Original version at http://iram-institute.org/medias/uploads/class-herschel-fits.pdf

IRAM Memo 2015-3
Importing Herschel-FITS into **CLASS**

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October, 21st 2015
Version 1.0

Abstract

Herschel/HIFI data were already readable by **CLASS** after conversion into specific FITS file by the HiClass task from HIPE. These FITS files are however not the ones served by the Herschel Science Archive as result of the standard data processing. The **CLASS** community thus requested the possibility to fill Herschel/HIFI archive science products directly into **CLASS**.

In a nutshell, the new filler automatically recognizes the Herschel/HIFI FITS level 2.0 and 2.5. The standard **CLASS** sections (`General, Position, Spectroscopy, Calibration`) are filled from the FITS header parameters. A dedicated Herschel section is added to the **CLASS** Data Format in order to attach HIFI specific metadata. The data are filled as one or several **CLASS** spectra depending of the FITS level and/or context (On-The-Fly, spectral survey, etc). The associated FLAG and LINE arrays are filled as associated arrays (new **CLASS** feature documented in a separate memo) to each spectrum data. This memo describes all these points in details.

Keywords: **CLASS** Data Format
Related documents: **CLASS** documentation, **CLASS** Associated Arrays.

Contents

1 Quick start guide

You can import Herschel-HIFI FITS files if you are using a **CLASS** version equal or newer than oct15. Older versions of **CLASS** will warn you about unsupported data and will give you hand back without importing anything.

1.1 Supported HIPE versions

The filler is able to import data created by versions[1] of the HIPE software equal or newer than 12. Older versions are rejected by **CLASS**. However, it is recommended to retrieve the latest Herschel-HIFI FITS files (version 14, expected mid-2016) from the Herschel Science Archive, as there were several fixes (*e.g.* missing keywords) added since the versions 12 and 13. This means the resulting spectra in **CLASS** will be incomplete (*e.g.* null values, in particular in the Herschel-HIFI section) or approximate for versions 12 and 13. If this happens, **CLASS** will issue warnings when it had to choose the default value for a parameter. Defaults are documented in the look-up tables in the Section 2.

1.2 Importing Herschel-HIFI FITS

Once you have installed a correct version of **CLASS**, importing Herschel-HIFI FITS is as simple as opening a **CLASS** output file and calling the command `FITS`, *e.g.*

```
LAS> file out myfile.hifi single
LAS> fits read herschel-hifi.fits
```

Depending on the observing mode and on the pipeline level used in the *Herschel Common Science System* (HCSS), **CLASS** will produce one or more spectra from a single FITS file. Once this is done, you can retrieve the spectra as usual in **CLASS**, *e.g.*:

```
LAS> file in myfile.hifi
LAS> find
LAS> list
LAS> get first
```

The first spectrum is stored in the `R` buffer and is ready for reduction with the **CLASS** analysis tools.

1.3 Observation header

The relevant metadata have been exported from the Herschel-HIFI FITS to the **CLASS** observation header, namely in:

- the General section in `R%HEAD%GEN%`,
- the Position section in `R%HEAD%POS%`,
- the Spectroscopic section in `R%HEAD%SPE%`,
- the Frequency Switch section in `R%HEAD%FSW%` if relevant,
- a subset of the Calibration section in `R%HEAD%CAL%`, and
- the new Herschel-HIFI section in `R%HEAD%HER%`, where the metadata specific to this instrument can be found.

A raw overview of the whole header can be displayed with the command `DUMP`. Each section can be listed (name and values) with the command `EXAMINE`. We present in the section 2 how these sections were filled from the Herschel-HIFI FITS headers.

[1] The version can be found in the header card `CREATOR`.

1.4 Associated Arrays

The spectra imported from Herschel-HIFI FITS are also one of the firsts to use the so-called *Associated Arrays* in the **CLASS** observation. These arrays can be found under the structure `R%ASSOC%`. **CLASS** can understand those special arrays (see below where the dedicated documentation can be found). In practice, the Herschel-HIFI spectra provides the usual intensity array (*i.e.* in the `RY` variable), but also 2 arrays of the same size (same number of channels):

- the `BLANKED` Associated Array is an integer flag array indicating if the `RY` values should be blanked out (1) or not (0), under the user choice. This array is similar the usual *bad* values in **CLASS**, except that the actual values (*i.e.* before blanking) are still available. The typical use of this array is:

```
LAS> LET RY R%HEAD%SPE%BAD /WHERE R%ASSOC%BLANKED%DATA.EQ.1
```

