Description of ALMA Ceres Data Bundle

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July 2022

1. Overview

This data package archives the high-resolution images and the spectrum of Ceres at about 1 mm wavelength (265 GHz) obtained with the Atacama Large Millimeter/submillimeter Array (ALMA) in three epochs in October - November 2015, September 2017, and October 2017. The corresponding raw ALMA data, as well as some calibrated products, are archived in the ALMA Science Archive[1] under program IDs 2015.1.01384.S, 2016.1.00748.S, and 2017.1.01640.S. Based on these data available in the ALMA Science Archive, a package of additional derived data products was produced. This documentation provides the details about the observations, the reduction and radiometric calibration of the data, the production of derived data products, and the description of the format and labels of archived data.

2. Observations

The data in this package are based on observations of Ceres in three ALMA Observing Cycles respectively: October - November 2015 (Cycle 3), September 2017 (Cycle 4), and October 2017 (Cycle 5). In each epoch, Ceres was observed in three to four nights that combined covered one full rotation. The objective of these observations was to obtain a high-resolution mapping of Ceres's surface temperature for one diurnal cycle in each epoch in order to determine its thermal and dielectric properties and any compositional heterogeneity in the shallow subsurface, particularly relevant being water ice. All observations were performed with the ALMA 12-meter array using Band 6 receivers. The timing of observations in each ALMA Cycle was chosen to achieve the optimal spatial resolution considering the ALMA configuration schedule and the geocentric distance and declination of Ceres during each cycle. The 12-meter array was in extended configurations for all observations, with the longest baselines reaching up to 15 km with 40 antennas at a minimum, allowing Ceres's disk to be spatially resolved in 10-20 beams across. The spectral setup was optimized for continuum measurement sensitivity, using four 2 GHz wide spectral windows tuned to 256, 258, 272, and 274 GHz for a total of 7.5 GHz of effective bandwidth.

In addition, observations from the ALMA Compact Array (ACA) using Band 6 receiver were obtained in October 2017, to measure the total flux of Ceres over one rotation to support the absolute radiometric calibration of the 12-meter data and to obtain a high-sensitivity

[1] https://almascience.nrao.edu/aq/

spectrum of Ceres to search for HCN via its J = 3-2 transition at a rest frequency of 265.886 GHz. The ACA observations had a spatial resolution of 5″, and did not spatially resolve Ceres. The receiver was tuned such that one spectral window was centered at the rest frequency of HCN J = 3-2 transition with a resolution of 244 kHz (275 m s^{-1} at the line frequency). The other three 2 GHz wide spectral windows were centered at 252.5, 254.5, and 269.5 GHz and dedicated to continuum integration.

The date and time and the geometry of Ceres corresponding to each observation are listed in Table 1.

Table 1. Dates and geometries of ALMA observations included in this data collection.

ALMA Cycle	Date	UT Start	UT Stop	Equivalent Beam Size Range (mas)	r_h (au)	Ceres Angular Diameter (arcsec)	Solar Phase Angle (deg)	Sub-Earth Longitude (deg)
3 (12-meter)	2015 Oct 31	22:59:46	02:08:46	39.2 - 42.5	2.97	0.436	19.4	356 - 240
	2015 Nov 1	23:00:05	02:07:27	33.1 - 38.6		0.434	19.3	124 - 0
	2015 Nov 12	19:32:01	20:57:24	42.6 - 42.6		0.413	18.7	233 - 184
		22:20:04	23:36:26	42.1 - 42.5		0.413	18.6	128 - 79
4 (12-meter)	2017 Sep 26	11:09:29	13:02:54	32.0 - 35.5	2.63	0.436	19.8	348 - 278
	2017 Sep 27	11:16:25	13:08:38	31.7 - 32.7		0.438	19.9	108 - 42
	2017 Sep 28	10:55:22	12:01:12	33.4 - 34.1		0.439	20.1	254 - 215
	2017 Sep 30	10:50:35	11:43:48	21.9 - 22.3		0.443	20.3	153 - 124
5 (12-meter)	2017 Oct 15	10:50:54	13:15:46	24.2 - 28.9	2.62	0.475	21.6	267 - 191
	2017 Oct 19	10:43:15	12:57:02	19.8 - 21.0		0.485	21.9	58 - 352
	2017 Oct 26	11:06:34	12:06:05	24.8 - 25.2		0.503	22.2	232 - 202
5 (ACA)	2017 Oct 15	12:29:06	13:29:34	-	2.62	0.475	21.6	212 - 172
	2017 Oct 18	09:28:10	11:56:08	-		0.482	21.8	354 - 258
	2017 Oct 19	09:24:44	11:52:28	-		0.485	21.9	126 - 29
	2017 Oct 20	10:45:50	11:22:36	-		0.487	21.9	201 - 177

