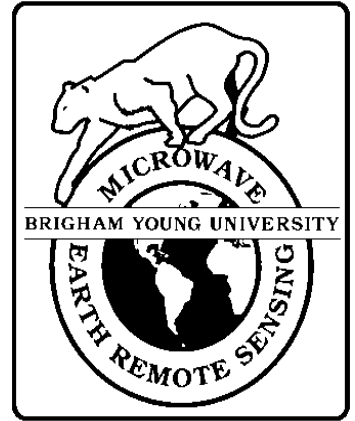




**Brigham Young University
Department of Electrical and
Computer Engineering**

**459 Clyde Building
Provo, Utah 84602**



NSCAT Views the Earth

**David G. Long, Ph.D.
James Dyal**

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**Microwave Earth Remote Sensing (MERS)
Laboratory**

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NSCAT SIRF IMAGE CREATION

David G. Long and James E.H. Dyal
Brigham Young University
Microwave Earth Remote Sensing Laboratory
459 CB, Provo, UT 84602
(801) 378-4383 FAX: (801) 378-6586 long@ee.byu.edu

Abstract—A spaceborne scatterometer is a radar instrument used to measure the radar backscatter of the earth's surface. Data retrieved by the NASA Scatterometer (NSCAT) has been used to create enhanced resolution images of the land and polar regions of the earth using the SIRF algorithm developed by Brigham Young University's Microwave Earth Remote Sensing Laboratory. We have developed a standard product suite of NSCAT-derived SIRF images. This report describes these products and their generation.

INTRODUCTION

NASA Scatterometer (NSCAT) is a spaceborne scatterometer mounted aboard the National Space Development Agency of Japan's ADvanced Earth Observing Satellite (ADEOS). A spaceborne scatterometer is a radar instrument designed to measure and record the radar backscatter of the earth's surface. Satellite mounted scatterometers such as Seasat, ERS1, and ERS2, have been used to collect information that has primarily been used in oceanic and wind studies. NSCAT is the latest such scatterometer and offers the highest resolution and measurement accuracy. Backscatter measurement data taken by NSCAT, although of higher resolution than data collected by previous spaceborne scatterometers, is still of insufficient resolution to be used for many land applications. The Scatterometer Image Reconstruction with Filter (SIRF) algorithm developed by the Brigham Young University Microwave Earth Remote Sensing (MERS) laboratory provides a means whereby the σ° values by several revolutions of the scatterometer can be used to produce images of much higher resolution than the intrinsic measurement resolution. These images can be used to study land and polar regions.

This paper explores the general process by which these images are made, and describes the standard NSCAT SIRF image product suite. The file naming convention and image storage format are also described.

THE SIRF ALGORITHM AND THE NSCAT SIRF PRODUCT

The Scatterometer Image Reconstruction with Filtering (SIRF) resolution enhancement algorithm is a multivariate nonlinear resolution enhancement algorithm based on modified algebraic reconstruction and maximum entropy techniques. This algorithm was originally developed for application to Seasat scatterometer (SASS) measurements [1] and has recently been optimized for application to NSCAT measurements [2].

NSCAT measures the σ° of the Earth's surface at several azimuth angles and over a variety of incidence angles at nominal resolution of 25 km [?]. Over a limited incidence angle (θ) range of $[20^\circ, 55^\circ]$, σ° (in dB) over land and ice is approximately a linear function of θ ,

$$\sigma^\circ(\theta) = \mathcal{A} + \mathcal{B}(\theta - 40^\circ)$$

where $\mathcal{A}$ and $\mathcal{B}$ are functions of surface characteristics, azimuth angle, and polarization. $\mathcal{A}$ is the σ° value at 40° incidence and is termed the incidence angle normalized σ° . $\mathcal{B}$ describes the dependence of σ° on θ . The SIRF algorithm generates image of $\mathcal{A}$ and $\mathcal{B}$ on a high resolution grid from the NSCAT σ° measurements using multiple satellite passes [1]. The $\mathcal{A}$ and $\mathcal{B}$ images are the primary SIRF product. Computation of the $\mathcal{A}$ and $\mathcal{B}$ images are described in detail in [1] and [2].

Several useful ancillary images are also produced as part of the NSCAT SIRF standard product, including a set of non-enhanced images. The ancillary images can be used for diagnostic evaluation of the $\mathcal{A}$ and $\mathcal{B}$ images and can be useful in scientific studies. Table 1 lists the image product types and their units.

Ancillary Images

In applying the SIRF algorithm we assume that the surface doesn't change over the imaging interval. When it does, SIRF nonlinearly weights the measurements when combining them to estimate an effective $\mathcal{A}$ and $\mathcal{B}$ over the imaging interval. When combined with variations in the temporal sampling, the question of what effective time should be

Type	Character Code	Code Number	Units	Description
$\mathcal{A}$ image	a	1	dB	σ° 40° incidence angle
$\mathcal{B}$ image	b	2	dB/deg	slope of σ° vs. incidence angle
counts	C	8	(none)	number of measurements hitting each pixel
err image	E	21	dB	mean σ° reconstruction err
inc std	I	7	deg	incidence angle standar deviation
mean inc	J	9	deg	mean incidence angle
time image	p	11	min	time estimate from start of interval
STD image	V	22	dB	σ° reconstruction err standard deviation
longitude image	x	30	deg	longitude of lower-left (SW) corners of pixels
latitude image	y	31	deg	latitude of lower-left (SW) corners of pixels

Table 1: Image type codes and units used for standard regions for SIRF products

assigned to the image arises. We have developed a simple time inference algorithm. The algorithm computes the time corresponding to a linear (in dB) average of the measurements assuming uniform motion. This time index is can vary over the image and is thus computed for each pixel. The ‘time’ image gives this time estimate as the time in minutes from the start of the imaging interval (given by `iyear`, `isday` and `ismin` in the image header – see Appendix 2).

The difference (in dB) between the σ° measurement and its back projection from $\mathcal{A}$ and $\mathcal{B}$ images is always non-zero due to noise in the measurements. Azimuth variation in σ° , temporal variation in the surface characteristics, and limitations in the resolution enhancement can increase the difference. For each pixel, the mean difference between the σ° measurement values for the σ° measurements which touch the pixel and the measurement’s backprojections is termed the ‘reconstruction error’. The standard deviation (‘ σ° reconstruction standard deviation’) of the difference is a particularly use parameter for discriminating ice and ocean. Large pixel values in the standard deviation image indicate areas of temporal and/or azimuth variation.

As a diagnostic tool for the SIRF images, “images” of the number of σ° measurements which hit each pixel (the ‘counts’ or ‘number of measurements’ image), the mean incidence angle of the measurements (‘mean incidence image’), and the standard deviation of the incidence angles (‘incidence standard deviation image’) are produced.

The output of the first iteration of the SIRF, known as AVE [1], is a simple resolution enhancement algorithm. AVE $\mathcal{A}$ and $\mathcal{B}$ are provided as a comparison product.

Low resolution comparison images are provided in the standard NSCAT SIRF product suite. This images are created by ‘binning’ or ‘gridding’ the σ° measurements into a low resolution (~ 25 km) grid according to the center point of the cell. $\mathcal{A}$ and $\mathcal{B}$ are computed using linear regression (in dB). In addition to this product and to aid in comparison, a ‘non-enhanced’ image product is produced by expanding the gridded image to the same size as the SIRF images.

For user convenience, “images” of the longitude and latitude of each pixel is computed. Thus, the user can avoid directly computing the lat/lon of each pixel if desired, since it precomputed and stored in these images.

DATA EXTRACTION, SORTING AND STORAGE

Backscatter data collected by NSCAT is distributed to MERS by Jet Propulsion Laboratories (JPL) NSCAT project on 8mm data tapes, having been formatted and processed to several different levels. Level 1.5 (L1.5) data is used to create SIRF land and polar images. The L1.5 data tapes contain a week’s worth of data divided into multiple files. Each file contains the data collected during one complete orbit revolution and are typically around 20Mbytes in size. Each file contains all the viable σ° values collected during the revolution of the satellite.

Since only land σ° measurements are generally used for creating images, the data is sorted before processing. All measurements in the polar regions are retained to enable imaging of both land and sea-ice. Ocean data over non-polar regions is discarded in the sorting. After reading from tape, the L1.5 measurements are separated into multiple categories: the polar regions, arctic and antarctic, and land-only. Once the data has been sorted into one of the four categories, it is copied onto 660 Mbyte CD’s according to Julian day for later processing.

