

# EXPRES Solar Archive

Interface Control Document (ICD) for the EXPRES Solar Data

Version 0.1

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Approved by:

## Document Revision History

Version Number	Description	Date
0.1	Initial Draft	2025-12-01

# 1. Contents

<b>Approved by:</b>	<b>2</b>
<b>Document Revision History</b>	<b>3</b>
<b>1. Contents</b>	<b>4</b>
<b>2. Introduction</b>	<b>5</b>
2.1 Background	5
2.2 Scope	5
2.3 Change Control	5
2.4 Controlling Documents	5
2.5 Reference Documents	6
2.6 Acknowledgement Text	6
<b>3. Detailed Interface Specifications</b>	<b>7</b>
3.1 Format Conventions	7
3.2 Archive Structure and Format	7
3.2.1 Archive Specifications	8
3.2.1.1 File Naming Convention	8
3.2.1.2 Internal Directory Structure	8
3.2.1.3 File Types and Contents	8
3.2.1.4 Archive Compression	9
3.2.1.5 Accompanying Manifest Files	9
3.2.1.6 Quality Assurance	9
3.2.1.7 Archive Organization	10
3.2.1.8 Data Access Pattern	10
3.3 Delivery Schedule	10
3.4 Re-delivery of data	10
<b>4. Level 1 Products</b>	<b>11</b>
4.1 File Format	11
4.1.1 Level 1 FITS HDUs	11
4.1.2 Level 1 Extension 0: PRIMARY Keyword Description	11
4.1.2 Level 1 Extension 1: INSTRUMENT_HEADER Keyword description	14
4.1.3 Level 2 Extension 1 “EXPOSURE METER + BARY CORR”	17
4.2 Data Structure	20
4.2.1 1-D Extracted Spectra	20
4.2.2 Exposure Meter Data	22
<b>5. Level 2 Products</b>	<b>23</b>
5.1 CCF Files	23
5.1.0 Primary Header	23
5.1.1 Combined CCF	24
5.1.2 Order-by-order CCFs	24

## 2. Introduction

### 2.1 Background

The EXtreme PREcision Spectrograph (EXPRES) is an optical fiber-fed echelle spectrograph designed and built by Yale University and commissioned at the 4.3-meter Lowell Discovery Telescope (LDT) in 2019. With a spectral resolution of  $R=137,500$  and wavelength coverage from 380 to 680 nm, EXPRES achieves an instrumental precision goal of better than 30 cm/s for radial velocity measurements. EXPRES uses both Thorium Argon and a laser frequency comb (LFC) for wavelength calibration.

During daytime operations, EXPRES is fed by the Lowell Observatory Solar Telescope (LOST), a 70-mm aperture solar feed that observes disk-integrated sunlight autonomously throughout the day. LOST achieves high signal-to-noise observations of the Sun with typical exposure times of approximately 150 seconds, providing data that is reduced using the standard EXPRES pipeline with minimal modifications to ensure comparability with nighttime stellar observations. The primary scientific motivation for LOST is to characterize stellar activity signals in the Sun, which serves as a template for understanding and mitigating activity-induced radial velocity variations in other stars, a fundamental obstacle in confirming the smallest exoplanets.

### 2.2 Scope

This document describes the data format specifically for the EXPRES Solar data as obtained by the Lowell Observatory Solar Telescope (LOST; PI. J Llama, Lowell Observatory).

### 2.3 Change Control

This document will be a living document. A change control board composed of J. Llama, D. Ardila, B.J. Fulton, J. Burt... shall review and approve all proposed changes to the document.

