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Full length article

The General Single-Dish Data format: A retrospective[☆]

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ABSTRACT

The General Single-Dish Data format (GSDD) was developed in the mid-1980s as a data model to support centimeter, millimeter and submillimeter instrumentation at NRAO, JCMT, the University of Arizona and IRAM. We provide an overview of the GSDD requirements and associated data model, discuss the implementation of the resultant file formats, describe its usage in the observatories and provide a retrospective on the format.

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1. Introduction

In the late 1970s and early 1980s millimeter and submillimeter single-dish astronomy was undergoing a significant period of growth (see e.g., Robson, 2013) with the National Radio Astronomy Observatory (NRAO) 12-m telescope leading the way (see e.g., Gordon, 2005) and with multiple observatories being developed such as the Institut de Radioastronomie Millimétrique (IRAM) 30-m (Baars, 1981), the 15-m James Clerk Maxwell Telescope (JCMT; Hills, 1985), the 10-m Sub-Millimeter Telescope (SMT; Wilson, 1985), the 15-m Swedish European Southern Observatory Submillimeter Telescope (SEST; Delannoy, 1985), and the Caltech Submillimeter Observatory (CSO; Phillips, 1988). In this environment it was recognized by some institutions that the ability for raw, or partially processed data taken on one telescope, to be reduced and analyzed by the software written at another telescope

would be extremely useful and could lead to significant savings on software development effort.

At this time the Flexible Image Transport System (FITS; Wells et al., 1981) was considered mainly suitable as a means of exchanging image data using tapes (Greisen et al., 1980). The FITS standard, which then lacked the capability to use binary tables and could only store a single ASCII table per file, was not deemed an efficient format to store complex mm/sub-mm time-series and spectral-line data from single-dish telescopes that usually required many sets of tabular data.

The General Single Dish Data format (GSDD) was developed in the 1980s to solve the data processing and acquisition requirements of the NRAO, IRAM, University of Arizona and JCMT observatories. Initial discussions between NRAO 12m and IRAM staff began in 1983, and subsequently included JCMT representatives. At around this same time, however, IRAM started development of the Continuum and Line Analysis Single-dish Software CLASS¹ (Pety, 2005, 1305.010) data reduction package,

[☆] These codes are registered at the Astrophysics Source Code Library (ASCL) with the code entries 1503.009 and 1503.007.

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¹ <http://www.iram.fr/IRAMFR/GILDAS>.

Table 1

Base classes defined for GSDD. The final two classes listed, 14 and 55, were only defined at JCMT.

Class number	Class name
1	Basic information
2	Pointing parameters
3	Observing parameters
4	Positions
5	Environment
6	Map parameters
7	Data parameters
8	Engineering parameters
9	Telescope dependent parameters
10	Open data reduction parameters
11	Phase block
12	Receiver configurations
13	Data values
14	Pointing history (JCMT)
55	Inclinometry (JCMT)

and they did not follow up on the GSDD initiative.² The GSDD format, agreed in 1986 (see e.g., Fairclough et al., 1987; Stobie, 1987), consisted of a data model for specifying centimeter, millimeter and submillimeter observations (continuum and spectral-line instrumentation) and a specification of how the bytes would be represented on disk. The format was described in both JCMT technical notes (Fairclough et al., 1987; Scobbie, 1994; Jenness et al., 1999) and an NRAO Newsletter article (Stobie, 1987), but a formal definition of the format was not published in the literature. In this article we present the first joint NRAO/JCMT description of the model and provide a retrospective on the history and usage of the format. A basic introduction to millimeter and submillimeter observing techniques is beyond the scope of this paper but good background information can be provided by Stanimirovic et al. (2002).

2. Data model

To allow interoperability of data files between differing observatories it was important to develop a shared data model. The initial approach was to define the simplest possible model to allow sharing of raw, or partially reduced spectra between multiple data reduction software packages. Since JCMT was still in the development phase during these discussions the focus became how to represent the raw instrument data on disk. This was simplified somewhat by the JCMT system not storing individual on-source and off-source or calibration data, but storing calibrated spectra from the heterodyne systems and chop subtracted time-series for the continuum instruments.

The model was designed to handle general sub-mm observing techniques using different switching techniques, such as position switching, beam switching and frequency switching, and included on-the-fly mapping techniques (where the telescope is moved during acquisition) as well as stare and gridded observations.

When designing the model related items were grouped into numbered classes and the parameter name was prefixed by that class number. The class groupings are shown in Table 1. In early JCMT documents (e.g. Fairclough and Padman, 1985; Fairclough

et al., 1987) there is disagreement in the class numbering, for example using S2EPH³ or C3EPH for the epoch of the coordinates rather than C4EPH, reflecting the uncertainty in the standardized model, but eventually (see e.g. Scobbie, 1994) the NRAO convention was adopted and the core model solidified (Stobie, 1985, defined the NRAO naming scheme). Seventy one data items were defined in the shared NRAO/JCMT GSDD data model.⁴ and those are detailed in Table 2. For example C3DAT referred to the UT date of the observation, C1SNO the scan number, and C7VR the source radial velocity.

At the JCMT these GSDD names (known locally as the “NRAO” names) were written to disk files but were mapped to local equivalents in the acquisition computers. For example C12RF, the rest frequency, mapped to FE_NUREST in the acquisition shared memory system and was equivalent to the RESTFREQ FITS keyword. A full list of the equivalences for JCMT can be found elsewhere (Jenness et al., 1999; Scobbie, 1994). As commissioning took place, new instrumentation arrived and new facilities were added, the JCMT data model diverged with many new items being added without consultation with NRAO. These items are listed in Table 3. Class 55 (Inclinometry) is not included here as the inclinometry data were not archived and therefore data files describing these observations are extremely rare.

One feature of the GSDD design was that some classes were explicitly reserved for local use. Class 9 was used for telescope dependent parameters and the defined set differed between Green Bank and the 12m with JCMT adopting a single item, C90T from the 12m.

The NRAO implementation, not including class 9, includes 26 items not found in the JCMT version and these are given in Table 4. The following list – which is not intended to be exhaustive – details the main discrepancies and major compatibility problems between the NRAO and GSDD data models. The first part describes in detail the items found in the NRAO model but not implemented at JCMT:

- C1DLN C1HLN are not needed at JCMT because the length of the header region and the length of the data region are encoded in the file format design.
- C1SNA is the source object name and exists as two separate items at JCMT, C1SNA1 and C1SNA2, to allow the object name to be specified in two parts or with an alternative name given. C1SNA1 is the primary source name and is equivalent to the OBJECT FITS keyword. Historically the alternate or secondary part of the name was rarely used at JCMT so the name change, in hindsight, turned out to be unnecessary.
- C2PC was used at NRAO to specify a four-element secondary pointing correction. The JCMT version specifies this as four discrete scalar items, C2PC1 to C2PC4, rather than using an array.
- C2UXP C2UYP are the user Az/RA and El/Dec pointing corrections in arcsec but at JCMT these were simply called UAZ and UEL with no class prefix and no RA/Dec equivalent.
- C4D0 is a three-element array labeled “Descriptive Origin” describing the position and angle of the coordinate system defined by the observer. At JCMT this was implemented as three distinct items C4D01 through C4D03 and specified the observing cell size and position angle with respect to local vertical. There was disagreement between

² The authors have been unable to find anyone from IRAM or the University of Arizona that recalls the GSDD discussions and can provide information from their side. JCMT and NRAO documents confirm the additional parties but no meeting minutes are available. An IRAM memo from January 1983 indicates they were strongly in favor of a FITS variant called IRAM Disk-oriented FITS (IDFITS) that supported VAX floating point, array header keywords, variable length headers (up to 80 characters) and CONTINUE cards and stored the data in separate files from the header information.