Region Name	Region Number	Region Abbreviation	LL-Lat	LL-Long	UR-Lat	UR-Lon
Antarctic	100	Ant	-90.0	-180.0	-52.0	180.0
Arctic	110	Arc	60.0	-180.0	90.0	180.0
Greenland	202	Grn	59.0	-74.0	84.5	-11.0
Alaska	203	Ala	50.0	-180.0	3.0	-130.0
Cntrl-Amer	204	CAm	5.0	-115.0	30.0	-57.0
North-Amer	205	NAm	25.0	-135.0	65.0	-50.0
South-Amer	206	SAm	-58.0	-83.0	15.0	-32.0
North-Afri	207	NAf	2.0	-20.0	40.0	65.0
South-Afri	208	SAf	-38.0	5.0	10.0	53.0
Siberia	209	Sib	50.0	60.0	75.0	180.0
Europe	210	Eur	35.0	-12.0	72.0	65.0
South-Asia	211	SAs	5.0	60.0	30.0	130.0
Chin-Japan	212	CnJ	25.0	60.0	55.0	150.0
Indonesia	213	Ind	-15.0	93.0	10.0	165.0
Australia	214	Aus	-48.0	110.0	-10.0	180.0

Table 2: Names, ID numbers used, and spatial coordinates (lower-left [LL] and upper-right [UR] corners in longitude and latitude) of the 15 standard regions for SIRF land/polar image processing

REGIONS

Because it is impractical to create global images at full resolution, the earth has been divided into overlapping regions for which full resolution images are practical. To create enhanced land and polar images, first, a setup file for each region of the earth is created. An additional setup file is created from which non-enhanced images are generated.

Each region of the 15 standard regions is defined by its name, specified region number, latitudinal and longitudinal coordinates, and are rectangular with the exception of the two polar regions (Arctic and Antarctic) which are circular. Table 2 lists the names, region numbers, and spatial coordinates of the 15 different regions. Images from these 15 regions constitute the standard product suite. For reference, Figures 2 through 16 give examples of $\mathcal{A}$ images for all the regions that comprise the standard set. Separate images are made for V-pol and H-pol. Images are created for different time periods based on region.

Imaging Periods

The SIRF resolution enhancement algorithm is based the spatial overlap of the σ^o measurements made by multiple passes of the scatterometer. Since the surface may vary during the “imaging interval”, there is a tradeoff between resolution enhancement and the imaging interval. Because of the coverage versus latitude characteristics of NSCAT, the optimum imaging interval can vary depending on the imaging location. For example, the polar regions are very frequently covered and since sea-ice can move or evolve rapidly a short imaging interval is used. In the equatorial regions the imaging interval must be longer since 2-3 days can pass between revisits. NSCAT makes also three times as many V-pol measurements as H-pol. Thus, a longer imaging interval is typically required for H-pol measurements as for V-pol.

For the standard NSCAT SIRF product suite, polar region images are produced using six day imaging periods for both polarizations while other regions use seven days for V-pol and 14 days for H-pol. Polar Images are time overlapped at 1/2 the imaging period, i.e., 6 day images are produced every 3 days in the polar regions.

Projection types

The images are a two-dimensional projection of the surface of the globe. While in general any projection can be used, images are distributed only in five standard projections. All of these are supported in the standard file format described later. The projection options include:

- Rectangular array (image data only, no projection information)
- A rectangular lat/lon array

- Two different types of Lambert equal-area projections which can be used in both non-polar and polar projections
- Polar stereographic projections (northern or southern hemisphere)
- EASE grid polar projections with various resolutions
- EASE global projection with various resolutions

While the enhanced images generally have a nominal pixel resolution of approximately 4.5 km, the actual resolution is dependent on the choice of projection. As part of the standard NSCAT SIRF product suite, SIRF images are produced using the Lambert fixed radius projection for the non-polar regions and the polar stereographic projections (reference latitude 70 deg) for polar (Arctic and Antarctic) images. Utilities are available to transform standard product images to other supported projections. Global images made at lower resolution from the individual region images use the rectangular Lat/Lon array. Figure 1 is an example of a low resolution global image.

Images are stored in the BYU SIR image file format described below. The file format includes a header containing all of the projection information.

IMAGE FILE NAMING SCHEME

A standardized UNIX naming convention has been developed which allows key information about a particular image to be determined by looking at the name. Note that the file header includes the same information as well as additional information in the file.

Each image file produced is named using the same format:

SENS-T-REGYR-DY1-DY2.RCNEXT

The string ‘SENS’ is a four character abbreviation that denotes the remote sensor from which the image is derived. In the case of NSCAT data, there are two possibilities for this category - ‘nscv’ and ‘nsch’, which refers to vertically polarized data and horizontally polarized data.

The character ‘T’ refers to the type of image the file contains. The types generated for NSCAT data include ‘a’, ‘b’, ‘C’, ‘E’, ‘I’, ‘J’, ‘p’, and ‘V’: (see Table 1)

- a: $\mathcal{A}$ image. σ° in dB at a 40° incidence angle.
- b: $\mathcal{B}$ image. T the slope of σ° in dB/degree.
- C: count of the number of measurements hitting each pixel.
- E: mean σ° reconstruction error in dB.
- I: incidence angle standard deviation for the measurements hitting each pixel in deg.
- J: mean incidence angle for the measurements hitting each pixel in deg.
- p: image pixel time estimate in minutes from the start of the imaging interval.
- V: σ° reconstruction error standard deviation in dB.
- x: longitude for each pixel.
- y: latitude for each pixel.

Examples of each of these images and their non-enhanced counterparts for a given region are shown in Figures 17 to 23. Note that the longitude and latitude images do not vary with time so the day range isn’t really needed.

The string ‘REG’ in the file name format gives the three letter region abbreviation (refer to Table 2).

The strings ‘YR’, ‘DY1’ and ‘DY2’ give the year as two digits, the three digit Julian day of the year at the start of the imaging interval, and the three digit Julian day of the year at end of the imaging interval.

The string ‘RCN’ denotes the image construction technique. The four choices for RCN are ‘sir’, ‘ave’, ‘grd’ and ‘non’:

- sir: SIRF-produced enhanced resolution image. These are the highest resolution products (see [2]).
- ave: SIRF-produced AVE image. An AVE image corresponds to the first iteration of SIRF and has lower effective resolution than SIRF but higher than gridding or non-enhanced images (see [1]).

- `grd`: non-enhanced image made by gridding or binning the measurements onto a low resolution (~ 25 km) grid.
- `non`: image at same pixel size as `sir` or `ave` image but with resolution of `grd` image. Made from `grd` image by pixel replication.

Note that the ‘`sir`’ lat/lon images are identical for ‘`ave`’ and ‘`non`’ so separate versions are not required.

The final string ‘`EXT`’ is optional extension and denotes additional post SIRF processing. Standard extensions include ‘`.Lmsk`’ ‘`.Imsk`’ ‘`.dif`’ and ‘`.ed`’:

- `.Lmsk`: land masked image. Ocean areas blacked out. For non-polar images this is the default unless overridden by ice masking and thus may not be explicitly stated.
- `.Imsk`: ice masked image. Non-land and ice-free ocean areas blacked out.
- `.dif`: a difference image between two images
- `.ed`: manual editing

By way of illustration ‘`nscv-a-Arc96-303-309.sir.Imsk`’ is an NSCAT v-pol $\mathcal{A}$ image of the Arctic region spanning JDs 303-309 made by SIRF and then ice masked.

THE SIR FILE FORMAT

The BYU-MERS SIR image format was developed by the BYU-MERS laboratory to store images of the earth along with the information required to earth-locate the image pixels. A SIR file consists of one or more 512 byte headers containing all the information required to read the remainder of the file and the map projection information required to map pixels to latitude and longitude coordinates on the Earth surface. After the header records, the image is stored and zero padded so that the file is an integer multiple of 512 bytes.

Pixel values are generally stored as 2 byte (high order byte first) integers though can be stored as bytes or IEEE floating point. The latter is not portable to all machines and so is not recommended. Scale factors to convert the integer or byte pixel values to native floating point units are stored in the file header. The origin of the image is at the lower left corner. The earth location of a pixel is identified by its lower-left corner.

