Depending on the level of processing you select, radar images you acquire from a commercial source may already be in ground range presentation.

Slant-range image
The near range portion of the image appears highly compressed compared to ground range.

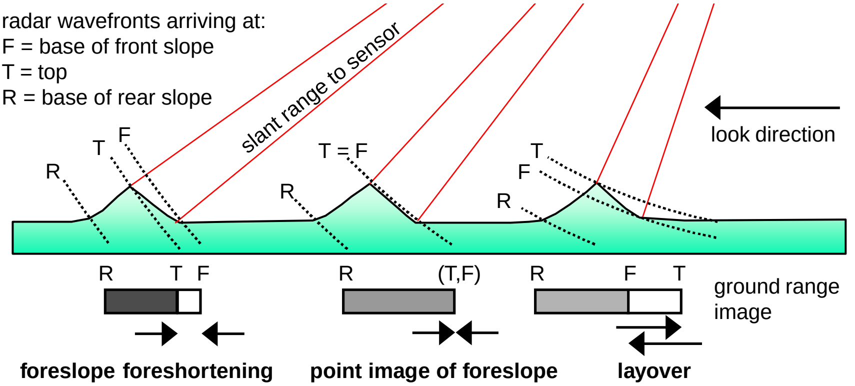


Near Range Far Range

Ground-range image

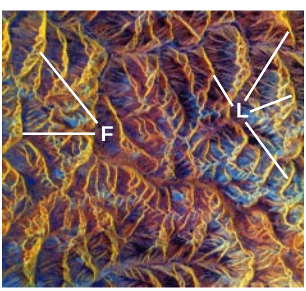


Terrain Distortions in Radar Images



A transmitted radar pulse can be modeled simply as an expanding spherical wavefront that sweeps across the terrain to one side of the sensor flight path. Variations in the elevation of the terrain affect the relative travel times of the radar energy that returns to the sensor, producing unique geometric distortions that remain in radar images even after conversion to ground range.

Gentle slopes (those less steep than the local portion of the radar wavefront) that face the sensor are imaged with *foreshortening*. The image of the top of a hill or ridge is displaced toward the near range compared to its actual map position and relative to the image of the base of the slope (see left side of illustration above). In essence, the facing slope is imaged in less time than the back slope (or a comparable area of flat terrain), which makes it appear that hills are leaning toward the sensor. If the foreslope has the same steepness as the radar wavefront (middle portion of illustration above), the entire slope is illuminated at the same instant, and its radar image collapses to a single bright cell in each image line.



A color display of SIR-C radar bands covering a rugged mountainous area in south-east Tibet. The look direction is toward the left side of the image. The labels indicate several of the many examples of foreshortening (F) and lay-over (L) of slopes facing the sensor.

If the foreslope is steeper than the radar wavefront (right side of above illustration), the top of the foreslope is actually imaged before the base, producing the extreme distortion called *layover*. Hills distorted by layover appear to have narrow, bright foreslopes. Layover is more severe in the near range portion of an image where the depression angle is higher, because the slope of the radar wavefront decreases with increasing depression angle.

Sources of Radar Imagery

RADARSAT: launched in 1995 by the Canadian Space Agency to monitor environmental change (especially Arctic Ocean sea-ice conditions) and to support resource sustainability. RADARSAT orbits at an altitude of 798 km with a 24-day revisit cycle. Its synthetic aperture radar (SAR) operates in C-band (5.7 cm) with HH polarization. The radar beam can be shaped and steered to create different image swath widths and resolutions. The standard beam mode has a 100 km swath width and 28-meter resolution. Data is distributed through RADARSAT International.

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ERS-1, ERS-2: operated by the European Space Agency (ESA), ERS-1 was launched in 1991 and ERS-2 in 1995. Both satellites orbit at 785 km altitude and include a C-band SAR operating with VV polarization. The swath width is 100 km with 30 meter resolution. The revisit cycle for each satellite is 16 to 18 days. The ERS radar sensors operate with a relatively steep depression angle (67 degrees) to emphasize ocean surface features, but land terrain interpretation is hampered by severe layover effects.

ERS-1 and ERS-2 radar images are distributed commercially by various dealers worldwide.

Technical information is available at the ERS Missions Home Page: http://earth1.esrin.esa.it/ERS/

JERS-1: launched by the National Space Development Agency of Japan as a multipurpose environmental monitoring platform. The satellite included an L-band SAR with HH polarization that operated from 1992 to 1998. The image swath was 75 km with 18-meter resolution.

SIR-C/X-SAR: this sensor was carried on two flights of the NASA Space Shuttle in 1994. Its antenna array operated in X-band, C-band, and L-band with multiple polarization modes and variable depression angles. Swath widths are 50 to 100 km with resolution from 25 to 50 meters. Radar imagery was acquired for research into applications in landscape ecology, environmental monitoring, hydrology, geomorphology, and volcanology.

Information on the SIR-C mission is available at: http://southport.jpl.nasa.gov/sir-c/

Data is distributed through the USGS: http://edcsns17.cr.usgs.gov/sir-c/survey.html

Advanced Software for Geospatial Analysis

Index