- the `LINE` Associated Array is an integer flag indicating if the `RY` values are in (1) or out (0) a spectral line window. If the option `/ASSOCIATED` is invoked with `SET WINDOW`, the command `BASE` will use this array (*i.e.* ignore channels in a spectral window) for baselining (see `HELP SET WINDOW` for details). Typical use is:

```
LAS> SET WINDOW /ASSOCIATED  ! Will use the LINE Associated Array
LAS> SHOW WINDOW             ! Check you will use the LINE Associated Array
LAS> DRAW WINDOW             ! Draw the LINE Associated Array on the spectrum
LAS> BASE                    ! Use the LINE Associated Array during baselining
```

Note that the *Associated Arrays* are removed by the commands that do not know how to process them. In this case, a warning is issued. This is being solved as the *Associated Arrays* are more and more integrated in **CLASS**. In order to know the current status, please check the dedicated documentation for your current **CLASS** version in the widget menu > Help > CLASS > Associated Arrays.

1.5 Setting the source velocity

The spectra are imported assuming a zero-valued velocity of the source in the LSR frame. This most probably implies that the line frequencies will appear redshifted. The standard use of **CLASS** is to deliver the frequency axis in the source frame. To stick to this use, you have to modify the source velocity for each spectrum early in the reduction process with the command `MODIFY VELOCITY` (see associated `HELP` for details). In order to help you, the source systemic velocity of the source provided in the HIFI observing setup by the user is imported into the variable `R%HEAD%HER%VINFO`. If its value is correct, the command

```
LAS> MODIFY VELOCITY R%HEAD%HER%VINFO
```

will shift the frequency axis to the rest frame of this velocity.

1.6 Going from T_A^* to $T_{\rm mb}$

In **CLASS**, the brightness scale is assumed to be expressed in T_A^* when the forward and beam efficiencies are equal. To check this, you can type

```
LAS> EXAMINE R%HEAD%CAL%BEEFF R%HEAD%CAL%FOEFF
R%HEAD%CAL%BEEFF = 0.9600000    ! Real    GLOBAL RO
R%HEAD%CAL%FOEFF = 0.9600000    ! Real    GLOBAL RO
```

In this case, if the source properties are better represented by the main temperature scale ($T_{\rm mb}$), you can convert the scale from T_A^* to $T_{\rm mb}$ with

```
LAS> EXAMINE R%HEAD%HER%ETAL R%HEAD%CAL%FOEFF  ! Check that they have identical values
R%HEAD%HER%ETAL = 0.9600000     ! Real    GLOBAL RO
R%HEAD%CAL%FOEFF = 0.9600000    ! Real    GLOBAL RO
LAS> EXAMINE R%HEAD%HER%ETAMB                  ! Check that the beam efficiency is sensible
R%HEAD%HER%ETAMB =   0.6223738  ! Real    GLOBAL RO
LAS> MODIFY BEAM_EFF R%HEAD%HER%ETAMB          ! Scale conversion
I-MODIFY,  Former beam efficiency: 0.9600, new: 0.6224
```

The MODIFY BEAM_EFF command will multiply the spectrum by R%HEAD%HER%ETAMB / R%HEAD%CAL%FOEFF and change the associated header parameters accordingly, *e.g.* baseline rms and T_{sys}.

2 Look-up tables

We describe here, section by section, how the **CLASS** observation header is filled from the Herschel-HIFI FITS header and data. You can refer to the **CLASS** or Herschel-HIFI documentations for the exact specification of each component. The concept of FITS cards and metacards is explained in the section 3.3.

Table 1: Look-up table between the **CLASS** General section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive. The elements not described here are set to their usual undefined value in **CLASS**.

Name	Type	Value	Default
num	I*8	Automatic	
ver	I*4	1	
teles	C*12	HIF-LL-SP-BB where:	
		- LL is 00 (level 2.5) or the subband number in the column flux_* name (level 2.0),	00
		- S is the spectrometer, W for WBS or H for HRS (1st letter of the card BACKEND, else of the metacard polarization)	Blank
		- P is the polarization, V or H (5th letter of the card BACKEND, else of the metacard polarization)	Blank
		- BB is the band name (2 first letters of the card BAND)	Blank
dobs	I*4	Integer part of average of card DATE-OBS and card DATE-END	Current day
dred	I*4	Current day	
kind	I*4	**CLASS** internal code for spectroscopic data	
qual	I*4	**CLASS** internal code for unknown quality	
scan	I*8	Metacard bbtype (level 2.5) or column bbtype (level 2.0)	0
subscan	I*4	Metacard bbnumber (level 2.5) or column bbnumber (level 2.0)	0
ut	R*8	Fractional part of average of card DATE-OBS and card DATE-END	Current time
tau	R*4	0.0	
tsys	R*4	Metacard tsys_median (level 2.5) or column tsys_median (level 2.0)	0 K
time	R*4	Metacard integrationTime (level 2.5) or column integrationTime (level 2.0)	0 sec

2.1 Intensity array

The intensity array (RY) is extracted from one or more columns in the binary table. There are 2 possibilities:

- the flux_* columns (where * is the subband number), each of them producing a different spectrum (level 2.0). In this case, one row of the column contains all the channel values. The associated frequency array is found in the column lsbfrequency_* or usbfrequency_*, else an error is raised.