Utilities for reading SIR image format files and making the projection transformations from pixel to lat/lon and lat/lon to pixel have been developed for fortran, C, matlab, IDL, and PVWAVE and are available on the BYU anonymous ftp site at [ftp.ee.byu.edu](ftp://ftp.ee.byu.edu) in the `mers/sir` subdirectory.

SUMMARY

NSCAT, the spaceborne scatterometer on ADEOS, collected valuable backscatter data from which much information about the earth can be derived. From NSCAT data, much has been and will be learned about the oceans and winds, the polar regions and tropical rainforests. Using the SIRF resolution enhancement algorithm, images with greater resolution and accuracy can be generated, enabling studies not otherwise possible.

References

- [1] D. Long, P. Hardin, and P. Whiting, “Resolution Enhancement of Spaceborne Scatterometer Data”, *IEEE Trans. on Geosci. and Rem. Sens.*, vol. 31, pp. 700–715, 1993.
- [2] Q. Remund, D. Long, “Optimization of SIRF for NSCAT”, *BYU MERS Technical Report MERS 97-03*, 1997.
- [3] Q. Remund, D.S. Early, D. Long, “Azimuth Modulation of Ku-band Scatterometer sigma-0 over the Antarctic”, *BYU MERS Technical Report MERS 97-02*, 1997.

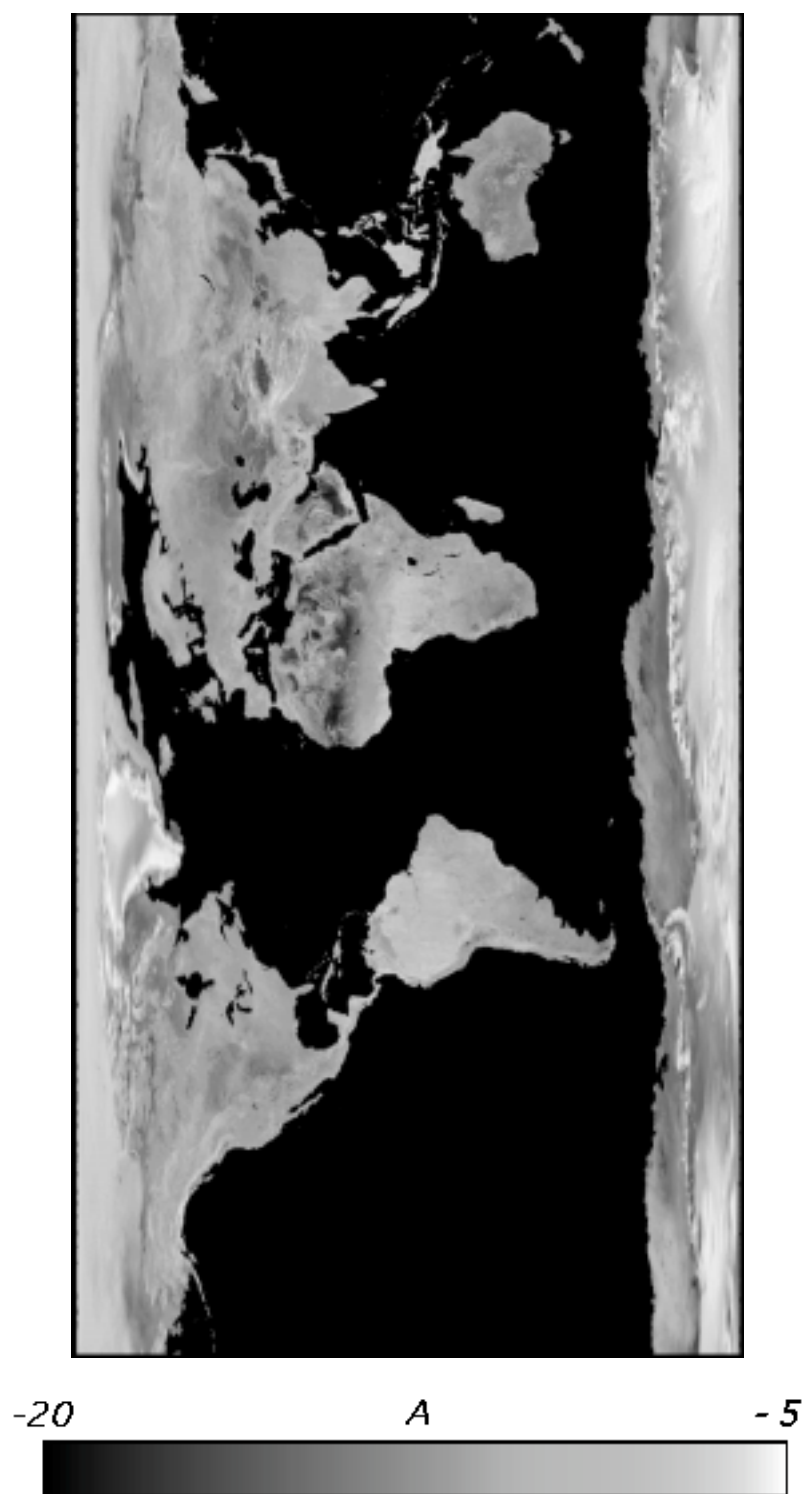


Figure 1: a low resolution ice masked global image days 344-350, 1996

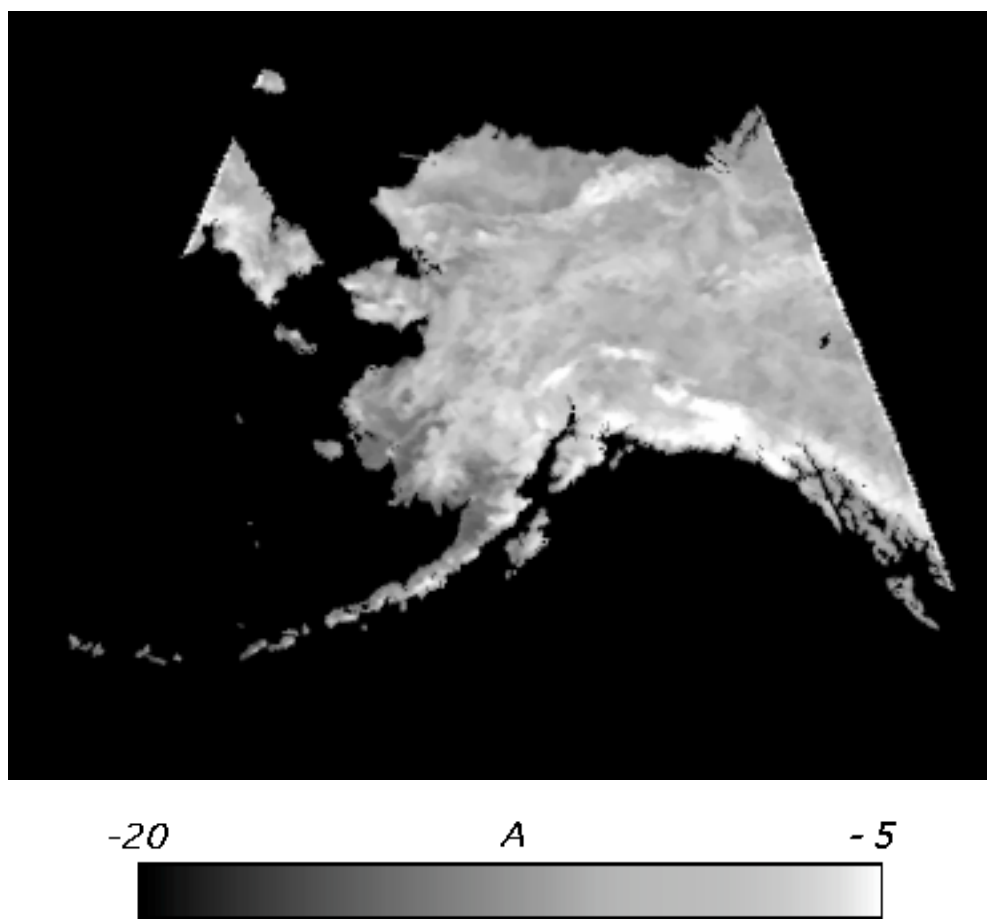


Figure 2: nscv-a-Ala96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Alaska for julian days 344 through 350, 1996