3. Data Reduction and Radiometric Calibration

All data were initially calibrated using ALMA's automated science pipeline package, CASA (McMullin et al., 2007). These calibration steps included the flagging of outlier data, correction of the spectral response (bandpass) using a bright reference quasar, correction of temporal gain variations (in phase and amplitude) using a nearby quasar, as well as adjustments of the absolute flux scale using reference flux calibration sources chosen automatically by the telescope operating system.

We then refined radiometric calibration (absolute flux scale) by using as flux reference the brightest and best monitored available sources on each date. When possible, the same flux reference was used for observations obtained close in time. The derived correction factor, varying between 2-10%, was applied to the flux scale. Considering the uncertainty on the assumed flux on the chosen reference sources, we estimate a global conservative 5% uncertainty on the flux level. After all these steps are performed, the data consist of calibrated visibilities – complex measurements corresponding to samples of the Fourier transform of the sky brightness distribution.

3.1. Imaging data

For 12-m data, one can image visibilities by performing inverse Fourier transform and deconvolution using cleaning options available in CASA. For a given observation day, the approach we took was to first self-calibrate the data phase using as a reference Ceres's image derived from all combined data from the given day, to improve corrections of short-term phase gain variations. After this step, the data was sliced into 10-20 minute long chunks, and images were derived for each of these data subsets. The size of the timestep was determined as the shortest timestep that would allow sufficient Fourier-plane coverage for high-fidelity deconvolution.

Given the high relative spatial resolution compared to the size of the source, the best results were obtained by subtracting a uniform disk model, cleaning the residuals, and then adding the initial model to the cleaned components. The multiscale deconvolution algorithm was used, with deconvolution scales of 1 - 10 times the synthesized beam size. Visibilities were weighted using the 'natural' scheme, which gives higher weight to shorter baselines. The obtained images, which are provided as .fits files can then be directly analyzed and manipulated. Note that all images have celestial north in the up direction and east to the left, and have the same pixel size (4 mas). The average frequency of all 12-meter images is 265 GHz.

3.2. Lightcurves

The provided lightcurves correspond to total flux measurements. For the total flux measurement from the 12-meter images, the flux density of all pixels is integrated within a 0.6″ - 0.8″ radius aperture centered at Ceres's center. Sky background is not a concern in interferometric data as large spatial features are filtered out by the absence of short spacings in the measured Fourier plane. The measured total flux densities are independent of the aperture size and slight offsets from the aperture center.

For the ACA observations, the flux densities are measured directly from the calibrated visibilities by averaging the visibility amplitudes' measurements with the same timestamp over all antenna pairs, all spectral windows, and both polarizations. Note that the average frequency of ACA lightcurve is 259.39 GHz, different from the average frequency of the 12-m images and lightcurves.

3.3. Spectrum

A high-spectral resolution spectrum centered around the HCN J = 3-2, 265.886 GHz transition was derived from the ACA spectral data. The ACA observations were performed in four runs on 2017 October 15, 18, 19, and 20. The raw spectra from each day were averaged over time, all antenna pairs, and both polarization settings, and were stored in four respective files in this archive. The smoothed spectrum was derived by first averaging the spectra from four days and then binned to a spectral resolution of 300 kHz, and included in this archive. The data from 2017 October 15 were discarded for the smoothed spectrum because of bad quality due to poor weather conditions.

