SOCRATES HIAPER Cloud Radar (HCR) and High Spectral Resolution Lidar (HSRL) data (CfRadial), Version 3.1

Changes from Version 3.0

Based on a method developed by Litai Kang, Robert Wood, and Roger Marchand from the University of Washington, we developed a bias correction algorithm for radial velocity for times when HCR is operating in zenith pointing mode. Details are given in the *Velocity correction* section below.

In the Particle IDentification (PID) field a temperature threshold of -40 °C was set. Liquid particles are no longer allowed at temperatures below this threshold and were set to precipitation or cloud.

Minor adjustments were made in the ECHO_TYPE fields to minimize mis-classifications of stratiform echo as convective.

The U and V ERA5 reanalysis wind fields are now provided on the whole 2D time-range grid instead of just at the surface.

Overview

This dataset contains HIAPER Cloud Radar (HCR) and High Spectral Resolution Lidar (HSRL) data collected aboard the NSF/NCAR GV HIAPER (Gulfstream-V High-performance Instrumented Airborne Platform for Environmental Research, HIAPER) (N677F) during SOCRATES (Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study). The data were collected during 15 research flights which took place between January 15 and February 24, 2018, over the Southern Ocean south of Australia. For more information on SOCRATES, see www.eol.ucar.edu/field_projects/socrates.

Flight	**Start date**	**Start time UTC**	**End date**	**End time UTC**
RF01	20180115	21:50	20180116	05:30
RF02	20180119	00:00	20180119	07:15
RF03	20180122	19:25	20180123	03:45
RF04	20180123	21:20	20180124	06:10
RF05	20180125	21:55	20180126	05:30
RF06	20180128	21:25	20180129	06:10
RF07	20180130	23:30	20180131	07:50
RF08	20180203	21:40	20180204	06:45

RF09	20180204	22:10	20180205	06:55
RF10	20180207	19:25	20180208	05:00
RF11	20180216	23:35	20180217	06:20
RF12	20180217	22:10	20180218	07:45
RF13	20180219	21:25	20180220	06:25
RF14	20180221	22:10	20180222	06:40
RF15	20180224	01:50	20180224	08:35

Instrument description

HCR

HCR is an airborne, polarimetric, millimeter-wavelength (W-band) radar that serves the atmospheric science community by providing cloud remote sensing capabilities to the NSF/NCAR G-V (HIAPER) aircraft. HCR detects drizzle, and ice and liquid clouds, and collects Doppler radial velocity measurements, which at vertical incident include the vertical wind speed and particle fall speed.

In a pod-based design, a single lens antenna is used for both transmit and receive. The transceiver uses a two-stage up and down conversion superheterodyne design. The transmit waveform, from a waveform generator, passes through the two-stage up-conversion to the transmit frequency of 94.40 GHz. It is then amplified by an extended interaction klystron amplifier (EIKA) to 1.6 kW peak power. System performance on transmit and receive paths are closely monitored using a coupler and a noise source. Raw in-phase and quadrature information are archived in HCR. For more information, see Vivekanandan et al. (2015) and www.eol.ucar.edu/instruments/hiaper-cloud-radar-hcr

HIAPER Cloud Radar Specifications	
Parameter	**Specification**
Antenna	0.30 m, lens
Antenna gain	46.21 dB
Antenna 3 dB beam width	0.73°
Transmit Polarization	Linear (V)
Transmit frequency	94.40 GHz
Transmitter	Klystron
Peak transmit power	1.6 kW

Pulse width	0.2 – 1.0 µs
PRF	up to 10 kHz
System noise power	-101 dBm
Receiver noise figure	8.9 dB
Receiver Bandwidth	20 MHz
Receiver Dynamic Range	76 dB
First IF	156.25 MHz
Second IF	1406.25 MHz
Range resolution	20 - 180 m
Unambiguous range	15 km
Typical reflectivity uncertainty	0.4 dB
Sensitivity	-35.0 dBZ at 1 km and 256 ns pulse
Unambiguous velocity	±7.75 m/s
Typical radial velocity uncertainty	0.2 m/s at W=2 m/s
Dwell time	100 ms

HSRL

The Gulfstream V High Spectral Resolution Lidar (GV-HSRL) is an eye-safe calibrated lidar system that measures backscatter coefficient and depolarization properties of atmospheric aerosols and clouds and cloud extinction coefficient. The instrument can also be used to detect the presence of oriented scatters in the atmosphere and determine the full (Mueller) backscatter phase matrix. For more information, see www.eol.ucar.edu/instruments/gv-hsrl.