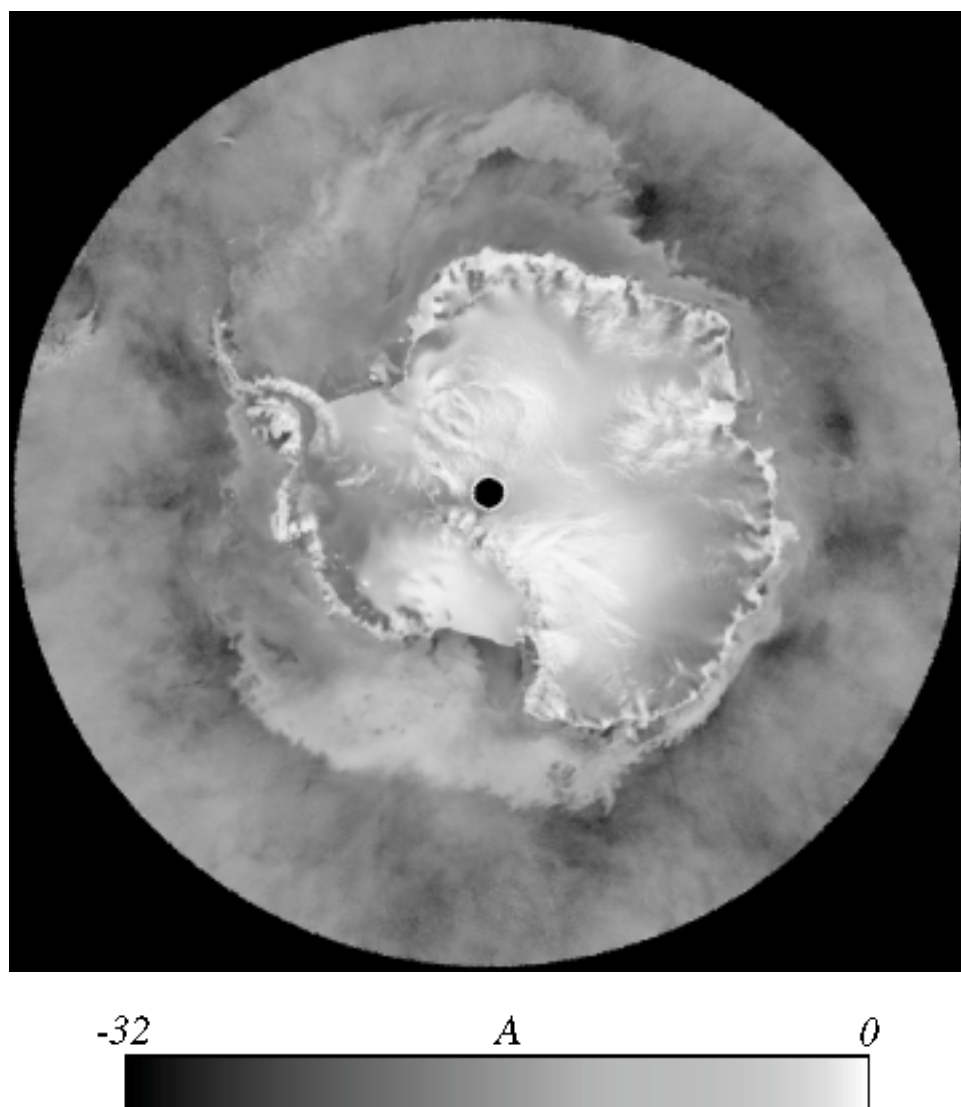


Figure 3: nscv-a-Ant96-343-348-ld.sir.imsk - an icemasked v-pol 'A' SIR image of Antarctica for julian days 343 through 348, 1996

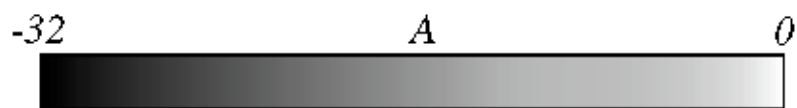
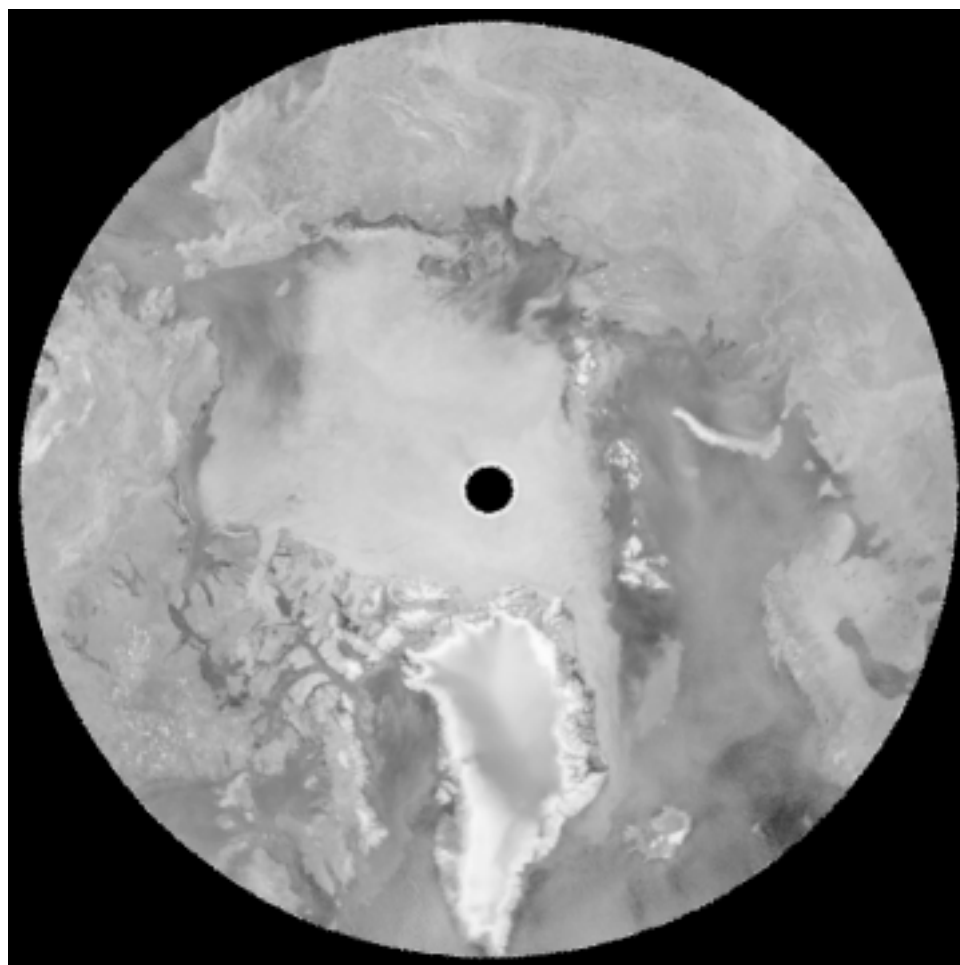


Figure 4: nscv-a-Arc96-343-348-ld.sir.imsk - an icemasked v-pol 'A' SIR image of the Arctic for julian days 343 through 348, 1996