4. Quality Assessment

After all calibration steps are completed, the calibrated visibilities will still be affected by thermal noise (Poisson noise which determines the sensitivity of the observation). On most visibilities, the thermal noise is globally very low (<0.1%) compared to the brightness of Ceres, ensuring a high signal-to-noise detection. The data quality is dominated by other effects as follows:

- The global absolute flux level for each observation day is uncertain at the 5% level, based on the uncertainty of the model for the flux reference source. On consecutive days, we estimate a 2% relative uncertainty from day to day during a given observing cycle.
- On spectrally-resolved visibilities, some residual wavelength-dependent gain variations are observed, at the 2% level over a spectral window. There are no significant gain variations observed over the typical size of a spectral feature, so the retrieval of spectral features is not affected.

Images, which are reconstructed products, present additional quality assessment considerations:

- Large-scale flux filtering: due to the size of Ceres with respect to the synthesized beam, and the low density of Fourier-plane points at small baselines, some of the flux may be lost and not retrievable. Especially on Cycle 3 data, this effect affects the measurement of total flux on an image significantly - we estimate up to a 20% level.
- Enhanced noise on maps due to imaging dynamic range limitations: the size and the brightness of Ceres are such that these limitations are the main factor producing non-real (artificial) flux variations across the imaged disk - as opposed to thermal noise. The best way to determine the level of this effect is to measure the standard deviation of pixel-to-pixel flux variations in a region outside the disk, or the normalized standard deviation in a small region within the disk. The level of these spatial artifacts varies between about 3% for Cycle 3 images, 1% for Cycle 4 images, and 2% for Cycle 5 images.

5. Data Format and Label Definition

5.1. Calibrated Ceres Images

All archived images are calibrated to Jy/arcsec^2, and saved in FITS format, with the PDS4 labels provided in the .xml file corresponding to each image. Each image is cropped to 256x256 pixels in dimension stored in the primary FITS extension. Images are organized by epochs and saved in three subfolders. The names of image files are in the format "ceres_*yyyynndd*t*hhmm*.fit", where "*yyyynndd*" is the UT year, month, and date, "t" is the letter "t", and "*hhmm*" is the start UT hour and minutes of each image.

Ceres is approximately centered in all images. The exact center of Ceres is measured by fitting an ellipse to the edge of the disk as determined by the maximum gradient in brightness. The measured centers are recorded in the FITS header for each image for reference. The image parameters, observing aspect, and Ceres geometry are all stored in the FITS headers of each image, with a selected subset listed in the PDS4 labels. The FITS header keywords are described in Appendix A.

5.2. Image Aspect Data

The observation time, beam parameters, and observing geometry of Ceres of all images are listed in ASCII tables for each cycle in this data collection for all three epochs of images. The observing time and beam parameters are provided by the ALMA data calibration process. The geometry parameters were calculated with the NAIF SPICE toolkit for the mid-observing time. The sub-Earth and sub-solar latitudes and longitudes were calculated assuming a pole orientation of Ceres at (RA, Dec) = (291.418º, 66.764º), a prime meridian parameter 170.650º, and a rotational rate of 952.1532°/day based on the Ceres SPC Shape Model (Park and Buccino, 2018, DAWN-A-FC2-5-CERESSHAPESPC-V1.0) as archived at PDS. Table 2 lists the column definitions of the image aspect data.

Table 2. Columns of image aspect data.

Column	**Type**	**Unit**	**Description**
file	string		Data file name
utc_start	date-time		UTC at the start of each image
utc_stop	date-time		UTC at the end of each image
utc_mid	date-time		UTC at the middle time of each image
bmaj	real	milliarcsec	Beam major axis
bmin	real	milliarcsec	Beam minor axis
bpa	real	degree	Beam major axis position angle (east of north)
ra	real	degree	Right ascension
dec	real	degree	Declination
rh	real	au	Heliocentric distance
range	real	au	Geocentric distance
phase	real	degree	Solar phase angle
sub-solar-lat	real	degree	Sub-solar latitude
sub-solar-lon	real	degree	Sub-solar longitude
sub-earth-lat	real	degree	Sub-Earth latitude
sub-earth-lon	real	degree	Sub-Earth longitude
north_pole_pa	real	degree	The projected position angle (east of north) of Ceres north pole in the sky
north_pole_inc	real	degree	The angle between Ceres's north pole and the sky plane (positive towards the observer)
sun_pa	real	degree	The projected position angle (east of north) of the Sun in the sky
sun_inc	real	degree	The angle between the Sun and the sky plane (positive towards the observer)

5.3. Ceres Millimeter Lightcurves

Data for four lightcurves are included as ASCII table files, corresponding to the three epochs of imaging data and the ACA data in the last epoch. The sub-Earth and sub-solar latitudes and longitudes are calculated in the same way as for the Image Aspect Data (Section 5.2). Table 3 lists the column definitions of these data. Note that the ACA lightcurve data table does not contain the "datafile" column as it is irrelevant to ACA data.