- the `flux` column, producing a single spectrum (level 2.5). In this case one row of the column contains 1 channel value. The associated frequency array is found in the column `frequency` if available, else `wave`, else an error is raised.

All spectra (flux and frequency arrays) are always sorted in ascending frequency (if needed), before setting the spectroscopic section as described in the Table 2. The Not-a-Number (`NaN`) values (if any) in the flux array are patched to the `bad` value defined in the **CLASS** header.

2.2 General section

A subset of the general section is filled. The elements *sidereal time*, *azimuth*, and *elevation* are left to the **CLASS** internal defaults as they have no meaning for space-based observations. Note that for spectral scans (frequency surveys), the `integrationTime` is set by HIPE to the integration time of the individual tunings multiplied by the median redundancy accross the frequency axis.

2.3 Spectroscopic section

Table 2: Look-up table between the **CLASS** Spectroscopic section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive.

CLASS	Type	Value
`line`	C*12	`DECON_SSB` if Card `OBS_MODE` contains `SScan` and if Card `CLASS___` contains `Spectrum1d`, else `XXXXXXXX_YYY` where `XXXXXXXX` is the `lofreq` in GHz and `YYY` is the metacard `sideband` value (`GHZ` if not defined)
`nchan`	I*4	Card `NAXIS2` (level 2.5) or Card `TDIM*` for column `flux_*` (level 2.0)
`restf`	R*8	Value at `rchan` in column `frequency` or `wave` (level 2.5) or value at `rchan` in column `lsbfrequency_*` or `usbfrequency_*` (level 2.0)
`image`	R*8	2*`lofreq-restf` if `lofreq` is defined, **CLASS** internal code for undefined value otherwise
`doppler`	R*8	0.d0
`rchan`	R*8	ceiling(`nchan`+1)/2 (*i.e.* middle of spectrum)
`fres`	R*8	Absolute of spacing in column `frequency` or `wave` (level 2.5) or absolute of spacing in column `lsbfrequency_*` or `usbfrequency_*` (level 2.0)
`foff`	R*8	0.d0
`vres`	R*8	$-c\times$ `fres` / `restf`
`voff`	R*8	0.d0
`bad`	R*4	-1000.0
`vtype`	I*4	code for LSR referential if Metacard `freqFrame` is `LSRk`, code for unknown referential if Metacard `freqFrame` is `source`, error otherwise.
Not in header:		
`lofreq`	R*8	Metacard `LoFrequency` else `LoFrequency_measured` (level 2.5) or Column `LoFrequency` else `LoFrequency_measured` (level 2.0), 0.d0 otherwise.

The exact status of the spectroscopic axes after HIFI calibration is available here:
`http://herschel.esac.esa.int/twiki/pub/Public/HifiCalibrationWeb/freq_vel_1.1.pdf`

In the context of **CLASS** we can note that the frequencies found in the Herschel-HIFI FITS are expressed in the LSR frame[2] (hence the null Doppler factor). The source velocity is assumed to be 0 at import time; this is consistent with the null Doppler factor. It is the responsibility of the user to apply the needed `MODIFY VELOCITY` correction to apply the frequency shift implied by the source systemic velocity (see section 1.5), *i.e.*, to get the frequency axis in the source frame.

Moreover, at import time, the default rest frequency of the spectrum is arbitrarily set to the middle of the spectrum bandpass. Here again, it is the responsibility of the user to apply the needed `MODIFY FREQUENCY` correction to center the velocity axis around the line rest frequency under consideration.

2.4 Position section

The position section is described in the Table 3. Note that the source position is described as the offsets between the actual (reconstructed) position (`RA` or `longitude`, `DEC` or `latitude`) and the nominal (commanded) position (`RA_NOM`, `DEC_NOM`). This also means that for Solar System Objects (SSO), the offsets are not expressed in the comoving frame, but from a fixed position on sky.

Table 3: Look-up table between the **CLASS** Position section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive.