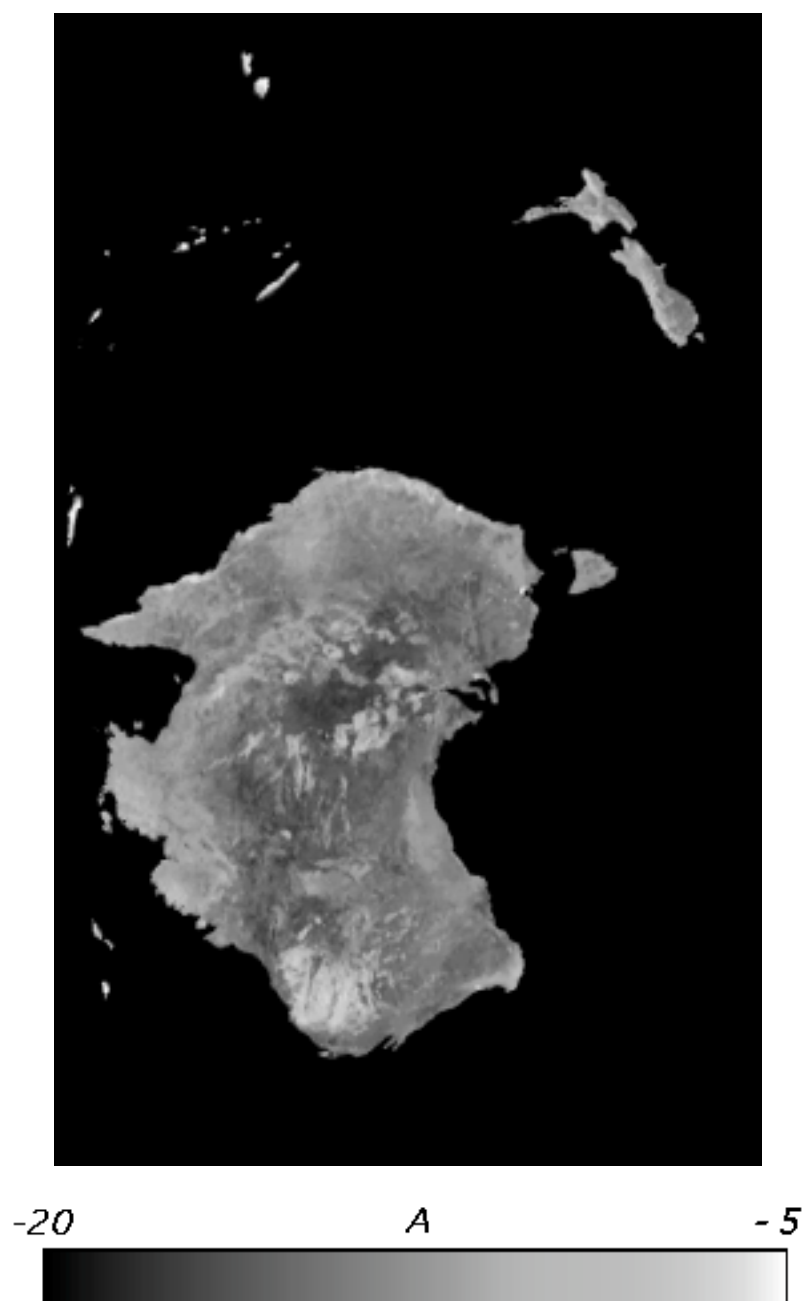


Figure 5: nscv-a-Aus96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Australia for julian days 344 through 350, 1996

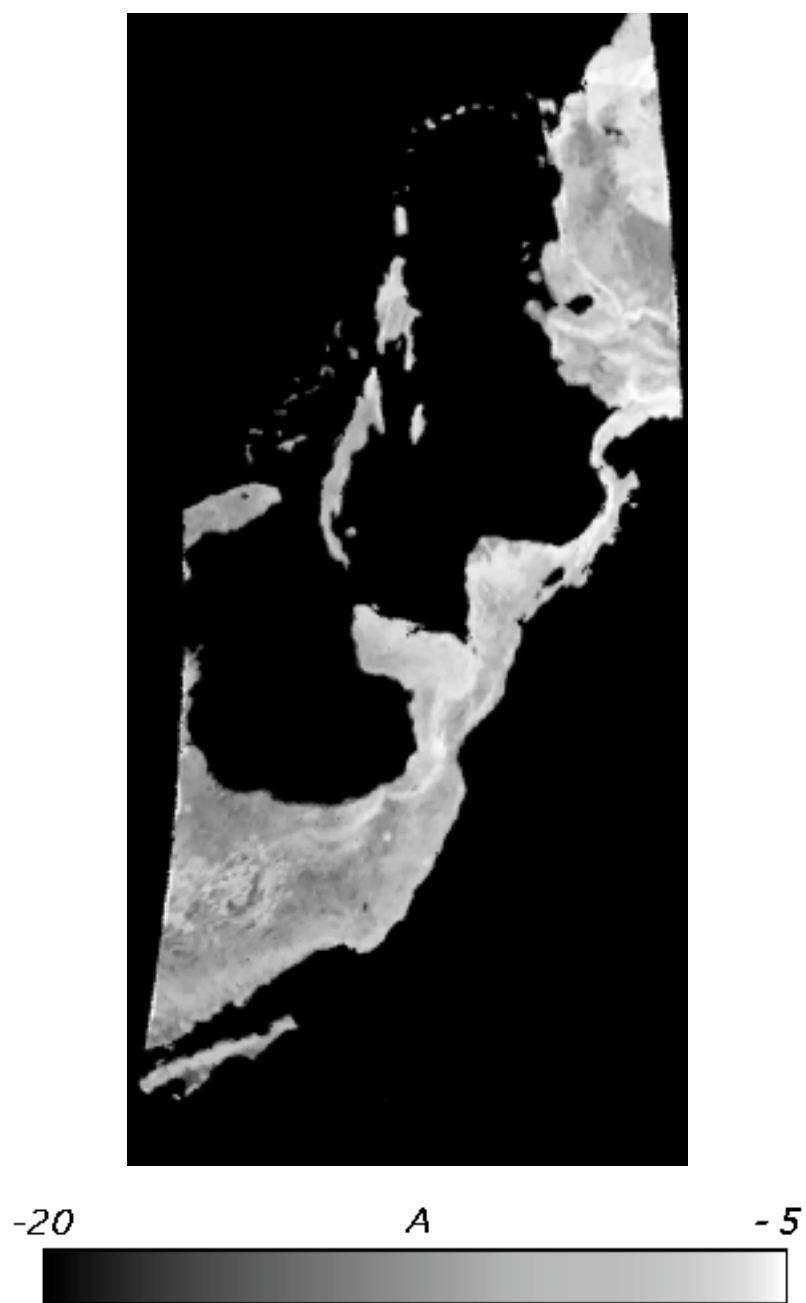


Figure 6: nscv-a-CAm96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Central America for julian days 344 through 350, 1996

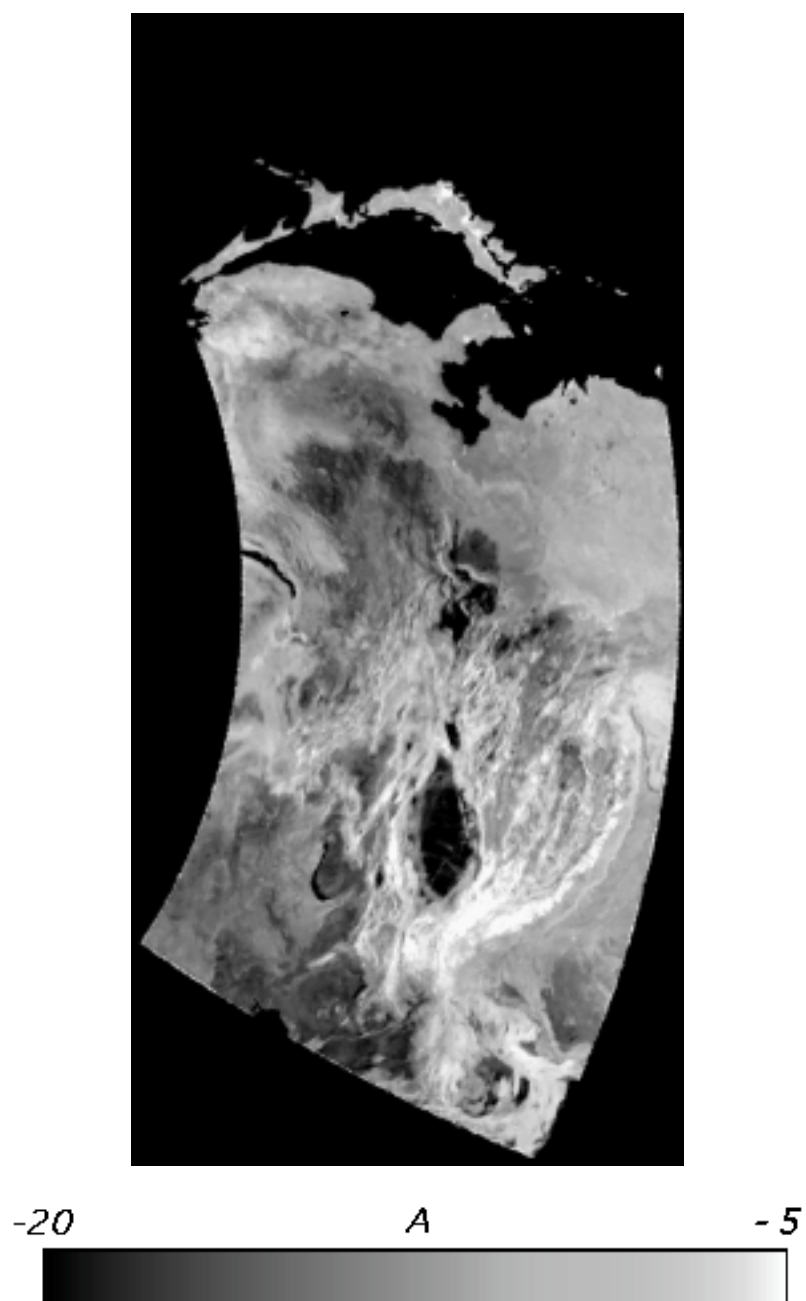


Figure 7: nscv-a-ChJ96-337-343.sir.Lmsk - a land masked v-pol 'A' SIR image of China/Japan for julian days 344 through 350, 1996