HSRL Specifications	
Parameter	**Specification**
Wavelength	532 nm
Pulse Repetition Rate	4000 Hz
Average Power	300 mW
Range Resolution - minimum	7.5 m

Telescope Diameter	40 cm
Field of View (FOV)	0.025°
Temporal Resolution - minimum	0.5 sec
Receiver Channels - 4	Molecular, Combined Hi, Combined Low, Cross-polarization
Iodine Blocking Filter Bandwidth	1.8 GHz
Etalon Filter Bandwidth	8.0 GHz

Data description

The 2 Hz time and 19 m range resolution moments data described here are available at http://data.eol.ucar.edu/dataset/552.034 in CfRadial format. For more information on CfRadial see www.ral.ucar.edu/projects/titan/docs/radial_formats/CfRadialDoc.pdf. HCR-only data at 10 Hz resolution is available at http://data.eol.ucar.edu/dataset/552.007 and HSRL-only data at 7.5 m range resolution is available at http://data.eol.ucar.edu/dataset/552.021.

The native resolution of the HCR in range is 19 m, while that of the HSRL is 7.5 m. The time resolution of the basic HCR data set is 10 Hz, while for the HSRL this is 2 Hz.

In order to merge the two data sets into combined volumes, the HCR data was averaged to 2Hz to match the HSRL in time. Then the closest HSRL gate to each HCR range gate was used to re-sample the HSRL data onto the HCR range resolution. The data fields are set to missing where no meaningful observations are available. This assists with compression to keep the data set as small as is reasonable.

One thing to note is that the data set is merged only when the two instruments are pointing in the same direction, within some margin of pointing error. The HCR antenna is stabilized to point either zenith or nadir, whereas the HSRL telescope is not - it always points at the same angle relative to the aircraft. Therefore during turns the data sets are not merged and the HSRL data will be missing. To see the full HSRL data set, view the unmerged version.

The result is a series of merged CfRadial volumes, 15 minutes in length, holding selected fields from each instrument. The field names start either with HCR or HSRL, to indicate the instrument to which the field belongs. Interpolated ERA5 reanalysis fields are also included.

The primary data products for scientific use are listed in the table below.

Variable	**Dimensions**	**Unit**	**Long Name**
time	time	seconds	Time in seconds since volume start
range	time	meters	Range from instrument to center of gate
latitude	time	deg	Latitude
longitude	time	deg	Longitude
altitude	time	meters	Altitude of radar
HCR_DBZ	time, range	dBZ	Reflectivity
HCR_VEL	time, range	m/s	Motion and bias corrected Doppler velocity
HCR_WIDTH	time, range	m/s	Spectral width
HCR_SNR	time, range	dB	Signal to noise ratio
HCR_DBMVC	time, range	dBm	Log power co-polar v transmit, v receive
HCR_NCP	time, range		Normalized coherent power
HCR_LDR	time, range	dB	Linear depolarization ratio (V/H)
HSRL_Aerosol_Backscatter_Coefficient	time, range	m^{-1} sr^{-1}	Calibrated measurement of aerosol backscatter coefficient
HSRL_Backscatter_Ratio	time, range		Ratio of combined to molecular backscatter
HSRL_Particle_Depolarization	time, range		Propensity of particles to depolarize assuming random orientation
HSRL_Particle_Linear_Depolarization_Ratio	time, range		Theoretically determined linear depolarization of particles assuming random orientation (molecular removed)
HSRL_Volume_Depolarization	time, range		Propensity of Volume to depolarize assuming random orientation
HSRL_Volume_Linear_Depolarization_Ratio	time, range		Theoretically determined linear depolarization of the volume assuming random orientation
HSRL_Merged_Combined_Channel	time, range	photon counts	Merged hi/lo gain combined channel
HSRL_Raw_Molecular_Backscatter_Channel	time, range	photon counts	Parallel polarization molecular backscatter returns
HSRL_Raw_Cross_Polarization_Channel	time, range	photon counts	Cross polarization combined aerosol and molecular returns
HSRL_Optical_Depth	time, range		Total optical depth from aircraft altitude
HSRL_Aerosol_Extinction_Coefficient	time, range	m^{-1}	Aerosol extinction coefficient
PRESS	time, range	hPa	Air pressure from ERA5
TEMP	time, range	C	Air temperature from ERA5