Table 3. Columns of lightcurve data.

Column	**Type**	**Unit**	**Description**
datafile	string		Image file names from which the total flux is measured
flux	real	Jy	Total flux of Ceres
utc_mid	date-time		UTC at the middle time of each image
mjd	real	day	Modified Julian date at the middle time of each image
rh	real	au	Heliocentric distance
range	real	au	Geocentric distance
phase	real	degree	Solar phase angle
solat	real	degree	Sub-Earth latitude
solon	real	degree	Sub-Earth longitude
sslat	real	degree	Sub-solar latitude
sslon	real	degree	Sub-solar longitude

5.4. Ceres Millimeter Spectrum

The spectrum of Ceres is stored in ASCII tabulated data. The raw spectrum data are stored in four files, with names like "ceres_spectrum_raw_201710*xx*.csv", where "*xx*" represents the four dates. The smoothed spectrum is stored in "ceres_spectrum_binned.csv". Both the raw spectra and the smoothed spectrum data include two columns as listed in Table 4.

Table 4. Column of smoothed ALMA Ceres spectrum.

Column	**Type**	**Unit**	**Description**
freq	real	GHz	Frequency
flux	real	Jy	Flux density

Appendix A. Example Image Metadata

FITS keyword and example	Description	Range of values
SIMPLE = T / conforms to FITS standards	Required in FITS standard	T
BITPIX = -32 / array data type	Images are all saved in 32-bit floating point numbers	-32
NAXIS = 2 / number of array dimensions	Number of axes	2
NAXIS1 = 256	Number of rows	256
NAXIS2 = 256	Number of columns	256
BMAJ = 1.186321179072E-05	Beam major axis in degrees	
BMIN = 1.007240369088E-05	Beam minor axis in degrees	
BPA = 5.362431335449E+01	Beam major axis position angle in degrees	
BTYPE = ‘Intensity’	Type of images is intensity	‘Intensity’
OBJECT = ‘Ceres’	Target name	‘Ceres’
BUNIT = ‘Jy / arcsec2’ / Brightness (pixel) unit	Unit of pixels	‘Jy / arcsec2’
TELESCOP = ‘ALMA’	Telescope name	‘ALMA’
OBSERVER = ‘jianyangli	Observer ALMA Science Portal ID	‘jianyangli’
DATE-OBS = ‘2015-10-31T22:59:46.656000’ / ISO-8601 time of observation	Observation start UTC	
TIMESYS = ‘UTC’ / Time scale	Time system	‘UTC’
OBSRA = 3.052364795700E+02	Right ascension of telescope pointing	
OBSDEC = -2.909761157075E+01	Declination of telescope pointing	
OBSGEO-X = 2.225142180269E+06 / [m] observatory X-coordinate	Observatory x-coordinate in Earth-centered frame	
OBSGEO-Y = -5.440307370349E+06 / [m] observatory Y-coordinate	Observatory y-coordinate in Earth-centered frame	