³ In early iterations S was used to indicate a scalar item and V a vector item, followed by the class number.

⁴ 72 if the telescope-specific C90T, Observing Tolerance, item is included which was present in the NRAO 12m definition and at JCMT but not used for Green Bank. In some very early files JCMT erroneously used C90T for this item due to a transcription error confusing the letter “O” with the number zero. This sometimes implies that JCMT used class 90.

Table 2
Core components of GSDD data model present in both NRAO and JCMT implementations (Stobie, 1985). Relevant units are given in square brackets using the NRAO convention. JCMT data files contain unit information explicitly.

C1BKE	Backend	C4CSC	Code for coordinate system	C6YGC	Starting Y grid position
C1DP	Precision of the data in bits and data type	C4EDC	Epoch declination [deg]	C6YNP	Number of Y grid points
C1OBS	Observer Initials	C4EL	Elevation at C3UT [deg]	C7BCV	Bad channel value
C1ONA	Observer name	C4EPH	Epoch of coordinates [years]	C7CAL	Calibration type
C1PID	Project ID	C4ERA	Epoch Right Ascension [deg]	C7OSN	Calibration scan/observation number
C1RCV	Frontend	C4GB	Galactic latitude [deg]	C7VC	Velocity correction [km/s]
C1SNO	Scan/Observation number	C4GL	Galactic longitude [deg]	C7VR	Radial velocity of source [km/s]
C1STC	Type of observation	C4RX	Reference X position [deg]	C7VRD	Velocity definition code
C1TEL	Telescope name	C4RY	Reference Y position [deg]	C8AAE	Aperture efficiency
C2FL	EW focus	C4SX	Source X [deg]	C8ABE	Beam efficiency
C2FR	Radial focus	C4SY	Source Y [deg]	C8EF	Forward spillover & scattering efficiency
C2FV	NS focus	C5AT	Ambient temperature [° C]	C8EL	Rear spillover & scattering efficiency
C2ORI	Secondary orientation	C5DP	Dew point [° C]	C8GN	Antenna gain
C2XPC	Az/RA pointing correction [arcsec]	C5IR	Refractive index	C11VD	Phase table names
C2YPC	El/Dec pointing correction [arcsec]	C5MM	Atmospheric vapor pressure [mm]	C12BW	Bandwidth
C3CL	Length of cycle [sec]	C5PRS	Atmospheric pressure [mm Hg]	C12CF	Observed frequency [MHz]
C3DAT	UT date (YYYY.MMDD format)	C5RH	Relative humidity [%]	C12CT	Calibration temperature [K]
C3LST	LST at start [hours]	C6DX	Delta X offset [arcsec]	C12FR	Frequency resolution [MHz]
C3NRC	Number of rx/backend channels	C6DY	Delta Y offset [arcsec]	C12RF	Rest frequency [MHz]
C3NSV	Number of switching/phase table variables	C6FC	Reference frame coord code	C12RST	Reference system temperature [K]
C3PPC	Number of phases per cycle	C6MSA	Scanning angle [deg]	C12RT	Receiver temperature [K]
C3SRT	Integration time [sec]	C6NP	Number of grid points	C12SST	Source system temperature [K]
C3UT	UT of observation [hours]	C6XGC	Starting X grid position	C12WO	Water opacity
C4AZ	Azimuth at C3UT [deg]	C6XNP	Number of X grid points		

Table 3
JCMT-specific keywords from class 1 to class 14. This includes the three items that were not allocated a class. Class 55 is not included here as that data was not archived.

CELL_V2Y	Position angle of cell y axis (CCW)	C3MAP	Map observation?
UAZ	User az correction	C3MXP	Maximum number of map points done in a phase
UEL	User el correction	C3NCH	Number of backend output channels
C1BTYP	Type of backend	C3NCI	Maximum number of cycles in the scan
C1FTYP	Type of frontend	C3NCP	Total number of xy positions observed during a cycle
C1HGT	Height of telescope above sea level	C3NCYCLE	Number of cycles done in the scan
C1IFS	Name of the IF device	C3NFOC	Number of frontend output channels
C1LAT	Geodetic latitude of telescope (North +ve)	C3NIS	Number of scans
C1LONG	Geographical longitude of telescope (West +ve)	C3NLOOPS	Number of scans per observation commanded at observation start
C1ONA1	Name of the support scientist	C3NMAP	Number of map points
C1ONA2	Name of the telescope operator	C3NOIFPBES	Number of IF inputs to each section (2 for correlator, 1 for AOS)
C1SNA1	Source name part 1	C3NO_SCAN_VARS1	Number of scan table 1 variables
C1SNA2	Source name part 2 or altern. name	C3NO_SCAN_VARS2	Number of scan table 2 variables
C2PC1	Angle by which lower axis is north of ideal	C3NPP	Number of dimension in the map table
C2PC2	Angle by which lower axis is east of ideal	C3NRS	Number of backend sections
C2PC3	Angle by which upper axis is not perpendicular to lower	C3NSAMPLE	Number of scans done
C2PC4	Angle by which beam is not perpendicular to upper axis	C3OVERLAP	Subband overlap
C3BEFENULO	Copy of frontend LO frequency per backend section	C3UT1C	UT1-UTC correction interpolated from time service telex (in days)
C3BEFESB	Copy of frontend sideband sign per backend section	C4AMPL_EW	Secondary mirror chopping amplitude parallel to lower axis
C3BEINCON	IF output channels connected to BE input channels	C4AMPL_NS	Secondary mirror chopping amplitude parallel to upper axis
C3BESCONN	BE input channels connected to this section	C4AXY	Angle between cell y axis and x-axis (CCW)
C3BESSPEC	Subsystem nr to which each backend section belongs.	C4AZERR	DAZ:Net Az offset at start (inc.tracker ball setting and user correction)
C3BETOTIF	Total IF per backend section	C4CECO	Centre coords. AZ = 1; EQ = 3; RD = 4; RB = 6; RJ = 7; GA = 8
C3CAL	Calibration observation?	C4DAZ	Telescope lower axis correction for secondary mirror XYZ
C3CEN	Centre moves between scans?	C4DECDATE	Declination of date
C3CONFIGNR	Backend configuration	C4DEL	Telescope upper axis correction for secondary mirror XYZ
C3DASCALSRC	DAS calibration source for backend calibration (POWER or DATA)	C4DO1	Cell x dimension; descriptive origin item 1
C3DASOUTPUT	Description of output in DAS DATA (SPECTRUM, T_REC, T_SYS, etc.)	C4DO2	Cell y dimension; descriptive origin item 2
C3DASSHFTFRAC	DAS calibration source for backend calibration (POWER or DATA)	C4DO3	Angle by which the cell x axis is oriented with respect to local vertical
C3FLY	Data taken on the fly or in discrete mode?	C4EDEC	Declination of source for EPOCH
C3FOCUS	Focus observation?	C4EDEC2000	Declination J2000
C3INTT	Scan integration time	C4ELERR	DEL:Net El offset at start (inc.tracker ball setting and user correction)
C3LSPC	Number of channels per backend section	C4EPT	Type of epoch, JULIAN, BESSELIAN or APPARENT

Table 3 (continued)