RH	time, range	%	Relative humidity from ERA5
SST	time	C	Sea surface temperature from ERA5
U	time	m/s	U wind component from ERA5
V	time	m/s	V wind component from ERA5
TOPO	time	m	Terrain elevation above mean sea level from GTOPO30
FLAG	time, range		Flag field to classify reflectivity (to mask unwanted data): 1 Cloud 2 Speckle (contiguous 2D echo areas of < 100 pixels) 3 Extinct (signal completely attenuated) 4 Backlobe echo (reflection from the land/sea surface when zenith pointing and flying low) 5 Out of range (second trip echo from land/sea surface when flying too high) 6 Transmitter pulse (echo from within the radar itself) 7 Water surface echo 8 Land surface echo 9 Below the surface 10 Noise source calibration 11 Antenna in transition (e.g. from nadir to zenith or vice versa) 12 Missing (not transmitting)
HCR_MELTING_LAYER	time, range		See Romatschke (2021) 10 below icing level 11 ERA5 0 °C isotherm below icing level 12 detected melting layer below or at icing level 13 interpolated melting layer below or at icing level 14 estimated melting layer below or at icing level 20 above icing level 21 ERA5 0 °C isotherm above icing level 22 detected melting layer above icing level 23 interpolated melting layer above icing level 24 estimated melting layer above icing level
HCR_ICING_LEVEL	time	m	Icing level altitude, which is defined as the lowest melting layer
HCR_ECHO_TYPE_2D	time, range		See Romatschke and Dixon (2022) 14 stratiform low 16 stratiform mid 18 stratiform high 25 mixed 30 convective 32 convective elevated 34 convective shallow 36 convective mid 38 convective deep
HCR_ECHO_TYPE_1D	time		As ECHO_TYPE_2D

PID	time, range		See Romatschke and Vivekanandan (2022) 1 rain 2 supercooled rain 3 drizzle 4 supercooled drizzle 5 cloud liquid 6 supercooled cloud liquid 7 melting 8 large frozen 9 small frozen 10 precipitation 11 cloud

HCR data processing and quality control

Details on HCR data and data processing can be found in Romatschke et al. (2021).

Removal of non-cloud echo

All radar echo that was not classified as “cloud” in the FLAG field was removed from all HCR fields except for HCR_DBMVC.

Noise source calibration and temperature dependency correction

As an external, pod-mounted system, which is deployed in a wide range of altitudes, HCR experiences large temperature variations. To maintain good system calibration, it is essential to monitor the radar system performance versus temperature. In order to ensure operational accuracy, a number of noise source calibration (NSC) events were performed during research flights, and on the ground. During each NSC event, a known noise signal, which is invariant to temperature changes, is injected into the radar and then used to characterize the receiver gain changes by comparing the received power (DBMVC) to a temperature-corrected noise power.

As the low noise amplifiers (LNAs) dictate the receiver’s performance, they are outfitted with heater circuits to maintain their temperatures between 37^0 and 40^0 C in the bench test environment. During deployment, as the heaters cycle on and off, the received power level (DBMVC) directly correlates to the temperature fluctuations, leading to a sinusoidal pattern when installed in the system. In some extreme cases, after flying at high altitudes and low temperatures for several hours, the heaters of the LNAs could not keep up with the heat loss to the environment, leading to a significant decline of the received power. Using the correlation between the LNA temperature and the received power level during the NSC events we calculated the correlation equation which we used (together with the calibration data obtained in the lab) to correct the power fields (DBMVC, DBMHX, and DBZ) for LNA temperature changes in the whole data set.

As mentioned above, the received power not only depends on the LNA temperatures but also on the pod temperature. After correcting for the LNA temperature changes we were able to establish a correlation between the pod temperature and the power output during the NSC events which was then again used to correct the whole data set. (Note that we define a mean of the Noise Source, EIK, Polarization Switch, and RF Detector temperatures as the "pod temperature".)