### 2.4 Controlling Documents

## 2.5 Reference Documents

- **EXPRES:** Jurgenson, C., Fischer, D., McCracken, T., Sawyer, D., Szymkowiak, A., Davis, A., Muller, G., and Santoro, F., "EXPRES: a next generation RV spectrograph in the search for earth-like worlds," Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99086T (9 August 2016); <https://doi.org/10.1117/12.2233002>
- **Solar Telescope :** Llama, J., Zhao, L. L., Brewer, J. M., Szymkowiak, A., Fischer, D. A., Collins, M., Tiegs, J., and Cornelius, F., "The Lowell Observatory Solar Telescope: a fiber feed into the Extreme Precision Spectrometer," Proc. SPIE 13094, Ground-based and Airborne Telescopes X, 130942O (11 September 2024); <https://doi.org/10.1117/12.3020494>
- **LDT:** Levine, S. E. and DeGroff, W. T., "Status and imaging performance of Lowell Observatory's Discovery Channel Telescope in its first year of full science operations," Proc. SPIE 9906, Ground-based and Airborne Telescopes VI, 990621 (8 August 2016); <https://doi.org/10.1117/12.2232732>
- **EXPRES Pipeline:** Petersburg, R. R., Ong, J. M. J., Zhao, L. L., Blackman, R. T., Brewer, J. M., Buchhave, L. A., Cabot, S. H. C., Davis, A. B., Jurgenson, C. A., Leet, C., McCracken, T. M., Sawyer, D., Sharov, M., Tronsgaard, R., Szymkowiak, A. E., and Fischer, D. A., "An Extreme-precision Radial-velocity Pipeline: First Radial Velocities from EXPRES," The Astronomical Journal, 159, 187 (2020); <https://doi.org/10.3847/1538-3881/ab7e31>
- **SELENITE Telluric Modeling:** Leet, C., Fischer, D. A., and Valenti, J. A., "Toward a Self-calibrating, Empirical, Light-weight Model for Tellurics in High-resolution Spectra," The Astronomical Journal, 157, 187 (2019); <https://doi.org/10.3847/1538-3881/ab0d86>

## 2.6 Acknowledgement Text

This work used the EXtreme PREcision Spectrograph (EXPRES) that was designed and commissioned at Yale with financial support by the U.S. National Science Foundation under MRI-1429365 and ATI-1509436 (PI D. Fischer).

This work used The Lowell Observatory Solar Telescope (LOST) that was funded in-part by the Mt. Cuba Astronomical Foundation and the Lowell Observatory Donor Opportunity Network.

## 3. Detailed Interface Specifications

### 3.1 Format Conventions

In the below tables, data formats are indicated for the purpose of archiving in a non-FITS database, and correspond to the following size standards:

Bool = 1 byte  
Char = 1 byte  
Int = 2 bytes  
Long = 4 bytes  
Double = 8 bytes

When stored values in a fits header keyword, these types are encapsulated within the standard fits definitions of 'String', 'Int', 'Float'.

Nulls are defined as in the fits standard. For strings, this means "". For non-strings, this means an empty field (i.e. UNDEFINED).

Filenames for the Level 2 data follow the convention:

Sun\_YYMMDD.NNNN.fits

Where NNNN is the exposure number.

Pyrheliometer data follows the naming convention: `expres_ljpyrheliometer_YYYYMMDD.csv`.

### 3.2 Archive Structure and Format

The EXPRES solar data are packaged as gzip-compressed tar archives (`.tar.gz`), with each archive containing a complete set of observations for a single observing date. Each archive follows a standardized directory structure containing Cross-Correlation Function (CCF) files, extracted 1-dimensional spectra files, and ancillary pyrheliometer data when available.

Archives are accompanied by machine-readable JSON manifests and human-readable text manifests that provide complete file inventories, checksums, and metadata for validation and tracking purposes. The archive naming convention uses the ISO 8601 date format (YYYYMMDD) followed by the suffix `_solar.tar.gz` to uniquely identify each observing date.