C4FRQ	Secondary mirror chopping period	C7VREF	Velocity reference code; reference point for telescope & source velocity
C4FUN	Secondary mirror chopping waveform	C11PHA	Phase table: switching scheme dependent
C4LSC	Char. code for local x–y coord.system	C12ALPHA	Ratio of signal sideband to image sideband sky transmission
C4MCF	Centre moving flag (solar system object)	C12BM	Correlation bit mode
C4MOCO	Mounting of telescope; defined as LOWER/UPPER axes, e.g; AZ/ALT	C12CAL	Units of spectrum data
C4NS_ENCODER	Secondary mirror ns encoder value	C12CALTASK	Calibration instrument used (FE, BE, or USER)
C4NS_SCALE	Secondary mirror ns chop scale	C12CALTYPE	Type of calibration (THREELoads or TWOLoads)
C4ODCO	Units of cell and mapping coordinates; offset definition code	C12CM	Correlation function mode
C4OFFS_EW	Secondary mirror offset parallel to lower axis (East-West Tilt)	C12ETASKY	Sky transmission from last calibration
C4OFFS_NS	Secondary mirror offset parallel to upper axis (North-South Tilt)	C12ETASKYIM	Frontend-derived sky transmission
C4PER	Secondary mirror chopping period	C12ETATEL	Telescope transmission
C4POSANG	Secondary mirror chop position angle	C12GAINS	Gain value (kelvins per volt or equivalent)
C4RA2000	Right ascension J2000	C12GNORM	Data normalization factor
C4RADATE	Right Ascension of date	C12GREC	Raw data units per Kelvin
C4SM	Secondary mirror is chopping	C12GS	Normalizes signal sideband gain
C4SMCO	Secondary mirror chopping coordinate system	C12INFREQ	BE input frequencies [GHz]
C4THROW	Secondary mirror chop throw	C12NOI	Noise value
C4X	Secondary mirror absolute X position at observation start	C12REDMODE	Way of calibrating the data (RATIO or DIFFERENCE)
C4Y	Secondary mirror absolute Y position at observation start	C12SBRAT	Sideband ratio
C4Z	Secondary mirror absolute Z position at observation start	C12SCAN_TABLE_1	Begin scan table
C5IR1	Refraction constant A	C12SCAN_TABLE_2	End scan table
C5IR2	Refraction constant B	C12SCAN_VARS1	Names of the cols. of scan table 1
C5IR3	Refraction constant C	C12SCAN_VARS2	Names of the cols. of scan table 2
C6CYCLREV	Cycle reversal flag	C12TAMB	Ambient load temperature
C6MODE	Observation mode	C12TASKY	Ratio of signal sideband to image sideband sky transmission
C6REV	Map rows scanned in alternate directions?	C12TCOLD	Cold load temperature
C6SD	Map rows are in X (horizontal) or Y(vertical) direction	C12TSKY	Sky temperature at last calibration
C6ST	Type of observation	C12TSKYIM	Frontend-derived Tsky, image sideband
C6XPOS	In first row x increases (TRUE) or decreases (FALSE)	C12TSYSIM	Frontend-derived Tsys, image sideband
C6YPOS	In first row y increases (TRUE) or decreases (FALSE)	C12TTEL	Telescope temp. from last skydip
C7AP	Aperture	C12VCOLD	IF V_COLD
C7FIL	Filter	C12VDEF	Velocity definition code - radio, optical, or relativistic
C7HP	FWHM of the beam profile (mean)	C12VHOT	IF V_HOT
C7NIF	Number of IF channels	C12VREF	Velocity frame of reference - LSR, Bary-, Helio-, or Geo-centric
C7PHASE	Lockin phase	C12VSKY	IF V_SKY
C7SEEING	Seeing at JCMT	C13DAT	Reduced photometric value or Spectrum data or Reduced data
C7SEETIME	SAO seeing time (YYMMDDHHMM)	C13ERR	Standard error
C7SNSTVTY	Lockin sensitivity in scale range units	C13RAW_ERROR	Raw error is accumulated over the scan, so store at end scan
C7SNTVYTRG	Sensitivity range of lockin	C13RAW_ERROR_OP	Raw (out of phase) error also to be stored at end scan
C7SZVRAD	Number of elements of vradial array	C13RESP	array of responsivities
C7TAU225	CSO tau at 225 GHz	C13SPV	Individual beam integrations or Raw data
C7TAURMS	CSO tau rms	C13SPV_OP	Raw out of phase data samples in each phase
C7TAUTIME	CSO tau time (YYMMDDHHMM)	C13STD	Phase data standard deviation
C7TIMECNST	Lockin time constant	C14PHIST	List of xy offsets for each scan

NRAO and JCMT on the definition here as the three elements at NRAO referred to the horizontal and vertical position and the position angle with respect to the horizontal axis. Documents and source code from JCMT indicate these items were not used and are duplicates of items C6DX, C6DY and C6MSA.

- C4IX C4IY are the coordinates of the telescope as measured by the encoders. This information was not recorded by JCMT.
- C6XZ C6YZ specify the position of the map origin. These coordinates are not stored at JCMT as the map is defined in terms of offsets from the specified tracking center.
- C7FW is the beam full width at half maximum in arcsec at NRAO but at JCMT the item used is C7HP and most JCMT data files do not seem to set it.
- C11* Most sub-mm telescope divide an “observation cycle” into a series of “phases”, where the separate phases represent different states (for example, on-source, off-source, cal-diode on, cal-diode off). The relevant information is stored in class 11, the “phase block”. At JCMT

C11VD specifies the names of the columns of the phase table information stored in C11PHA where the dimensionality is specified by C3NSV (number of phase table variables) and C3PPC (number of phases per cycle). NRAO use C11VV to store the values of a single switch state and the phase table is C11PHT.

- C12IT is the total time spent collecting data, including any blanking time. This item was not used at JCMT.
- C12NI C12SPN indicate the number of integrations (or channels for spectral line data) and the starting point (channel) in the data vector. UniPOPS used this information to limit display and processing to a sub-set of the data array and to associate those limits with the data on disk. JCMT data did not need these quantities for any similar purpose.
- C12ST C12RMS are the computed source temperature and the RMS value. The JCMT online observing system did not calculate these.
- C12SP is a description of the polarization type and angle encoded in an eight character field. This item was not used at JCMT.

Table 4

Items of the GSDD model only defined for use at NRAO.

C1DLN	Length of data [bytes]
C1HLN	Length of header [bytes]
C1SNA	Source name
C2PC	Pointing constants(4)
C2UXP	User Az/RA pointing correction [arcsec]
C2UYP	User El/Dec pointing correction [arcsec]
C4DO	Descriptive origin(3)
C4IX	Indicated X position [deg]
C4IY	Indicated Y position [deg]
C6XZ	X Position at map reference position zero [deg]
C6YZ	Y Position at map reference position zero [deg]
C7FW	Beam fullwidth at half maximum [arcsec]
C11TP	Phase table
C11VV	Variable value
C12DX	Delta X
C12IT	Total integration time [sec]
C12NI	Number of integrations
C12OO	O2 opacity
C12OT	O2 temperature [K]
C12RMS	RMS of mean
C12RP	Reference point number
C12SP	Polarization
C12SPN	Starting point number
C12ST	Source temperature
C12WT	H2O temperature [K]
C12X0	X value at the reference point

C12RP C12X0 C12DX These give the reference channel, X value at the reference channel, and spacing along the X axis. For spectral line data, the X axis is velocity at each channel and for continuum data this is position along the direction of telescope motion for each continuum integration in that scan. These items were not used at JCMT.