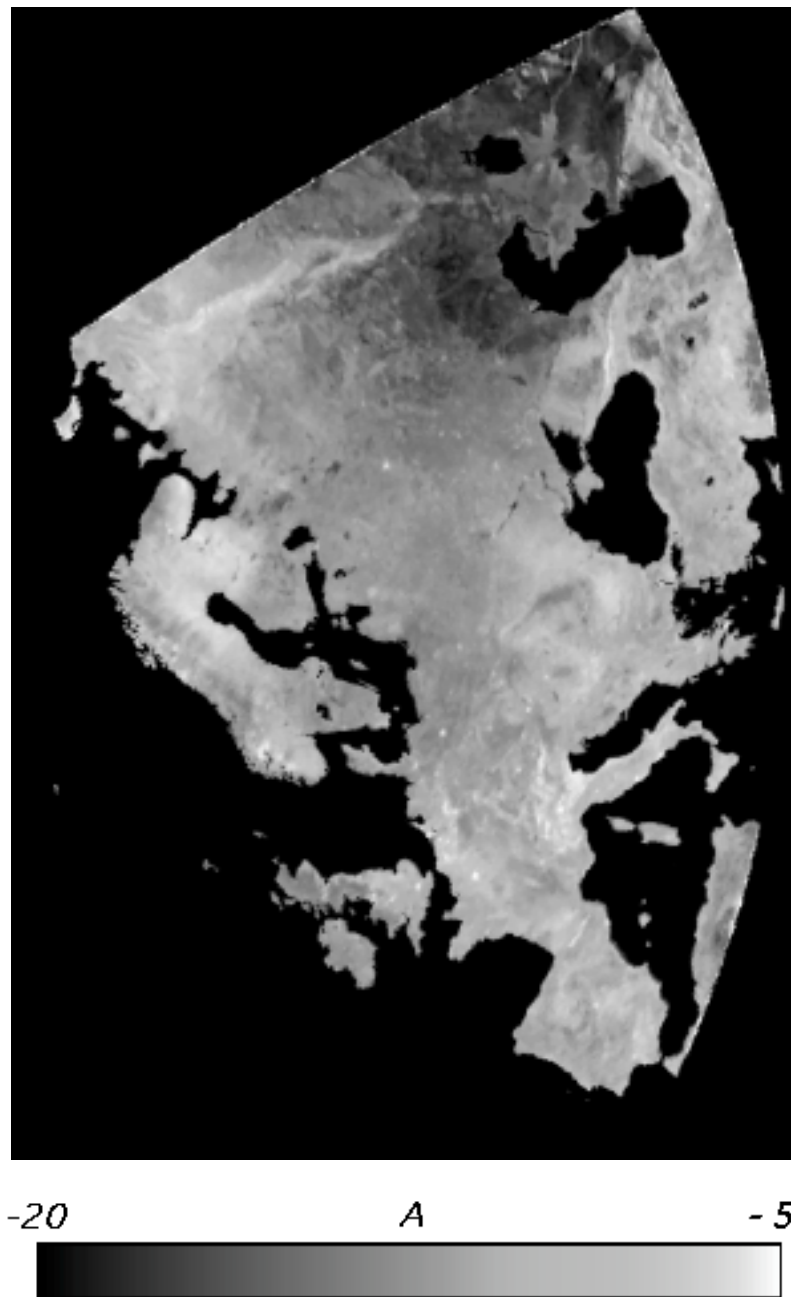


Figure 8: nscv-a-Eur96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Europe for julian days 344 through 350, 1996

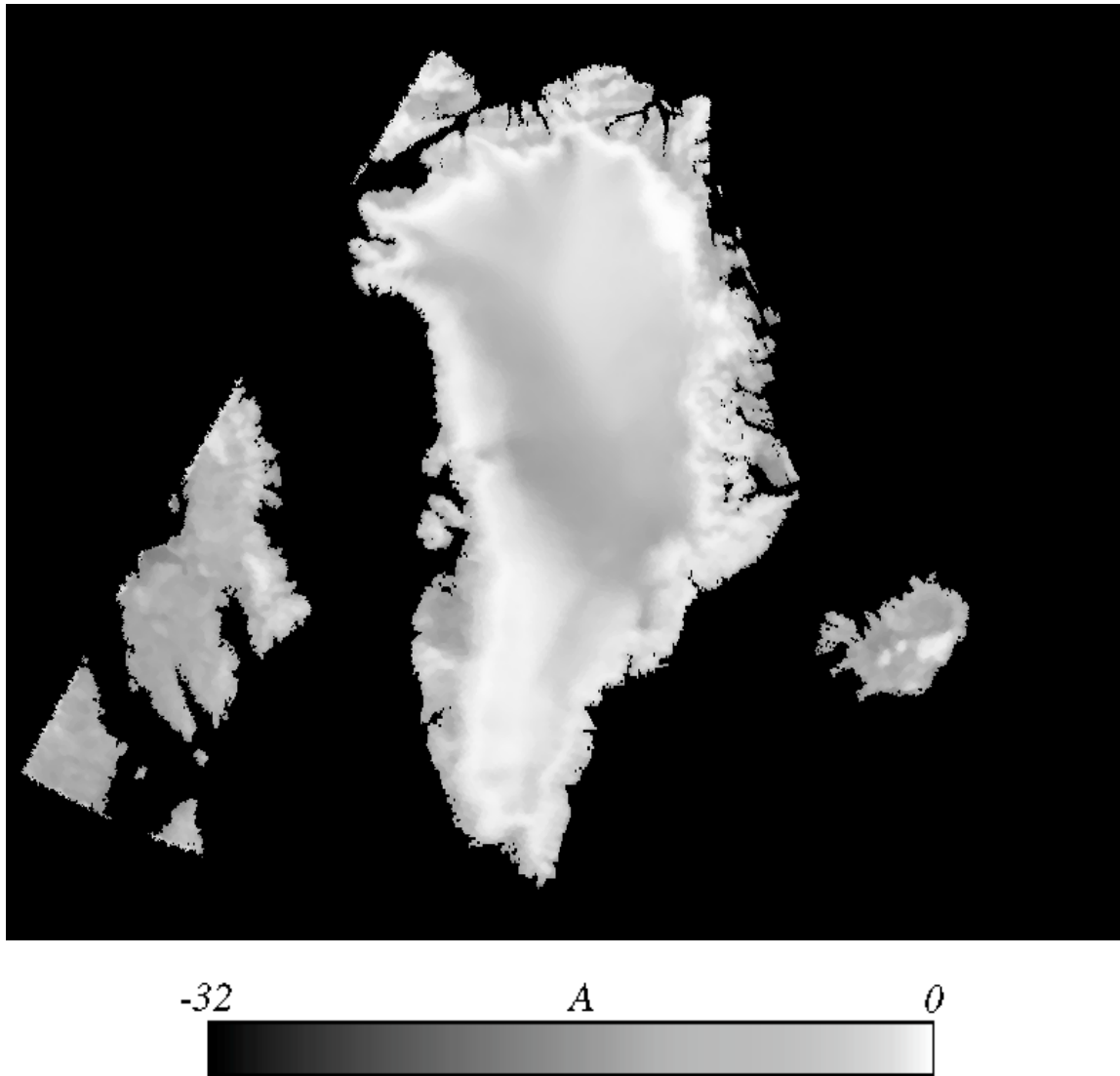


Figure 9: nscv-a-Grn96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Greenland for julian days 344 through 350, 1996



Figure 10: nscv-a-Ind96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of Indonesia for julian days 344 through 350, 1996