## 3.2.1 Archive Specifications

### 3.2.1.1 File Naming Convention

- **Archive filename format:** `YYYYMMDD_solar.tar.gz`
  - `YYYYMMDD`: ISO 8601 date format (e.g., `20240115`)
  - `_solar`: Fixed identifier for solar observations
  - `.tar.gz`: Gzip-compressed tar archive extension
- **Example:** `20240115_solar.tar.gz` contains all observations from January 15, 2024

### 3.2.1.2 Internal Directory Structure

- **Root directory:** `YYYYMMDD_solar/` (matches archive filename without extension)
- **Subdirectories:**
  - `ccf/`: Cross-Correlation Function data files
  - `fitspec/`: Fitted spectrum data files
- **Root-level files:**
  - `expres_ljpyrheliometer_YYYYMMDD.csv`: Pyrheliometer measurements (when available)

### 3.2.1.3 File Types and Contents

- **CCF Files (`ccf/` subdirectory)**
  - **Format:** FITS binary tables
  - **Naming convention:** `Sun_yymmdd.NNNN.fits`
    - `Sun`: Fixed target identifier
    - `yymmdd`: Two-digit year, month, day (e.g., `240115` for 2024-01-15)
    - `NNNN`: Four-digit sequence number (0001-9999)
  - **Content:** Cross-correlation function data for radial velocity determination
  - **Typical count:** 100-250 files per observing date
- **Fitspec Files (`fitspec/` subdirectory)**
  - **Format:** FITS binary tables
  - **Naming convention:** `Sun_yymmdd.NNNN.fits` (matches corresponding CCF filename)
  - **Content:** Fitted stellar spectrum data
  - **Coverage:** Subset of CCF files; not all observations may have corresponding fitspec files
- **Pyrheliometer Data (root level)**
  - **Format:** CSV (Comma-Separated Values)
  - **Naming convention:** `expres_ljpyrheliometer_YYYYMMDD.csv`
  - **Content:** dateobs (DATETIME), intensity (pyrheliometer reading)
  - **Availability:** Optional; may be absent for some observing dates

### 3.2.1.4 Archive Compression

- **Method:** GNU gzip (RFC 1952)
- **Compression level:** Standard gzip compression
- **Typical compression ratio:** ~10-15% size reduction for FITS files
- **Typical archive size:** 1.0-2.5 GB compressed

### 3.2.1.5 Accompanying Manifest Files

Each archive is accompanied by two manifest files located in the same directory:

- JSON Manifest (`YYYYMMDD_solar_manifest.json`)
  - **Format:** JSON (RFC 8259)
  - **Purpose:** Machine-readable archive inventory for automated validation
  - **Contents:**
    - Archive metadata (filename, date, creation timestamp, size)
    - Complete file listings for each subdirectory (sorted alphabetically)
    - File counts by type and total
    - Pyrheliometer filename (if present)
  - **Schema:**

```
JSON
{
  "archive": "string (archive filename)",
  "date": "string (YYYYMMDD format)",
  "created": "string (ISO 8601 timestamp)",
  "archive_size_mb": number,
  "contents": {
    "ccf": ["array of filenames"],
    "fitspec": ["array of filenames"],
    "pyrheliometer": "string (filename, optional)"
  },
  "file_counts": {
    "ccf": integer,
    "fitspec": integer,
    "pyrheliometer": integer (0 or 1),
    "total": integer
  }
}
```

### 3.2.1.6 Quality Assurance

- **Completeness:** All CCF files for an observing date are included in a single archive
- **Consistency:** Fitspec files use identical naming to their corresponding CCF files
- **Validation:** Manifest files provide complete inventories for automated integrity checking
- **Traceability:** Creation timestamps and file counts enable verification of archive completeness

### 3.2.1.7 Archive Organization

- **Temporal grouping:** One archive per observing date
- **Storage hierarchy:** Archives organized by year in subdirectories (YYYY/)
- **Manifest co-location:** JSON and text manifests stored alongside archives
- **Naming consistency:** Archive name, root directory name, and manifest prefix all use identical YYYYMMDD\_solar identifier

### 3.2.1.8 Data Access Pattern

1. Locate archive by date: `YYYY/YYYYMMDD_solar.tar.gz`
2. Verify integrity using manifest: `YYYY/YYYYMMDD_solar_manifest.json`
3. Extract archive to access data files
4. Cross-reference CCF and fitspec files using identical base filenames
5. Access pyrhelimeter data (if present) from root directory of extracted archive

## 3.3 Delivery Schedule

The previous day's data will be delivered at 16:00 from Lowell Observatory ([207.192.243.66](https://207.192.243.66)) to NExScI (IP).