OBSGEO-Z = -2.481029851874E+06 / [m] observatory Z-coordinate	Observatory z-coordinate in Earth centered frame	
DATE = '2016-03-04T21:13:51.380000' / Date FITS file was written	Date FITS file was written by ALMA calibration pipeline CASA	
ORIGIN = 'CASA 4.5.1-REL (r35996)'	Calibration pipeline software name and version number	
UTCSTART = '2015-10-31T22:59:45.600' / Observation start time (UT)	Observation start UT	
UTCSTOP = '2015-10-31T23:12:45.100' /Observation stop time (UT)	Observation end UT	
UTCMID = '2015-10-31T23:06:15.350' / Observation mid time (UT)	Observation mid-time UT	
RH = 2.972236514807055 / [au] Heliocentric distance	Heliocentric distance	
RANGE = 2.928116396871659 / [au] Target-Earth range	Geocentric distance	
PHASE = 19.35014701240398 / [deg] Solar phase angle	Solar phase angle	
RA = 305.2355907840968 / [deg] Right ascension	Right ascension of target	
DEC = -29.09876222975744 / [deg] Declination	Declination of target	
SOLAT = 6.43364479172338 / [deg] Sub-observer latitude	Sub-observer latitude	
SOLON = 356.4695290623308 / [deg] Sub-observer longitude	Sub-observer longitude	
SSLAT = 3.816826097766984 / [deg] Subsolar latitude	Subsolar latitude	
SSLON = 15.72132732699995 / [deg] Subsolar longitude	Subsolar longitude	
POLEPA = 354.5633616222945 / [deg] Body north position angle (east of north)	Projected north pole position angle (east of north) in the sky plane	
POLEINC = 6.433644791723376 / [deg] Body north inclination (positive to Earth	Angle between north pole and the sky plane, with positive	

	values towards the Earth	
SUNPA = 257.7334085846396 / [deg] Sun position angle (east of north)	Projected Sun position angle (east of north) in the sky plane	
SUNINC = 70.64985298759602 / [deg] Sun inclination (positive to Earth)	Angle between the Sun and the sky plane, with positive values towards the Earth	
CTR_X = 118.21229 / [pix] Body center in horizontal direction	Center of object in horizontal direction	
CTR_Y = 128.88828 / [pix] Body center in vertical direction	Center of object in vertical direction	
WCSAXES = 2 / Number of coordinate axes	WCS keyword	2
CRPIX1 = 128.75 / Pixel coordinate of reference point	WCS keyword	128.75, 129.0
CRPIX2 = 128.75 / Pixel coordinate of reference point	WCS keyword	128.75, 129.0
CDELT1 = -1.1111111111112E-06 / [deg] Coordinate increment at reference point	WCS keyword	-1.1111111111112E-06
CDELT2 = 1.1111111111112E-06 / [deg] Coordinate increment at reference point	WCS keyword	1.1111111111112E-06
CUNIT1 = ‘deg’ / Units of coordinate increment and value	WCS keyword	‘deg’
CUNIT2 = ‘deg’ / Units of coordinate increment and value	WCS keyword	‘deg’
CTYPE1 = ‘RA---SIN’ / Right ascension, orthographic/synthesis projection	WCS keyword	‘RA---SIN’
CTYPE2 = ‘DEC--SIN’ / Declination, orthographic/synthesis projection	WCS keyword	‘DEC--SIN’
CRVAL1 = 305.23647957 / [deg] Coordinate value at reference point	WCS keyword	
CRVAL2 = -29.09761157075 / [deg] Coordinate value at reference point	WCS keyword	
PV2_1 = 0.0 / SIN projection parameter	WCS keyword	0.0
PV2_2 = 0.0 /SIN projection parameter	WCS keyword	0.0
LONPOLE = 180.0 / [deg] Native longitude	WCS keyword	180

of celestial pole		
LATPOLE = -29.09761157075 / [deg] Native latitude of celestial pole	WCS keyword	
RESTFRQ = 256000000000.1 / [Hz] Line rest frequency	WCS keyword	256000000000.1
MJDREF = 0.0 / [d] MJD of fiducial time	WCS keyword	0.0
MJD-OBS = 57326.95817889 / [d] MJD of observation	WCS keyword	
RADESYS = 'ICRS' / Equatorial coordinate system	WCS keyword	'ICRS'
SPECSYS = 'TOPOCENT' / Reference frame of spectral coordinates	WCS keyword	'TOPOCENT', 'LSRK'

References:

McMullin, J.P., Waters, B., Schiebel, D., Young, W., Golap, K., 2007. CASA Architecture and Applications. Astronomical Society of the Pacific Conference Series, 376, Astronomical Data Analysis Software and Systems XVI, pp. 127.

Park, R.S., Buccino, D.R., Ceres SPC Shape Model Dataset V1.0. DAWN-A-FC2-5-CERESSHAPESPC-V1.0. NASA Planetary Data System, 2018.