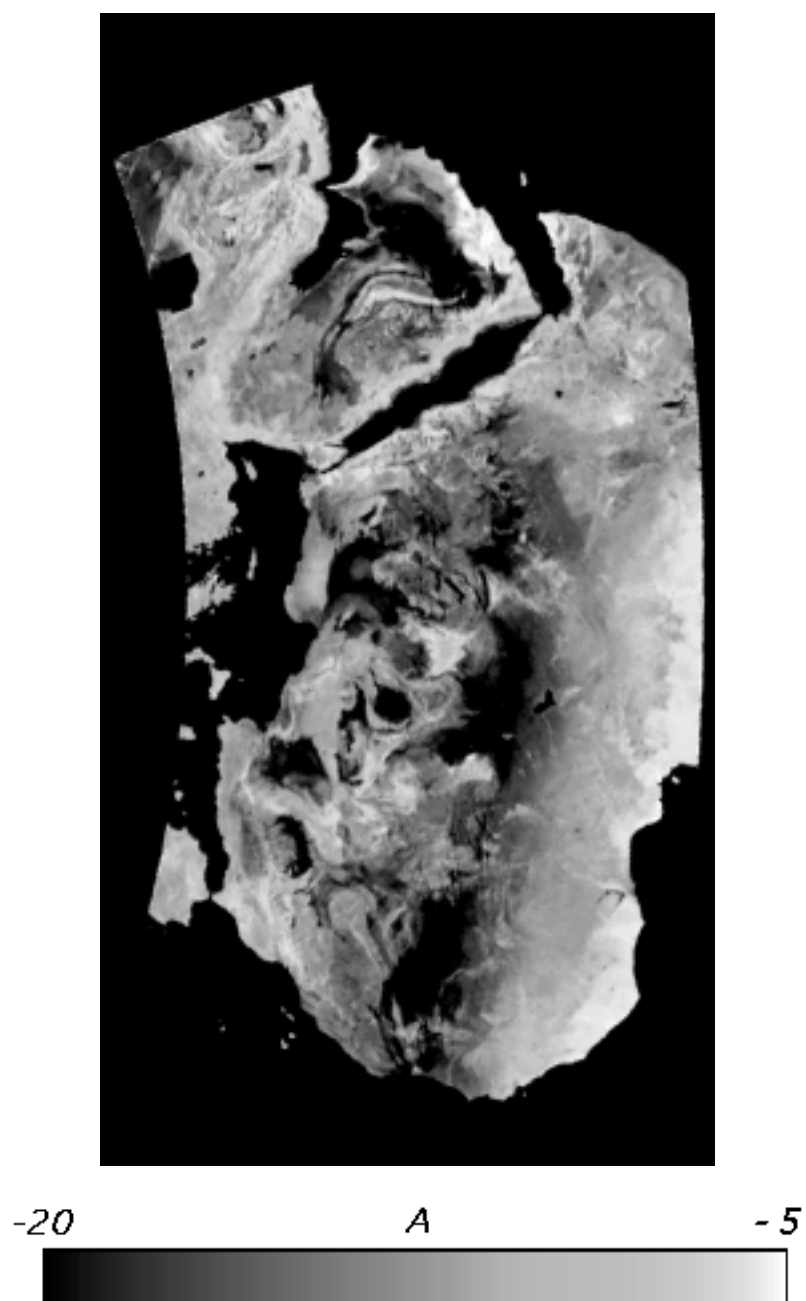


Figure 11: nscv-a-NAf96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of North Africa for julian days 344 through 350, 1996

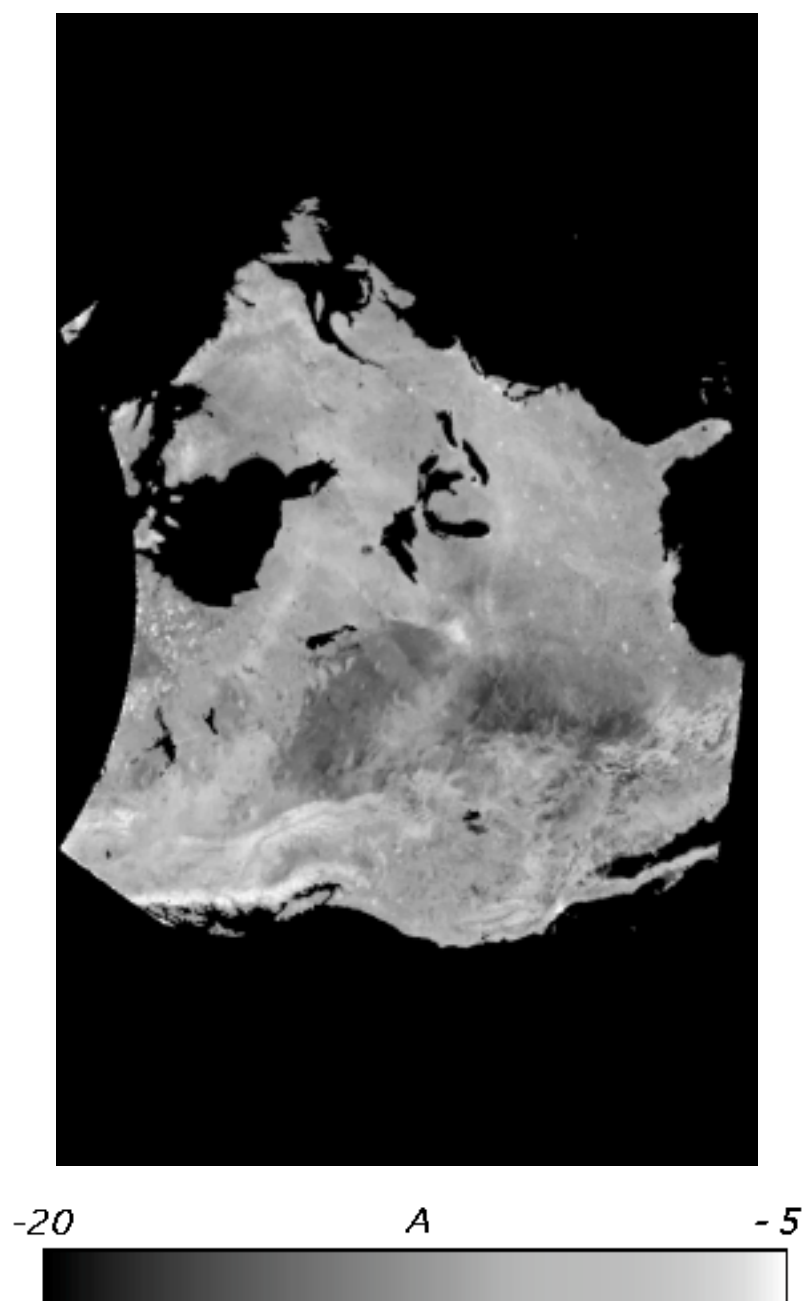


Figure 12: nscv-a-NAm96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of North America for julian days 344 through 350, 1996