C12WT is the water temperature. Not measured directly at JCMT during this period.

C1200 C120T is the oxygen opacity and temperature. Not measured at JCMT.

The following items are found in both implementations. Some discrepancies are noted as follows.

C1DP This is used to specify the precision and data type used to store the instrument data. This was used in early variants of the JCMT system but was later dropped due to the data format being able to report the data type associated with each item.

C10NA JCMT used this as a synonym for C10BS and instead added C10NA1 to indicate the name of the support scientist for the observing run and C10NA2 to indicate the name of the telescope operator.

C1STC specifies the type of observation. At NRAO this was defined as two 4 character strings defining the type of data and the observing mode. For example LINEPSSW for a position-switched spectral line observation. JCMT used this item solely to define the switching mode (position-switched, beam switch, frequency switch and no switch), preferring instead to use C1FTYP to specify the frontend type (heterodyne versus bolometer) and C1BTYP to indicate the backend type (line versus continuum). In later versions JCMT dropped C1STC completely, preferring to specify the switching mode explicitly in C6MODE.

C3UT is the Universal Time in decimal hours, yet at JCMT it was decided that this should refer to UT1.

C4CSC The JCMT coordinate system codes (Kenderdine, 1985) were a two-character code such as RB to indicate B1950 RA/Dec. NRAO used a completely distinct set of codes using eight characters; RB being equivalent to 1950RADC. The full list is shown in Table 5.

Table 5

Coordinate codes used at NRAO and JCMT for item C4CSC.

	NRAO	JCMT
Galactic	GALACTIC	GA
B1950 RA/Dec	1950RADC	RB
Epoch RA/Dec	EPOCHRADC	RD
Mean RA/Dec	MEANRADC	–
Apparent RA/Dec	APPRADC	–
Apparent HA/Dec	APPHADC	EQ
1950 Ecliptic	1950ECL	EC
Epoch ecliptic	EPOCECL	–
Apparent ecliptic	APPECL	–
Azimuth/Elevation	AZEL	AZ
User defined	USERDEF	UD
J2000 RA/Dec	2000RADC	RJ
Indicated Ra/Dec	INDRADC	–

C5IR Whilst JCMT did use C5IR to report the mean refractive index, the JCMT implementation also stored the three refraction constants defined in the JCMT refraction model (Kenderdine et al., 1988) as C5IR1, C5IR2 and C5IR3.

C6FC is the coordinate frame to use when offsetting, which allows the offset system to be distinct from the telescope tracking center. At NRAO this was an eight character string made up of two four character components (polar versus cartesian and step versus scanning). At JCMT this item was an integer indicating which coordinate frame should be used with options of AZ = 1, EQ = 3, RD = 4, RB = 6, RJ = 7 and GA = 8 (using the same definition explained in item C4CSC).

C7VRD is defined as the velocity definition and reference at NRAO, by combining two four character strings into a single item. It describes how the source radial velocity, C7VRD, should be interpreted. The allowed velocity definitions were RADI (radio), OPTL (optical) and RELV (relativistic). The velocity reference was allowed to be LSR (Local Standard of Rest), HELO (Heliocentric), EART (earth), BARI (barycentre) and OBS (observer). At JCMT this item was reserved entirely for the velocity definition but deprecated in later versions. The velocity definition was later defined in C12VDEF (allowed values being RADIO, OPTICAL and RELATIVISTIC) and the standard of rest indicated in C12VREF (allowed values being TOPO(centric), LSR, HELI(ocentric), GEO(centric), BARY(centric) and TELL(uric)).

3. National Radio Astronomy Observatory

The 12-m Telescope was upgraded to write GSDD format data in the summer of 1986 (Brown and Stobie, 1986; Stobie, 1987); requiring that the data analysis system was also updated to understand it.

In 1988 the NRAO decided for a number of reasons to unify the data reduction systems for its single-dish telescopes: the Tucson 12-m, and the Green Bank 300 ft and 140 ft telescopes. At the time all three telescopes used what looked like a very similar data reduction system, the People Oriented Parsing Service (POPS; Hudson, 1982). But, at the code level the applications in Green Bank and Tucson had been diverging rapidly since the early 1980s, essentially due to the different computer architectures at the two sites (early 1970s Modcomps in Green Bank and mid-1980 DEC VAX's in Tucson). The NRAO wanted to reduce maintenance costs as different staff were needed to maintain and develop each version. The NRAO was also migrating to Unix-based (primarily Sun) computers, a change that would require major modifications to POPS. The unified analysis system, UniPOPS (Salter et al., 1995,

1503.007), was started in early 1989 and first released to users in early 1991 (vanden Bout, 1991). Although the 300 ft collapsed in 1988 (vanden Bout, 1990), and the 140 ft was decommissioned for routine general-user astronomy in 1999, UniPOPS is still in use today at some level by the University of Arizona who took over the running of the 12-m telescope in 2004.

Since the majority of the FORTRAN code that was modified to create UniPOPS came from the 12-m version of POPS, the UniPOPS developers decided that UniPOPS would also inherit with little modification the underlying data structure and export formats of the 12-m version of POPS. Internally, the UniPOPS data structure used to hold the data is the same as the 12-m version of the GSDD data model with additional items added as described in Section 2 and a new Class 9 to hold the values that were unique to the Green Bank telescopes. The UniPOPS file format is nearly identical to the POPS Data File (PDFL) format in use at the 12-m prior to UniPOPS. This data structure and file format were used by UniPOPS to hold data at all stages of processing (raw, calibrated, averaged, smoothed, etc.). Adapting 140 ft and 300 ft data to use the GSDD data model was relatively easy, good evidence that GSDD was indeed a rather versatile and useful standard. Additional details on the export file format used by UniPOPS and the format of the raw data written at each NRAO telescope are provided in the next section.

Two modifications were made to the PDFL files when they were incorporated into UniPOPS, solely to boost the performance of the system. The binary representation was changed from that of the DEC architecture to that of Sun workstations. The index that was at the start of a PDFL file was extended to include such items as the sky location and observing frequency to expand the items that could be efficiently searched in UniPOPS. To distinguish the UniPOPS Sun-specific exported files from VAX PDFL files, the NRAO developers changed the name of the export format to Single Dish Data (SDD) format. Other than a modification that expanded the capabilities of the index section of the NRAO SDD files, the SDD format adopted for UniPOPS (Fig. 1) remained unchanged until UniPOPS was retired at the NRAO in the mid-2000s. By the late 1980s, users of the NRAO telescopes were very interested in seeing a FITS format implemented for the NRAO's single-dish telescopes (see Section 5.7). By the mid 1990s, UniPOPS could export and import data in Single Dish FITS (SDFITS) and SDD formats, as well as many of the historical NRAO formats. The NRAO found that very few users went away with SDFITS format; most took home SDD files. Since users were installing UniPOPS on their home computers, they probably found transporting SDD files more convenient than using SDFITS files. It was probably very rare that a UniPOPS SDD file was imported into another analysis system. For example, a separate utility was developed that would prepare data files that could be imported into the CLASS package. Furthermore, when SDFITS was released, few FITS readers at the time could actually usefully import binary tables. Thus, we suspect that frequent observers grew into the habit of avoiding SDFITS files.