Regardless of data acquisition, a manifest will be delivered daily to ensure accurate book-keeping.

## 3.4 Re-delivery of data

Should there be significant changes to the EXPRES pipeline, we would trigger a redelivery of impacted data (most likely Level 1 and 2 files). This is not expected to happen more than once-per-year.

## 4. Level 1 Products

### 4.1 File Format

Level 1 data products are derived from the Level 0 products, following the EXPRES extraction pipeline procedure outlined in Petersburg et al. 2020. These files inherit all the header keywords that were present in the Level 0 primary header. Level 1 data files are stored as 2D FITS image arrays where the x-axis of the 2D arrays correspond to the x-axis of the detector and the y-axis corresponds to the echelle order.

#### 4.1.1 Level 1 FITS HDUs

HDU #	Name	Description
0	PRIMARY	
1	OPTIMAL EXTRACTION	
2	EXPOSURE METER + BARY_CORR	

#### 4.1.2 Level 1 Extension 0: PRIMARY Keyword Description

Keyword	Value	Data Type	Static / Dynamic	Comment
SIMPLE	T	BOOLEAN	Static	conforms to FITS standard
BITPIX	8	INTEGER	Static	array data type
NAXIS	0	INTEGER	Static	number of array dimensions
EXTEND	T	BOOLEAN	Static	
SITELONG	-111.422515	FLOAT	Static	East longitude site(decimal degrees)
SITELAT	34.744305	FLOAT	Static	Latitude of site (decimal degrees)
SITEELEV	2337	INTEGER	Static	Elevation of observatory site (meters)
TELESCP	DCT	STRING	Static	Name of telescope
INSTRMNT	EXPRES	STRING	Static	Name of instrument
DETECTOR	STA1600	STRING	Static	Detector type
FPA	EXPRES-D0	STRING	Static	Focal Plane Array Identifier
CNTRTYPE	STA-Archon	STRING	Static	Detector Controller

CNTRVRS	1	INTEGER	Static	Controller firmware version
CNTRFIRM	/Users/expresadmin/archon/	STRING	Static	Location of firmware; currently a stati
OBSERVER	Solar . Telescope	STRING	Dynamic	Name of observer
OBJECT	Sun	STRING	Dynamic	
OBS_ID	210616.5095	STRING	Dynamic	Observation ID
PROGRAM	201	INTEGER	Dynamic	Program identifier
RA	05:40:14	STRING	Dynamic	RA of Sun at time of exposure
DEC	23:21:32	STRING	Dynamic	DEC of Sun at time of exposure
FRAME	FK5	STRING	Static	Frame of RA and DEC
OBSTYPE	Solar	STRING	Dynamic	Observation type
PRESETMO	Solar	STRING	Dynamic	Preset mode
REQRA	05:40:14	STRING	Dynamic	Target right ascension
REQDEC	23:21:32	STRING	Dynamic	Target declination
MAXEXP	600	FLOAT	Dynamic	Maximum exposure time
REXPTIME	600	FLOAT	Dynamic	Requested exposure time in seconds
HDRVRSN	1	INTEGER	Static	See EXPRES FITS Headers Documentation.
MIDPOINT	2021-06-16 16:56:14	DATETIME	Dynamic	Geometric midpoint btwn DATE-SHT and DATE-
AEXPTIME	195.076	FLOAT	Dynamic	Actual exposure time in seconds
EXPMTR	TRUE	BOOLEAN	Dynamic	Exposure meter state
AGITATOR	TRUE	BOOLEAN	Dynamic	Fiber agitator state
ADCSTAT	Standing By	STRING	Dynamic	ADC Status at Beginning of Exposure
EXPTHRES	2500000	INTEGER	Dynamic	Target signal on exposure meter
EXPCOUNT	2507391	INTEGER	Dynamic	Final signal on exposure meter
CRYTEMP0	-187.88576	FLOAT	Dynamic	Cryostat getter temperature
CRYTEMP1	-110.000112	FLOAT	Dynamic	Cryostat coldplate temperature
CRYTEMP2	-66.4262	FLOAT	Dynamic	Cryostat ccd temperature
CRYPRESS	6.12E-07	FLOAT	Dynamic	Cryostat pressure