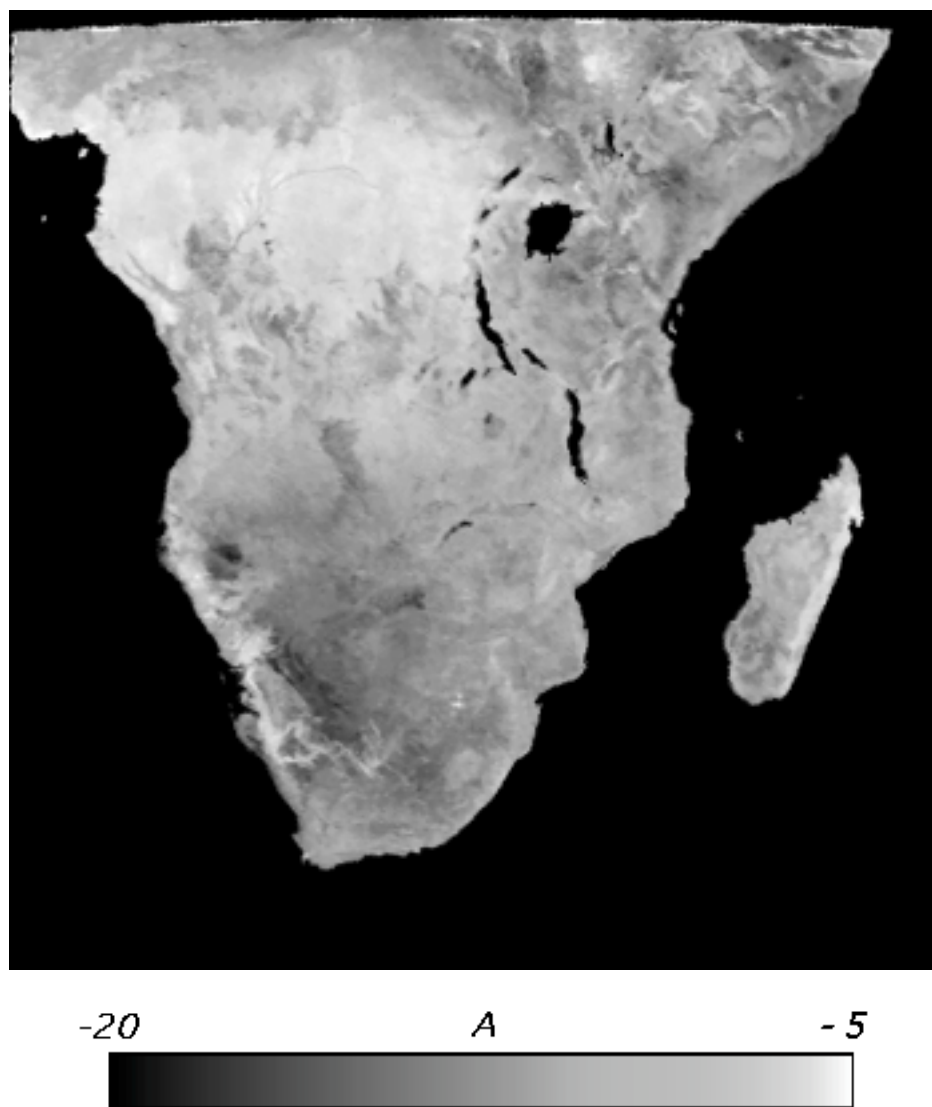


Figure 13: nscv-a-SAf96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of South Africa for julian days 344 through 350, 1996



Figure 14: nscv-a-SAm96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of South America for julian days 344 through 350, 1996



Figure 15: nscv-a-SAs96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of South Asia for julian days 344 through 350, 1996

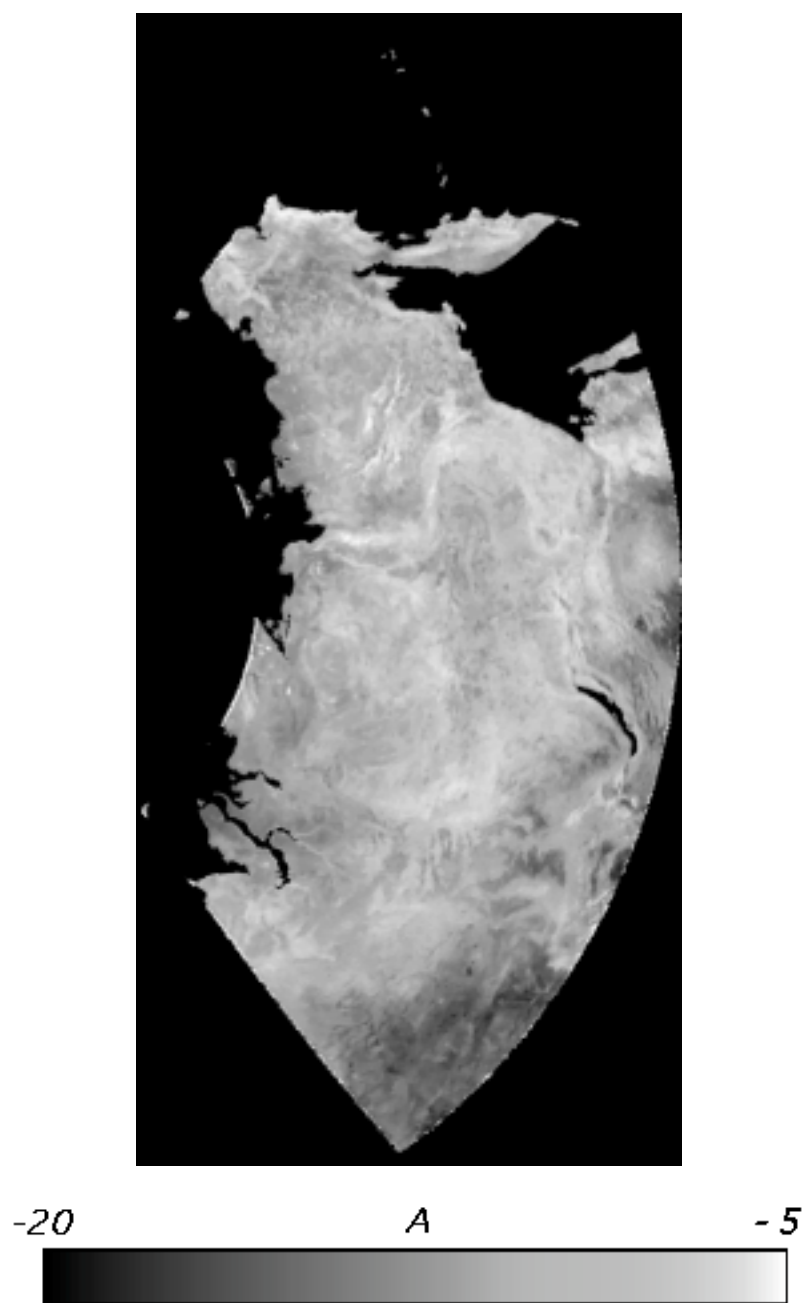


Figure 16: nscv-a-Sib96-344-350.sir.Lmsk - a land masked v-pol 'A' SIR image of alaska for julian days 344 through 350, 1996

APPENDIX

Standard product information

Region Name	Image file size (bytes)		Imaging Interval (days)	
	sir,grd,ave	non	v-pol	h-pol
Antarctic	7527936	302080	6	6
Arctic	4682752	187904	6	6
Greenland	1102336	45056	7	14
Alaska	1021440	41472	7	14
Cntrl-Amer	2016768	81408	7	14
North-Amer	4347904	174592	7	14
South-Amer	4847616	194560	7	14
North-Afri	4791808	192512	7	14
South-Afri	3075072	123904	7	14
Siberia	2770944	111616	7	14
Europe	3183104	128000	7	14
South-Asia	2534912	101888	7	14
Chin-Japan	3762688	151040	7	14
Indonesia	2448896	98816	7	14
Australia	3802112	152576	7	14

Table 3: Standard NSCAT SIRF product image sizes and imaging intervals

Image type	Images available
sir	A,B,C,E,I,J,p,V
ave	A,B
non	A,B,C,E,I,J,p,V
grd	A,B,C,E,I,J,p,V

Table 4: Image types

Standard header information

The following lists information available in the SIR file format header records. For storage details, see source code.

- nhead: number of 512 byte header blocks
- nhtype: file header type code (internal use)
- idatatype: image data storage code:
 - 2 = 2 byte integer (standard)
 - 1 = bytes
 - 4 = 4 byte floating point (non portable)
- nsx, nsy: image dimensions
- xdeg, ydeg, ascale, bscale, a0, b0: projection information
- iopt: projection type:
 - 1 = none
 - 0 = rectangular lat/lon
 - 1 = Lambert fixed radius
 - 2 = Lambert local radius
 - 5 = polar stereographic
 - 11 = northern hemisphere EASE
 - 12 = northern hemisphere EASE
 - 13 = global EASE
- ioff, iscale: image storage scale factors
 - if idatatype = 1 or 2 the value is computed as
$$\text{actualvalue} = \text{float}(\text{storedvalue} + \text{minv}) / \text{float}(\text{iscale}) + \text{float}(\text{ioff})$$
where
 - minv=128 if idatatype = 1
 - minv=32766 if idatatype = 2
 - if idatatype = 4 the stored value is the actual value and ioff and iscale are ignored
- anodata: value used to denote no data
- vmin, vmax: expected range of image actual values
- iyear: year (two digit for nscat)
- isday: Julian data of start of imaging interval
- ismin: minutes from midnight on Julian data at start of imaging interval
- ieday: Julian data of end of imaging interval
- ismin: minutes from midnight on Julian data at end of imaging interval
- iregion: region id number code (see Table 2)
- itype: image type code (see Table 1)
- sensor: 20 byte character string: describes sensor
- title: 80 byte character string: image title
- type: 80 byte character string: description of image type
- tag: 20 byte chracter string: creator program byline
- crproc: 100 byte character string: name and version of creating program

- crtime: 40 byte character string: date and time of creation
- ldes: number of bytes in optional extra description string
- nia: number of two byte integers in optional extra integer string
- descrip: optional extra description string
- iaopt: array of optional extra two byte integers