3.1. SDD file format

The layout of an SDD file is shown in Fig. 1 (see also Salter et al., 1995). The file consists of 3 parts: a bootstrap record, the index, and the data. An SDD file has an integer number of records where the size of a record is given in the bootstrap. Each section (index and data) is also an integer number of records. Within the data section, each individual “scan” is one instance of the data structure that evolved from the original GSDD data model. Each scan occupies an integer number of records within the file (any extra space is padded with zeros). An SDD file can hold both spectral line and continuum data. The type of data is indicated by the C1STC value found in the data for each scan. The order and type of the values in the

<p>Bootstrap</p> <p># Records in index # Data records following index Bytes per record # bytes per index entry # index entries used Update counter Type of SDD file Version</p>
<p>Index</p> <p>Start record # for current scan Last record for current scan Horizontal and Vertical coordinates Source name and scan number Freq resolution or slew rate Rest frequency or integration time LST Observing mode Record + phase Position code</p>
<p>Scans</p> <p>...</p>

Fig. 1. Layout of a UniPOPS data file. The concepts are similar to those used in the GSD format (Fig. 2). The bootstrap field describes the basic layout of the file and the index indicates where each of the scans are located in the file. A key difference between GSD and SDD is that GSD contains a single observation whereas an SDD file contains many observations for a single science program.

bootstrap record and within each index entry are set by the version number recorded in the bootstrap. The update counter item in the bootstrap record was an integer that was incremented each time the file was modified. This was used at the 12-m where the telescope control system was writing to multiple SDD files while one or more running UniPOPS sessions were reading from the same set of SDD files. This is not a self-describing format like FITS.

The bootstrap record contains information used to read the index records. The size of the index entry and record were chosen so that there are an integer number of index entries in each record without any extra space. The index record is read into memory in UniPOPS when an SDD file is opened and the copy in memory is kept in sync with the contents of the file as changes are made. Data selection in UniPOPS only uses the fields in the index. Every scan in the file must have an entry in the index section. Empty index entries have zeros for the start and last record numbers. The current largest index number in use is indicated in the bootstrap. If the data query involved the index associated with one of the SDD files being written by the 12-m during observing, then the update counter value in the bootstrap record on disk was checked. When a change was seen in that value then the copy of the index in memory was regenerated from the data file before the data query was done.

Each index entry indicates where the associated scan data starts and ends. The scan data consists of a preamble, which is 16 short integers giving the number of classes and the starting 8-byte location in the header where each class of header words started. Within each class, the type and order of each value is fixed. The C1HLN value gives the length of all of the header values. Over time, new items were added to the ends of some classes so that UniPOPS retained the ability to read previous versions of the SDD

format by not attempting to read header words past the end of a class as indicated by the values in the preamble and C1HLM. These new items are the differences between the NRAO and JCMT versions of the GSDD data model mentioned in Section 2. Those differences grew over time as needed by NRAO to accommodate new instruments, observing techniques and reduction methods. All numerical values in the header are stored as 8-byte floats. All string values are stored as multiples of 8 characters, depending on the specific value. The data vector immediately follows the header. The data are always 4-byte floats.

In order to accommodate spectral line and continuum data within the same structure and minimize the amount of space needed to store the associated header, some header values have 2 meanings depending on the type of data. This is most obvious in class 12, where the associated X axis is described. For spectral line data the X axis is the frequency or velocity at each channel. For continuum data, the data vector is a series of regularly sampled data (each sample is one integration) so the X axis is related to the position on the sky as the telescope is slewed. UniPOPS was started either in spectral line mode or continuum mode and would need to be restarted to switch modes. It was never possible to work on both continuum data and spectral line data within the same session of UniPOPS so typically a single SDD file only contained one type of data although that was not required by the file format.

3.2. SDD usage

UniPOPS dealt directly only with SDD format files. An SDD file could contain raw data, individual integrations and calibrated data. When writing to an SDD file, UniPOPS could extend that file by appending to the end or it could overwrite existing data in the file provided that the size of the scan being overwritten was at least as large as the scan being written. In either case, the appropriate index entry was updated. In the case of appending to the file, the next index location after the current end as indicated in the bootstrap record was used. The index entries do not need to reflect the order that the data appear in the file, although that typically is the case. If a user tried to overwrite a scan with a scan with more channels UniPOPS would append the new scan to the file, replace the index entry for the original scan with an appropriate index entry for the new scan, and replace the original scan records in the SDD file with zeros.

UniPOPS provided observers with access to their raw data in near real-time. For the 12-m this was direct access to the current set of SDD files being written by the telescope control software. Multiple files could be written at the same time, depending on the backend, and UniPOPS could access the desired data from any of those files while the data was being taken. For long observing sessions multiple versions of each backend-specific file were written. The 12-m also provided SDD files containing system temperature across the bandpass for each scan. UniPOPS provided separate methods for accessing that calibration data but the file format was identical to all other SDD files. For the 140 ft, the raw data was written in the original telescope format produced by the Modcomps. This raw 140 ft telescope format predates the GSDD data model. A conversion step to the NRAO version of the GSDD data model was necessary for UniPOPS to use that data. While observing, that conversion step happened on demand within UniPOPS. Access to the raw 140 ft data within UniPOPS could be done remotely by an observer running UniPOPS at their home institution. The UniPOPS user could then choose to save that raw 140 ft data directly to disk in an SDD format file or they could process the data and only save those scans to disk. A separate data conversion tool was also provided to convert an entire observing session at the 140 ft from raw telescope format data to an SDD

format file which could be read directly by UniPOPS without any network connection to the raw data.

SDD format files could be used interchangeably for input and output by UniPOPS. Typically a raw, uncalibrated data set was used as input and the user would save processed spectra to a separate SDD file. UniPOPS users could choose to save their data to disk at any stage of processing. Any single SDD file could contain raw, calibrated, or reduced data in any combination. Typically most users kept the raw data separate from the processed data as that made it simpler to keep track of what had been done. A single output SDD file often contained the same data at different processing steps. The UniPOPS user needed to keep track of what had been done to the data as no processing history information was associated with data either internally or in the SDD file.

With the interactive UniPOPS environment, users had the ability to modify any of the GSDD data model items (header values) for any scan. These header values were referenced by the UniPOPS interpreter using slightly more readable names (e.g. C1SNA is OBJECT in UniPOPS). The UniPOPS Cookbook (Salter et al., 1995) uses those more readable names to reference the GSDD data model items. Internally, the compiled code that comprises UniPOPS (mostly fortran) uses the original GSDD data model names (known at the JCMT as the “NRAO” names).

The number of scans that an SDD file can contain is set by the size of the index section. Scripts were provided with UniPOPS to expand an existing SDD file if more index space was necessary. UniPOPS could not read or write SDFITS directly. Separate conversion tools were necessary to produce and consume SDFITS. Conversion tools were also provided for historical NRAO formats including the PDFL format used at the 12-m prior to UniPOPS.

Archives from both the Green Bank 140 ft and Tucson 12-m telescopes exist. For the 12-m, there are about 200 GB of archived SDD format files. The archive from the 140 ft consists entirely of telescope format files. The current Green Bank single dish analysis package, GBTIDL (Marganian et al., 2006, 1303.019), can read archived SDD files. GBTIDL uses SDFITS as its primary data format.

4. James Clerk Maxwell telescope

4.1. Requirements

During the development of the JCMT software libraries at the Mullard Radio Astronomy Observatory, a number of options were considered for the raw data file format. Two obvious options were available in the astronomical community in the form of the Flexible Image Transport System (FITS; Wells et al., 1981) and the Starlink Hierarchical Data System (HDS; Disney and Wallace, 1982; Jenness, 2015, 1502.009).