DATE-OBS	2021-06-16 16:54:36	DATETIME	Dynamic	Time of observation (expres_mgr shutter open t
DATE-SHT	2021-06-16 16:54:36	DATETIME	Dynamic	Time shutter opened
DATE-END	2021-06-16 16:57:51	DATETIME	Dynamic	Time shutter closed
EQUINOX	2000	INTEGER	Static	
CAL-TYPE		STRING	Dynamic	Calibration type
LAMP	Off	STRING	Dynamic	Lamp mode in calibration box
FOC-POS	11800	INTEGER	Dynamic	Current EXPRES focus motor position
EFI-POS	34000	INTEGER	Dynamic	Current EXPRES extended flat motor position
TELMJD	59381.4668	FLOAT	Dynamic	MJD of telescope ALT, AZ, and airmass - Not updated for solar observations
TELALT	89:59:54	STRING	Dynamic	Altitude of telescope at TELMJD - Not updated for solar observations
TELAZ	167:36:48	STRING	Dynamic	Azimuth of telescope at TELMJD - Not updated for solar observations
HA	23:59:58	STRING	Dynamic	Hour angle of telescope at TELMJD
MOONDIST	-1	INTEGER	Dynamic	Distance in degrees from the Moon - Not updated for solar observations
SUNDIST	-1	INTEGER	Dynamic	Distance in degrees from the Sun - Not updated for solar observations
AIRMASS	1.213722298	FLOAT	Dynamic	Average airmass at center of exposure
AMBEG	1.218569221	FLOAT	Dynamic	Airmass at beginning of exposure (TELMJD)
AMEND	1.208957733	FLOAT	Dynamic	Airmass at end of exposure
CCDBIN	(1,1)	STRING	Static	

#### 4.1.2 Level 1 Extension 1: INSTRUMENT\_HEADER Keyword description

Keyword	Value	Data Type	Comment
XTENSION	BINTABLE	string	binary table extension
BITPIX	8	integer	array data type
NAXIS	2	integer	number of array dimensions
NAXIS1	799922	integer	length of dimension 1
NAXIS2	86	integer	length of dimension 2
PCOUNT	0	integer	number of group parameters
GCOUNT	1	integer	number of groups
TFIELDS	17	integer	number of table fields
VERSION	0.4.1	string	EXPRES Pipeline code version
EXTNAME	optimal	string	Extraction algorithm
DATE-EXT		datetime	Date and time of extraction
SCATLGH	T	boolean	Scattered light removed before extraction
EXT_SIZE	33	integer	Size of the extraction window (pixels)
FLAT_REL	T	boolean	Flat relative extracted spectral values
EXT_BKGD	F	boolean	Background fit and removed during extraction
COSMSIGM	8	float	Sigma cut for cosmic rays
COSMTAIL	2	float	Sigma cut for the tails of cosmic rays
OPT_ATOL	1.00E-12	float	Absolute tolerance during optimal extraction
OPT_RTOL	1.00E-10	float	Relative tolerance during optimal extraction
MAX_ITER	1000	integer	Maximum iterations during optional extraction
CHI_DEG	3	integer	Polynomial degree when smoothing reduced chi
DATE-WAV		datetime	Date and time of wavelength calibration
WAVE-CAL	LFC+ThAr	string	Wavelength calibration source
INTP-PRM	line	string	Wavelength interpolation parameter
INTP-MTD	poly	string	Wavelength interpolation method
INTP-DEG	2	integer	Wavelength interpolation degree
CONT_EXT	continuous	string	Extent of the approximated continuum
CONT_FNC	spline	string	Function used to fit the continuum
CONT_DEG	3	integer	Continuum fit function degree