Sea surface calibration check

Based on the work of Li et al. (2005) we use the backscattering properties of the ocean surface to assess how well HCR reflectivity is calibrated. Sea surface calibration (SSC) events were performed during research flights, each consisting of a few minutes of cross-track scanning from 20° to -20° off-nadir. Again following Li et al. (2005) we used

$$\sigma_{0meas} = dBZ + 10log_{10}\left(\frac{\pi^5 c\tau\,|K|^2}{2\lambda^4 10^{18}}\right) + 2l_{a0} - 10log_{10}\left(cos\Theta\right)$$

to calculate the normalized radar cross section $\sigma_{0\,meas}$ of HCR in dB, where Z is the measured reflectivity, c is the speed of light m s^{-1}, τ is the pulse width s, $|K|^2$ is the radar dielectric factor, λ is the signal wavelength in m, l_{a0} is the nadir atmospheric attenuation in dB, and Θ is the elevation angle in degrees.

The measured $\sigma_{0\,meas}$ is then compared to theoretical values of the normalized ocean surface radar cross section $\sigma_{0\,theory}$ which were obtained from three models by Cox and Munk (1954), Freilich and Vanhoff (2003), and Wu (1972, 1990). $\sigma_{0\,theory}$ depends on the surface wind speed, and the sea surface temperature (SST). A weak dependency on ocean salinity is ignored. The wind speed and SST are obtained from ERA5 data.

The atmospheric attenuation was calculated using the methods of Liebe (1985) and the ITU Recommendation (2013). Both methods depend on atmospheric pressure, temperature, and relative humidity which are again obtained from ERA5 data. The attenuation results of the two methods differed by ~0.2 dB.

Comparison of $\sigma_{0\,meas}$ and $\sigma_{0\,theory}$ reveals that the bias of $|\sigma_{0\,meas} - \sigma_{0\,theory}|$ is less 1 dB depending on the model and the specific SSC event.

Velocity correction

The radial velocity is corrected for platform motion and pointing uncertainties. We first correct all data for platform motion using INS/GPS measurements (Romatschke et al., 2021). To correct for remaining biases additional corrections are applied to the nadir and zenith pointing data separately. For nadir pointing rays, the radial velocity of the surface, which is assumed to be 0 m/s, is used as a reference to correct the data with a running 3rd degree polynomial filter (Ellis et al., 2019, Romatschke et al., 2021). A similar method is applied to the zenith pointing data, but instead of the zero velocity assumption of the surface, we assume that cloud top velocities of zenith pointing times are similar to those of the surrounding nadir pointing times. First, cloud top velocities are calculated from the corrected nadir pointing data. These nadir cloud top velocities are then compared to those from the zenith pointing times and a difference between the nadir and zenith pointing cloud top velocities is used for bias correction of the zenith pointing velocity data.

Width correction

The radar has a 0.73 degree beam width. Therefore, when pointing nadir or zenith, the beam spread is about 0.36 degrees forward of vertical, and 0.36 degrees aft of the vertical. The sine of 0.36 degrees is 0.006, so at a ground speed of 200 m/s the velocity error at the forward edge of the beam is -0.006 x 200 = -1.2 m/s, since the motion is towards the radar. Similarly the velocity error at the aft edge of the beam is +1.2 m/s. These errors, across the width of the beam, increases the variance of the measured velocity, and hence increase the spectrum width. The computed width correction (delta below) is based on ground speed and beam width, and attempts to correct for this increase.

$$\delta = |(0.3 * speed * sin(elevation) * beamWidthRadians)|$$
$$corrected = \sqrt{(measured^2 - \delta^2)}$$

Known problems

Radial velocity

The surface based velocity correction worked well the majority of the time, however there are some regions in which problems were noted. These problems manifest themselves as columns of biased radial velocity at each range bin over several rays. We think these velocity pillars are caused by the filtering process over-smoothing surface velocity variations due to variable pointing error (Ellis et al. 2019). The zenith pointing correction is much less detailed than the nadir pointing correction and only corrects for major biases.

Another problem that cannot be corrected is, that the radar, while it rotates 360˚ around the along-plane axis, has only limited range of motion along the cross-plane axis. This means, that when the plane has significant pitch, e.g. during steep climbs, the tilt angle correction of the radar is not sufficient, reports erroneous angles, and the first step of the velocity correction fails. Times when this was the case are masked out.