FITS was discounted as the primary data format because of the large amount of overhead required to format the header information when writing files and the inability of the format (at that time) to store more than one data array or table in a file. FITS files at the time were not capable of storing binary tables and ASCII tables were all that was possible (Harten et al., 1988) and those were not standardized until 1987. It was also felt that the DEC Backup Utility was more reliable for transport and archiving than using a specialist FITS tape format. Whilst the FITS community would eventually support multiple data arrays (Grosbøl et al., 1988) and binary tables (Cotton et al., 1995), it was not possible to wait for that to happen.

HDS was discarded for I/O efficiency reasons and the inability for the entire file to be mapped into memory in one operation. Additionally it was felt that the HDS library API required too many calls to do simple tasks, and although these calls could be wrapped in higher level subroutines, the overhead associated with the many lower level calls would be too high. One further option was to use

<p>File Description</p> <p>Version Maximum number of items Number of items Start and end of data segment Comment File Size</p>
<p>Item Descriptors</p> <p>Array item? Name (and length of name) Unit string (and length of unit) Data type Location in data segment Number of bytes in data segment Number of dimensions Dimensions (by scalar item reference)</p>
<p>Data</p> <p>...</p>

Fig. 2. Layout of a JCMT GSD data file. The file descriptor indicates where the data starts and the number of items in the data. The item descriptors describe each of those items and where they are located in the data segment. The size of each dimension in array items is defined in terms of other scalar items. The file was pre-allocated by the acquisition system at the start of the observation rather than being continually extended.

the NRAO 12-m file format (PDFL) but that also suffered (from the JCMT perspective) from serious I/O issues and could not be used on the acquisition hardware initially targeted for JCMT.

The computer used during testing and commissioning in 1985/1986 was a VAX 11/730 with 4 MB of RAM and which had severe performance limitations. This was upgraded to a MicroVAX with 16 MB of RAM just before operations started at JCMT in 1987 but performance was the key design driver: the control system was required to minimize the overheads in data capture and therefore maximize the observing time. The VAX Record Management System (RMS) was the basis of all standard VAX records-based file handling. The performance of this system was not suitable for real-time operation as it was not acceptable for the system to pause while opening or closing or extending a file in the middle of the data collection. Furthermore, limits on the maximum record length in RMS meant that additional complexity would be required when writing out data from long observations. The JCMT disk I/O approach was instead designed to utilize the VAX System Services library that allowed a program to map a section of virtual memory (referred to as a Global Section) and then manage the scalar and array data in that memory directly in the program. This was very fast and did not cause the problems encountered with RMS. Performance benchmarks on a VAX 750 (Fairclough, 1988) suggested that I/O operations using RMS were approximately five times slower than using a Global Section. The use of a Global Section also allowed other applications read access to the contents of the file whilst it was being written and also meant that the data already acquired would be usable even if the acquisition software crashed mid-observation.

These requirements led to a new disk format being devised and an associated I/O library written which used the GSDD data model, but used Global Sections for writing to disk. This led to

the JCMT implementation of the library being known as the Global Section Datafile System (GSD; Fairclough, 1988).⁵ The file format design was influenced by the NRAO idea of a self-describing GSDD implementation and also the concept of an “in memory data base management system”⁶ from the MON library being used in the JCMT control system.⁷ JCMT adopted the GSDD data model in the hope that downstream the data reduction systems could be compatible through the shared metadata conventions.

Unlike the NRAO PDFL/SDD files which grow throughout the night as more data are taken, a JCMT GSD file was only required to store data from a single observation. At JCMT an observation was defined as data being taken in a single switching mode at a single tracking position with a single instrument frontend/backend combination. A single observation could include multiple offsets in a grid or on-the-fly map and includes the full map area, rather than a single row or column. This approach resulted in more files to track in a night but was felt to simplify the acquisition software (each observation was completely independent of what had gone before), and make it easier to distribute subsets of a night’s data amongst different observers (a pre-requisite for flexible scheduling) and simplify queries for individual observations from the data archive. Of course, this meant that the data reduction packages had to do more work to collate related observations into a coherent data set as they now worked with many independent files rather than being able to treat a night’s observing as a single coherent entity.

4.2. File format design

The layout of a JCMT GSD format file is shown in Fig. 2 (see also Fairclough et al., 1987). The file is split into three segments: the file descriptor, the item descriptors and the data itself. The file descriptor contains a general description of the file indicating its version, the number of items written and the start position of the data array. The item descriptors define each of the items in terms of the label and units and the position within the data array. The data itself is a single block at the end of the file following the item descriptions; the item descriptions having defined exactly where in the data array a relevant item is located and how many bytes in the data array it occupied.

For array items (GSD supported up to 5 dimensions), the identity of each dimension is specified in terms of the number of a scalar item. This allows the label and unit to be associated with each dimension of an array item in addition to the size of the dimension. A negative number of dimensions indicates that an item is a scalar that defines an array dimension. For example, the C11PHA array entry in a JCMT DAS spectrum (Bos, 1986) is dimensioned according to the scalar items C3NSV, the number of phase table variables, and C3PPC, the number of phases per cycle. The item descriptor for C11PHA would therefore contain a dimensions array of two elements containing the item numbers (position in the item descriptor section) for C3PPC and C11PHA. A library user would then look up those two items to determine the dimensionality of C11PHA.

⁵ In retrospect, the similarity of acronyms between GSD and GSDD – two quite separate concepts – was rather unfortunate. The naming of the library as GSD eventually led to JCMT users referring to the files as being of “GSD format” and it being assumed that “GSDD format” was an historical artifact.

⁶ A database system designed to work entirely in memory rather than requiring lots of disk I/O. See also http://en.wikipedia.org/wiki/In-memory_database.

⁷ The MON library was a shared memory system, based on Global Sections, in use at the JCMT to allow the individual control system tasks to easily share state information. It was the precursor to the Noticeboard System (NBS; Lupton et al., 1995).

This file design resulted in a fully self-describing system where there was no requirement for items to be grouped by class in the file and no requirement for the order of items to be predetermined (an issue for the NRAO implementation where the order was specified in a compiled include file requiring that the order of items within a class be preserved and also that new items could only be added to the end of a class). A user of the format could either request an item by number or request an item by name. Storing the units with the data also allowed for more flexibility in data model representation at the expense of more logic in the application code that might have to understand unit conversions. Application software would use the file version number to decide which variant of a data model was present in the file. At JCMT this became important as the system evolved in the first few years.⁸

The JCMT format implementing GSDD supports the standard Fortran data types of byte, word, logical, integer, real, double and character strings, and uses VAX floating point format (see [Payne and Bhandarkar, 1980](#), for more information on VAX floating point format). To simplify the format, character strings have a fixed size of 16 characters, item names are fixed at 15 characters and unit strings are fixed at 10 characters. The format supported the concept of a “null” value by reserving the most negative value of each data type for that purpose (using a single space as the null character value and false as the null logical value). Additionally, the JCMT GSD library supported data type conversion, allowing a user to request a value in a different type to how it was stored natively in the file. This was an important aspect of the library interface, simplifying code required by the reduction software, enabling users of the library to request data in the form most suitable for them. This feature was influenced by earlier work on the Starlink Catalog Access and Reporting (SCAR) relational database management system for astronomical catalog handling ([Walker et al., 1990](#)).⁹

4.3. Format usage

The JCMT took data in the GSD format for all instruments (heterodyne and continuum) from the telescope commissioning (circa 1986) to the delivery of SCUBA in 1996 ([Holland et al., 1999](#)). The GSD format continued to be used for heterodyne instruments until the delivery of the new ACSIS correlator in 2006 ([Buckle et al., 2009](#)). SCUBA and newer instruments wrote data in the Starlink extensible *N*-dimensional Data Format (NDF; [Jenness et al., 2015](#)), although SCUBA’s data model was not precisely copied for ACSIS and SCUBA-2 ([Holland et al., 2013](#)) data. NDF had a key advantage that it was being used throughout the Starlink Software Collection as the primary data format ([Allan, 1992](#)). Writing data using NDF meant that JCMT data files had immediate access to all the visualization and analysis applications already available to the community such as KAPPA ([Currie and Berry, 2013, 1403.022](#)). Many of the performance worries from the mid-1980s concerning the overhead associated with the HDS library were no longer relevant in the late 1990s.