CONT_RES	100	float	Continuum spline knot resolution
CONT_CUT	-1.5	float	Continuum sigma cut for absorption lines
BARYMJD		float	Barycentric MJD (This is HJD for solar)
WATRCOL		float	Telluric water column density
AIRMASS		float	Telluric air mass
DATE-TEL		datetime	Date and time of telluric modeling
DATEEXCL		datetime	
EXCTINTP	local1	string	
EXCPINTP	pchip	string	
TTYPE1	spectrum	string	
TFORM1	7920D	string	
TTYPE2	uncertainty	string	
TFORM2	7920D	string	
TTYPE3	offset	string	
TFORM3	7920D	string	
TTYPE4	offset_uncertainty	string	
TFORM4	7920D	string	
TTYPE5	reduced_chi	string	
TFORM5	7920D	string	
TTYPE6	n_pixels	string	
TFORM6	7920I	string	
TUNIT6	pixels	string	
TTYPE7	pixel_mask	string	
TFORM7	7920L	string	
TTYPE8	blaze	string	
TFORM8	7920D	string	
TUNIT8	e-	string	
TTYPE9	orders	string	
TFORM9	l	string	
TTYPE10	wavelength	string	
TFORM10	7920D	string	
TUNIT10	angstroms	string	
TTYPE11	continuum	string	
TFORM11	7920D	string	

TTYPE12	continuum_mask	string	
TFORM12	7920L	string	
TTYPE13	bary_wavelength	string	
TFORM13	7920D	string	
TUNIT13	angstroms	string	
TTYPE14	tellurics	string	
TFORM14	7920D	string	
TTYPE15	bary_excalibur	string	
TFORM15	7920D	string	
TUNIT15	angstroms	string	
TTYPE16	excalibur	string	
TFORM16	7920D	string	
TUNIT16	angstroms	string	
TTYPE17	excalibur_mask	string	
TFORM17	7920L	string	
TUNIT17	unitless	string	
QUALITY		float	Quality factor of the solar observation (0-1), >0.9 considered good exposure
S-VALUE		float	May not be present for low SNR - Calcium H&K S-value
HALPHA		float	May not be present for low SNR - H-alpha emission
HWIDTH		float	May not be present for low SNR - H-alpha equivalent width
CCFFWHM		float	May not be present for low SNR - FWHM of the CCF
CCFFWHME		float	May not be present for low SNR - FWHM of the CCF error
BIS		float	May not be present for low SNR - BIS indicator a la Queloz+ 01
CCFVSPAN		float	May not be present for low SNR - Velocity span of the CCF
BIGAUSS		float	May not be present for low SNR - Bi-Gaussian Fit to the CCF
SKEWNORM		float	May not be present for low SNR - Skew-normal Gaussian fit to the CCF
DATE-ACT		datetime	May not be present for low SNR - Date of activity indicator calculation

## 4.1.3 Level 2 Extension 1 “EXPOSURE METER + BARY CORR”

Keyword	Value	Data Type	Comment
XTENSION	BINTABLE	string	binary table extension
BITPIX	8	integer	array data type
NAXIS	2	integer	number of array dimensions
NAXIS1	8720	integer	length of dimension 1
NAXIS2	71	integer	length of dimension 2
PCOUNT	0	integer	number of group parameters
GCOUNT	1	integer	number of groups
TFIELDS	5	integer	number of table fields
VERSION	0.4.1	string	EXPRES Pipeline code version
EXTNAME	EXPOSURE METER + BARY_CORR	string	extension name
EXTVER	1	integer	extension value
CAL_DATE		float	Date the wavelength calibration image was taken
CAL_SLOP		float	Slope of the linear wavelength solution
CAL_INT		float	y-intercept of the linear wavelength solution
DATE-EXP		datetime	Date and time of exposure meter reduction
RAW		string	Exposure meter path (truncated)
DATE-BC		datetime	Date and time of barycentric correction
n_channels	8	integer	Number of channels for chromatic correction
poly_order	3	integer	Order of the fitted polynomial to chromatic bc
geo_mdpt		float	JD
geo_mdpt_bc		float	JD
wtd_mdpt		float	
wtd_mdpt_bc		float	
wtd_single_channel_bc		float	
poly_coeff0		float	
poly_coeff1		float	
poly_coeff2		float	
poly_coeff3		float	
channel1_wav		float	
channel2_wav		float	
channel3_wav		float	