Backlobe echo in zenith pointing

When the HCR is pointing at zenith and the GV is near the surface, there is often an echo that results from the backlobe of the radar reflecting off of the surface. This backlobe contamination is typically characterized by a band of low reflectivity, highly variable radial velocity, and high spectrum width. The backlobe appears in the zenith data at a range equal to the altitude of the radar. So as the GV ascends or descends the backlobe contamination will recede and approach in range, respectively. An attempt was made to identify the backlobe echo and flag it in the FLAG field but the identification process does not always completely remove all backlobe echo.

Period during which transmit was in H instead of V mode

On 2015/08/07, from 16:44 to 17:41, the transmitter was transmitting in the H channel instead of the V channel. Care should be taken in using some of the data fields in this period:

- The reflectivity calibration is incorrect for H transmit
- The DBMVC and DBMHX fields will be missing during this period.
- The velocity and spectrum width are unaffected, as is NCP.

Periods during which the HCR transmitter was disabled

In the HCR data, there are some short periods during which the transmitter was disabled for safety reasons. These show up as gaps in the power fields.

HSRL data processing

GV-HSRL makes four range-resolved backscatter observations:

(i) combined_hi - High receiver efficiency observation of parallel polarized total backscatter (clouds, aerosols, and molecules). Analogous to an elastic backscatter signal.
(ii) combined_lo - low receiver efficiency observation of parallel polarized total backscatter (clouds, aerosols, and molecules). Analogous to an elastic backscatter signal.
(iii) molecular - Molecular only parallel polarized backscatter channel. Aerosol and cloud signals are blocked using an iodine absorption filter which blocks the spectrally narrow particulate backscatter but passes the wings of the spectrally broad molecular backscatter.
(iv) cross - The cross-polarized total backscatter channel. HSRL transmits and receives circularly polarized light.

The primary data products of the GV-HSRL are:

Aerosol_Backscatter_Coefficient - Optical property of the scattering volume describing how strongly it scatters light at a 180 degree scattering angle. It is obtained through the relative ratio of total backscatter to molecular backscatter (B) then multiplying by the expected molecular backscatter coefficient (based on estimated temperature and pressure profiles).

$$\beta_a = B\tilde{\beta}_m$$

Particle_Linear_Depolarization_Ratio (δ_L)- When particles are randomly oriented, this is a measure of the tendency for particles in the scattering volume to reduce the degree of polarization of incident light upon backscattering. This is generally an indicator for asphericity of particles (d_a) This data product has molecular scattering effects removed. The linear depolarization ratio uses the volume_depolarization (obtained using combined parallel and cross-polarized returns) and the Backscatter_Ratio (the ratio of total to molecular scattering).

$$\delta_L = \frac{d_a}{2-d_a}$$

Note that the HSRL measures polarization using circular polarization, so the conversion to d_a and subsequently, δ_L is founded on the assumption that the particles are randomly oriented.

Optical_Depth (OD) - One-way optical depth measured from the lidar to the volume. Optical depth is the exponent of the atmospheric transmission to the scattering volume, and therefore an accumulation of extinction in each point up to the scattering volume. It is derived from the observed molecular backscatter (N_m) relative to the expected molecular backscatter coefficient.

$$OD = -\frac{1}{2}\ln\frac{N_m}{\tilde{\beta}_m}$$

Aerosol_Extinction_Coefficient (α)- The optical property describing the tendency of the volume to extinguish light by either scattering it or absorbing it. Extinction is the range derivative of the optical depth.

$$\alpha = \frac{\partial}{\partial z}OD$$

Other variable definitions used for the derived data products:

Volume depolarization - The propensity of the observation volume to depolarize including both aerosol and molecular contributions. The concept of “depolarization” in contrast to “depolarization ratio” is discussed in Gimmestad 2008.

$$d_v = \frac{N_{c\perp}}{N_{c\|} + N_{c\perp}}$$

Backscatter_Ratio (B) - the ratio of all scattering particles to only molecular scattering. This quantity is polarization independent.

$$B = \frac{N_{c\perp} + N_{c\|}}{N_m}$$

Particle_Depolarization - depolarization resulting from only particulate scatterers. The molecular contribution is removed.

$$d_a = \frac{Bd_V - d_m}{B-1}$$

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Contact

EOL Data Support: eol-datahelp@ucar.edu

UCAR/NCAR - Earth Observing Laboratory
Remote Sensing Facility
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