The GSD data access library was a VAX-specific library ([Hewish et al., 1986; Fairclough et al., 1987](#)) written in Fortran and making extensive use of VAX system calls. When the last instrument moved off of the VAX/VMS data acquisitions computers the format could no longer be used and was retired. There was little motivation to port the data model to the newer instruments as it was clear by this time that GSDD had not succeeded and that

NDF would be more useful to the JCMT user community despite the resulting necessity for new ways of describing raw JCMT data. There was seen to be no advantage to moving the GSDD class and item names to the newer NDF-based raw data models. Indeed, as described in Section 5.1 the standards effort was dead and it was not obvious to later users and software developers from where such opaque names had originated.

The GSDD data files are archived at the Canadian Astronomy Data Centre and approximately 440 000 GSD format files are in the archive, totaling approximately 30 GB. In order to access these data files on a Unix system a new read-only version of the GSD library was written in C ([Jenness et al., 1999, 1503.009](#)) and integrated into the standard data reduction tools SPECX ([Padman, 1990, 1993, 1310.008](#)), COADD ([Hughes, 1993, 1411.020](#)) and JCMTDR ([Lightfoot et al., 2003, 1406.019](#)). The GSD format is relatively simple and the main complication in the new C (and later pure Java) implementations was the conversion of VAX floating point format to IEEE format. Furthermore, computers were sufficiently more powerful by the time the Unix version was written that there was no need to use memory mapping; the entire contents of a file is read into memory. GSD was solely used as a data acquisition format at JCMT, with there being one application on the VAX to enable the editing of contents if there was a need to fix some metadata. Data reduction applications never wrote data out in GSD format and the Unix port of the library did not have the ability to write a GSD file. A Perl interface to the Unix C GSD library ([Jenness et al., 1999](#)) was implemented to allow the preview of spectra for remote observers when doing flexible scheduling ([Jenness et al., 1997](#)).

The GSD format files are no longer part of the publicly available query system at the CADC. This was driven by funding constraints when the CADC system was re-engineered to use a common internal data model ([Redman and Dowler, 2013](#)) and a requirement that federal interfaces be compliant with Canadian language regulations. The JCMT Science Archive (JSA; [Economou et al., 2015](#)) therefore does not contain GSD data. To extend the useful life of the GSD format observations and to make the observations available to the widest possible community through the JSA and the Virtual Observatory, there was a project to convert the GSD heterodyne files archived at CADC to the modern ACSIS format ([Jenness et al., 2007](#)) such that they can be processed (baseline subtracted, co-added, placed into data cubes) using the standard JCMT data reduction pipelines ([Jenness et al., 2015b, 2008](#)). The SMURF data reduction application ([Jenness et al., 2013, 1310.007](#)) contains the ability to read GSD files and migrate them to the modern format ([Balfour, 2008](#)). The GSD files from the earlier continuum instruments, such as UKT14 ([Duncan et al., 1990](#)), will remain in the archive although they will not be visible through the JSA interface.

5. Retrospective

GSDD has had a mixed history and in this section we look back on the good and bad of GSDD.

5.1. The hidden standard

The key failure of GSDD was that most of the developers and users of the format did not realize that it was a standard and therefore there was no impetus for the respective observatory staff to continue to communicate as systems evolved. The initial developers of the JCMT system did not maintain the data acquisition software in Hawaii and, at NRAO, the lead developer of the 12m GSDD system left NRAO before the end of the 1980s. Interviewing staff from NRAO and JCMT following the respective implementations of GSDD compatible systems, it was very rare for anyone to remember that there was an intent for a standard to

⁸ Version 4 of the JCMT data model was the first stable implementation, released late in 1988, and the final version was release 5.3. It is version 5.3 that is documented here.

⁹ HDS also supported automatic type conversion ([Lupton, 1989](#)). The authors are not sure when equivalent facilities were added to FITS I/O libraries.

be in place. As can be seen from the evolution of the JCMT class names and the divergence of data models, items were added to the respective data formats without any communication between the nominal GSDD partners. 12-m development continued with tweaking of the acquisition and reduction formats independently. As the GSDD model evolved, the NRAO implementation resulted in 24 items that are not present in the JCMT implementation (not including the classes explicitly specified to be locally defined), and 154 items that are defined by JCMT but not defined by NRAO.

The goal of unified data reduction software understanding GSDD never materialized. Indeed, interoperability usually occurred, if at all, by exporting the files into a completely different format that could be understood by CLASS.

In conclusion, it is impossible for a standard to survive as a standard if no-one knows they are using a standard; the effort must be made to broadcast and properly document the effort within the wider community as part of the original development.

5.2. A model must define the values and units

Whilst the data model provided a reasonable baseline for how to name items, it broke down almost immediately when it came to storing values in those items. For example, the coordinate codes, C4CSC, were not standardized, the reference frame coordinate code, C6FC, had a whole different concept at JCMT and NRAO and, indeed, the specification of how observing grids were defined at both observatories differed despite sharing the same underlying item names. If an attempt had ever been made to transfer data between observatories special code would have to be written to import the data, removing most of the gains of a shared model. The was due to a failure to fully develop the standard prior to starting its implementation. In some sense, the development/initiative was not initiated with/subjected to proper project management procedures as we currently understand them.

5.3. Embrace flexibility

A major advantage of GSDD is that the standard actually allowed sites to alter the format and data model as they saw fit. NRAO sites using the NRAO file format had to follow some minor rules in order to guarantee that any other site's GSDD reader could still manage the files. Such rules as: do not touch the pre-defined keywords (which were to have predefined byte sizes and were always to be in a certain order at the start of a class), you are free to add new keywords to any class but only at the end of the pre-defined section of each class, modify class 9 for your particular telescope, modify class 10 as convenient, and be sure to use the well-defined pre-ambule to designate the byte at which every class begins. We maintain that GSDD was actually a very good implementation for its time because these rules could be easily adhered to while simultaneously giving sufficient versatility to each telescope. The JCMT GSD file format encouraged far more flexibility than this since the constraints on class keyword ordering were removed and software did not need to compile-in knowledge of where the individual items were meant to be located in the file. This led to much more explosive and dynamic modifications to the data model in the early years of telescope operations.