channel4_wav		float	
channel5_wav		float	
channel6_wav		float	
channel7_wav		float	
channel8_wav		float	
channel1_bc		float	
channel2_bc		float	
channel3_bc		float	
channel4_bc		float	
channel5_bc		float	
channel6_bc		float	
channel7_bc		float	
channel8_bc		float	
channel1_SNR		float	
channel2_SNR		float	
channel3_SNR		float	
channel4_SNR		float	
channel5_SNR		float	
channel6_SNR		float	
channel7_SNR		float	
channel8_SNR		float	
channel1_mdpt		float	
channel2_mdpt		float	
channel3_mdpt		float	
channel4_mdpt		float	
channel5_mdpt		float	
channel6_mdpt		float	
channel7_mdpt		float	
channel8_mdpt		float	
SolSystemTarget	Sun	string	From BARYCORRPY kwargs
predictive	T	boolean	From BARYCORRPY kwargs
EPHEMERS		string	Planetary ephemeris
LAT	34.744305	float	From BARYCORRPY kwargs
LONGI	-111.422515	float	From BARYCORRPY kwargs
ALT	2337	float	From BARYCORRPY kwargs
ZMEAS	0	float	From BARYCORRPY kwargs

LEAP_UPD	F	boolean	Leap update
TTYPER1	expm_specs	string	
TFORM1	512D	string	
TTYPER2	midpoints	string	
TFORM2	D	string	
TTYPER3	wavelengths	string	
TFORM3	512D	string	
TTYPER4	cosmics	string	
TFORM4	512L	string	
TTYPER5	mdpt_bcs	string	
TFORM5	D	string	

## 4.2 Data Structure

### 4.2.1 1-D Extracted Spectra

The Level 1 extracted spectra are stored in Extension 1 of the FITS file. The contents of these data are:

Field Name	Data Type	Shape	Description
spectrum	Float	(86, 7920)	Extracted values using flat-relative optimal extraction method. Values are unitless and relative to a flat image constructed for the night, not corresponding directly to physical properties.
uncertainty	Float	(86, 7920)	Errors for each pixel propagated through extraction. Should be continuum normalized when working with continuum normalized spectra.
offset	Float	(86, 7920)	
offset_uncertainty	Float	(86, 7920)	
reduced_chi	Float	(86, 7920)	
n_pixels	Integer	(86, 7920)	
pixel_mask	Boolean	(86, 7920)	Mask excluding pixels with too low signal to return proper extracted values, largely pixels on edges of orders. Masked pixels set to NaNs.
blaze	Float	(86, 7920)	Counts of the median flat exposure used for extraction. Multiply spectrum by blaze to recover original counts.

orders	Integer	(86,)	
wavelength	Float	(86, 7920)	Wavelengths for each pixel across the entire detector.
continuum	Float	(86, 7920)	Fit to the continuum for each order.
continuum_mask	Boolean	(86, 7920)	
bary_wavelength	Float	(86, 7920)	Chromatic-barycentric-corrected wavelengths for each pixel.
tellurics	Float	(86, 7920)	SELENITE-constructed telluric model specific to this exposure.
bary_excalibur	Float	(86, 7920)	Chromatic-barycentric-corrected Excalibur wavelengths for each pixel.
excalibur	Float	(86, 7920)	Wavelengths from Excalibur (non-parametric, hierarchical wavelength calibration method). Less systematic/instrumental error but smaller spectral range (~4775-7225 Å epoch 4, ~4940-7270 Å epoch 5). Returns RVs with lower scatter.
excalibur_mask	Boolean	(86, 7920)	Mask excluding pixels without Excalibur wavelengths (set to NaNs). Excludes pixels not between calibration lines or outside LFC line range.