5.4. Too much flexibility is not always good

The alternative view is that allowing a class 9 for particular telescopes to use as they liked was an impediment to standardization. In many cases an item being added to class 9 could have been made generically useful with some discussion or may well have been very similar to an item already in use by another telescope. The

use of the escape hatch class should have been treated as a last resort after debate within the community. Only when it was determined that a particular item was unique for a telescope should class 9 have been used, and even then a case could be made that it would still be more helpful for the item to have been placed in the correct class and documented as such, to help the next telescope that required similar functionality. In some sense this was the approach used at JCMT (without the communication effort) which was simply to ignore class 9 completely and add items to the “correct” classes without discussion in the wider community. As the JCMT model evolved it was soon clear that many of the items were not relevant to particular observing modes. Rather than attempting to always write them out regardless, it was decided to treat them as true optional items. This difference between JCMT and NRAO may have been driven by file format design given the difference in approach between the self-describing GSD and the more statically defined PDFL. In retrospect it would have been better to attempt to standardize even at the expense of having to spend more time in discussion.

5.5. Clear separation of model from file format

GSDD benefited by explicitly defining the data model for single-dish observing distinct from bytes on the disk. However, whether by accident or design, the GSDD standard resulted in multiple software implementations writing the data to disk in different formats and using different techniques. The JCMT GSD format was never written on anything other than a VAX but the NRAO format migrated from PDFL to SDD going from VAX to Unix. Unfortunately these multiple formats also meant that data reduction software wishing to read the data would need to implement multiple file readers. The reality is this work was never done. Given the focus of both institutions on the use of GSDD in data acquisition using different hardware platforms and different performance constraints, this split is not surprising, but it is interesting to contemplate how interoperability would have improved if the standards effort had also included the definition of an interchange format. Being easily able to compare a JCMT spectrum with a NRAO 12-m spectrum from within the same data analysis package would have been extremely useful to the young sub-mm community.

5.6. A success apart

Despite the lack of communication between implementors and the drift in specifications, the GSDD format itself can be thought of as a success when the uses of the format are looked at independently. The JCMT GSD format was used for many years and files in this format are still available. The related format continues to be used at the 12-m Telescope.

5.7. Feeder for SDFITS

GSDD was a very early attempt for independently funded and operated observatories to agree on a shared data model. The goals of true interoperability of raw telescope data amongst multiple data reduction software packages was an important goal that was ahead of its time. Arguably the key outcome of GSDD was that it motivated people to work together towards a shared data format based on FITS. The GSDD experience fed into a 1989 workshop held at Green Bank in late 1989¹⁰ that discussed how the community could migrate to a single-dish FITS format. This was a key motivator for the adoption of binary tables into the FITS standard (Cotton et al., 1995) and ultimately led to the SDFITS standard (Garwood, 2000).

¹⁰ <http://fits.gsfc.nasa.gov/dishfits/dishfits.8910>.

5.8. Communication

A failing of GSDD is that when developers had real, practical reasons to break a rule (e.g., needing a double precision word for a pre-defined keyword when the standard required single precision, a string needing 32 char instead of 16, changing the byte representation from that of a VAX to IEEE), a forum had not been set up that could negotiate modifications to the standard. This is unlike the FITS world where revisions to the definition have to pass through a standards group. A key lesson is that when a standard is set up, the agreement should go beyond the expectation that ad hoc conversations between staff at different observatories are a sufficient means of keeping the standard viable.

The JCMT GSD library was documented and stable and the UK had the Starlink Project (Disney and Wallace, 1982) to publish the software and data files to the UK community. However, access to that network from other countries, such as the US, was problematic, and hindered the spread of the software and prevented take up. Fears of lack of support also drove people to create their own in-house solutions.

Today, 30 years on, the Internet and the culture of open-source development make that much less likely and good ideas have a tendency to become distributed and generate a supporting community outside of the original developers that ensures its survival and growth.

6. Thoughts on the future

Many of the lessons exposed by the history of GSDD have already been learned in the 30 years since the key decisions were made and much improved communications infrastructure has changed the way that people work. The current debate on future developments of data formats for astronomy (see e.g. Thomas et al., 2015; Mink, 2015; Mink et al., in press) indicates that there is a desire within the community for a format that builds on the lessons learned using the FITS format to develop a format with more modern underpinnings. As noted in the debate described in Mink et al. (in press), representing data on disk is becoming a secondary concern relative to the discussion of data models. A data model can be serialized into many different transport and archive formats, and it is relatively easy to make applications flexible enough to be able to cope with these differences. Instead, it is much harder to deal with different data models and implementation efforts should concentrate on optimizing and generalizing the data model that is being used. This is, after all, the underlying *business logic* that enables science to progress. It may be true that all data models can be represented in a FITS file but that does not mean that a FITS file is the most compact or most efficiently accessed format. Changing the underlying file format used in astronomy may simplify infrastructure libraries and result in new abilities not available from within FITS. The easiest way to migrate people to a new format may well be to do it without people knowing what underlying format really is being used by their applications. As we move forward with discussions on data formats and look again at hierarchical approaches (e.g. Price et al., 2015; Jenness, 2015; Greenfield et al., 2015), these may adjust the way that people view data models. A hierarchical view is very different to a flat view and data modelers should not be constrained by how their models are represented on disk.

GSDD failed to unify the single-dish radio telescope community to use a single file format. Focusing on the data model as a first step was the correct decision at the time but it was poorly implemented with little buy-in from the people writing the software. Failing to agree on units, coordinate codes and the approach to adding additional keywords removed any chance of GSDD being a generically useful data model for the community. Ideally a GSDD

data model library should have been written to abstract the file format completely from the user, but this was all occurring before object-oriented programming was a common paradigm. If GSDD were being implemented now it would be obvious how to wrap data representing millimetre observations within object-oriented classes involving differing receiver types and observing modes.

Abstracting the data model from the underlying file format is an idea whose time has come. The Large Synoptic Survey Telescope data management system (Ivezic et al., 2008; Kantor and Axelrod, 2010) uses a *butler* to mediate file access. The user requests data from the system and the butler then pulls all the relevant data items together (from a database or from files or from a combination of the two) and instantiates an object representing that data. For LSST this *Exposure* class represents something relevant to an optical imager, but it could just as easily return an object that is relevant to millimeter observing.

7. Conclusions

The GSDD data model was used at NRAO and JCMT for many years but failed in its original goal of unifying single dish millimeter astronomy and simplifying data reduction software reuse. As data reduction packages have evolved it has become clear that the most important aspect of such packages is format conversion such that the software can map the external data model to an internal data model. It is very hard to motivate individual observatories to target a global standard for raw data without significant commitment and obvious return on investment. NRAO and JCMT made a solid attempt but could not maintain the momentum as other priorities intervened and staff involved in the effort moved to other projects. Recent examples where observatories have collaborated on a shared raw data format (e.g. MBFITS; Muders et al., 2006) has shown that this is possible but depends critically on the motivation of individuals and on available funding¹¹ Interoperability of reduced data products has significantly improved since the mid-1980s such that there is a general expectation that reduced data cubes will be viewable in general tools. By contrast, interoperability of raw data has remained a much more elusive goal, at least amongst the sub-mm radio telescope community.

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The source code for the JCMT GSD library (C, Perl wrapper, and Java) and the source code for UniPOPS are available from Github¹² and both are distributed under the Gnu General Public Licence. The JCMT GSD library is distributed as part of the Starlink software collection (see e.g., Currie et al., 2014, 1110.012). Some of the harder to find documents referenced by this paper have been collected and made available on Github at https://github.com/timj/aandc-gsdd/tree/master/support_docs.

¹¹ Ironically, the more money available the less chance there is an observatory will adopt a pre-existing system that might constrain their design decisions.

¹² UniPOPS at <https://github.com/nrao/UniPOPS> and JCMT GSD at <https://github.com/Starlink/starlink>.

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