For example, to plot the continuum-normalized spectrum for relative order 66 of EXPRES data in python (which has an index of 65 and corresponds to absolute order 160-65=95), one would use:

```
Python
data = hdul[1].data
plt.errorbar(data['wavelength'][65],
             data['spectrum'][65]/data['continuum'][65],
             yerr=data['uncertainty'][65]/data['continuum'][65])
plt.xlabel('Wavelength [A]')
plt.ylabel('Continuum Normalized Counts')
```

#### 4.2.2 Exposure Meter Data

Field Name	Data Type	Shape
expm_specs	Float	(n_seconds, 512)
midpoints	Float	(n_seconds,)
wavelengths	Float	(n_seconds, 512)
cosmics	Boolean	(n_seconds, 512)
mdpt_bcs	Float	(n_seconds,)

where:

```
Python
n_seconds = np.ceil(float(hdul[0].header['AEXPTIME'])).astype(int)
```

## 5. Level 2 Products

### 5.1 CCF Files

The Level 2 CCF products are stored as 2D FITS files as described below.

#### 5.1.0 Primary Header

Keyword	Value	Data Type	Comment
SIMPLE	T	boolean	conforms to FITS standard
BITPIX	8	integer	array data type
NAXIS	0	integer	number of array dimensions
EXTEND	T	boolean	
VERSION	0.4.2	string	EXPRES pipeline code version
DATE-CCF		datetime	Date and time of CCF calculation
FILENAME	Sun_yymmdd.nnnn.fits	string	Original filename
MJD		float	MJD of geometric midpoint for stellar observations. For solar observations this is HJD
MASK	ESPRESSO_G2.fits	string	CCF mask linelist used
EXPCOUNT		integer	Exposure meter counts
SNR	369	integer	Maximum per-pixel SNR in order 111
V		float	Fitted velocity in cm/s
E_V		float	Posterior error in cm/s
CHI2		float	Reduced chi-squared of model fit
BLUE_ORD	126	integer	Bluest echelle order in CCF
RED_ORD	87	integer	Reddest echelle order in CCF
WINDOW	cos	string	Window function used in CCF
BARYCOR	chromatic	string	Type of barycentric correction
AIRMASS		float	Airmass of exposure
EXPTIME		float	Exposure time in seconds
RVEPOCH	5	integer	RV calibration epoch
WAVE_CAL	LFC+ThAr	string	Wavelength calibration in source FITS file
CCOR	F	boolean	HARPS-style colour correction
BLAZE	T	boolean	Pixels weighted by blaze in CCF
CONTNORM	F	boolean	Continuum normalized spectrum in CCF
SUB_CONT	F	boolean	Continuum subtracted before running CCF
DIV_TELL	F	boolean	Tellurics divided before CCF

PLATESCL	2	float	CCF platescale
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### 5.1.1 Combined CCF

Keyword	Value	Data Type	Comment
XTENSION	BINTABLE	string	binary table extension
BITPIX	8	integer	array data type
NAXIS	2	integer	number of array dimensions
NAXIS1	24	integer	length of dimension 1
NAXIS2	1001	integer	length of dimension 2
PCOUNT	0	integer	number of group parameters
GCOUNT	1	integer	number of groups
TFIELDS	3	integer	number of table fields
TTYPE1	V_grid	string	
TFORM1	D	string	
TTYPE2	ccf	string	
TFORM2	D	string	
TTYPE3	e_ccf	string	
TFORM3	D	string	

To plot the ccf in km/s one would use:

```
Python
plt.plot(hdul[1].data['V_grid']/1e5, hdul[1].data['ccf'])
```

### 5.1.2 Order-by-order CCFs

Keyword	Value	Data Type	Comment
XTENSION	BINTABLE	string	binary table extension
BITPIX	8	integer	array data type
NAXIS	2	integer	number of array dimensions
NAXIS1	16034	integer	length of dimension 1
NAXIS2	75	integer	length of dimension 2
PCOUNT	0	integer	number of group parameters
GCOUNT	1	integer	number of groups
TFIELDS	5	integer	number of table fields
TTYPE1	orders	string	

TFORM1	I	string	
TTYPE2	ccfs	string	
TFORM2	1001D	string	
TTYPE3	errs	string	
TFORM3	1001D	string	
TTYPE4	v	string	
TFORM4	D	string	
TTYPE5	e_v	string	
TFORM5	D	string	