CLASS	Type	Value	Default
`sourc`	C*12	Card `OBJECT`	`UNKNOWN`
`system`	I*4	**CLASS** internal code for Equatorial system	
`equinox`	R*4	Card `EQUINOX`	Error
`proj`	I*4	**CLASS** internal code for Radio projection	
`lam`	R*8	Card `RA_NOM`	Error
`bet`	R*8	Card `DEC_NOM`	Error
`projang`	R*8	0.d0	
`lamof`	R*4	Offset in current projection between card `RA_NOM` and card `RA` (level 2.5) or column `longitude` (level 2.0)	0, *i.e.* actual position defaults to nominal
`betof`	R*4	Offset in current projection between card `DEC_NOM` and card `DEC` (level 2.5) or column `latitude` (level 2.0)	0, *i.e.* actual position defaults to nominal

2.5 Calibration section

The **CLASS** calibration section is activated and partially filled if the metacard `temperatureScale` is defined. The rules are detailed in Table 4.

Table 4: Look-up table between the **CLASS** Calibration section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive. The elements not described here are set to their usual undefined value in **CLASS**.

CLASS	Type	Value	Default
`beeff`	R*4	Metacard `forwardEff` if metacard `temperatureScale` is `T_A*`, else metacard `beamEff` if metacard `temperatureScale` is `T_MB`, else error	0.0
`foeff`	R*4	Metacard `forwardEff`	0.0
`gaini`	R*4	Metacard `*sbGain` (`usb` or `lsb`)	0.0
`tchop`	R*4	Metacard `hbbTemp` (level 2.5) or 1st value in Column `hot_cold` (level 2.0)	0.0
`tcold`	R*4	Metacard `cbbTemp` (level 2.5) or 2nd value in Column `hot_cold` (level 2.0)	0.0

[2]LSR frame, except for the Solar System Objects for which Herschel-HIFI FITS uses the source frame ($v = 0$); in this case, the velocity type is set as *unknown* in **CLASS**.

2.6 Frequency Switch section

This section is enabled and filled in the **CLASS** observation header if the FITS card `OBS_MODE` contains the string `FSwitch` and if a non-null LO throw value is found in the FITS data.

Table 5: Look-up table between the **CLASS** Frequency Switch section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive. Some values are not read from the FITS but explicitly set.

CLASS	Type	Value	Default
`nphas`	I*4	2	
`swmod`	I*4	Metacard `isFolded` (T/F), translated to **CLASS** internal code	code for False
`decal[1]`	R*8	0.d0	
`duree[1]`	R*4	1.0	
`poids[1]`	R*4	+0.5	
`decal[2]`	R*8	Column `LoThrow` else `lothrow` (level 2.0), or Metacard `LoThrow` else `loThrow` (level 2.5)	
`duree[2]`	R*4	1.0	
`poids[2]`	R*4	-0.5	

2.7 Herschel-HIFI section

The Herschel-HIFI section is filled from the FITS according to the table 7. Some of the parameters here are available for bookkeeping purpose, some others are essential for data analysis. In particular, the sideband gain coefficients[3] will be used for double-side band deconvolution.

2.8 Associated Arrays

CLASS imports each Herschel-HIFI spectrum together with the 2 Associated Arrays `BLANKED` and `LINE`. They are arrays of 0 or 1, set according to the rules exposed in Table 6. More information about these arrays is available in the dedicated **CLASS** documentation.

Table 6: How the Herschel-HIFI FITS flags are translated into the corresponding **CLASS** Associated Arrays. Some flags apply to the whole spectrum, others per channel (marked *ichan*).

CLASS name	Value
`BLANKED[ichan]`	1 if bit 20 (IGNORE_DATA) is set in metacard `rowflag` (level 2.5), else 1 if bit 20 (IGNORE_DATA) is set in column `rowflag` (level 2.0), else 1 if bit 7 (SPUR_CANDIDATE) is set in column `flag[ichan]` (level 2.5), else 1 if bit 7 (SPUR_CANDIDATE) is set in column `flag_*[ichan]` (level 2.0), else 1 if bit 30 (IGNORE_DATA) is set in column `flag[ichan]` (level 2.5), else 1 if bit 30 (IGNORE_DATA) is set in column `flag_*[ichan]` (level 2.0), 0 otherwise.
`LINE[ichan]`	1 if bit 28 (LINE) is set in column `flag[ichan]` (level 2.5), else 1 if bit 28 (LINE) is set in column `flag_*[ichan]` (level 2.0), else 1 if bit 29 (BRIGHT_LINE) is set in column `flag[ichan]` (level 2.5), else 1 if bit 29 (BRIGHT_LINE) is set in column `flag_*[ichan]` (level 2.0), 0 otherwise.

[3]See HIPE documentation for details.

Table 7: Look-up table between the **CLASS** Herschel-HIFI section and the Herschel-HIFI FITS. Depending on the FITS structure (pipeline level), some elements found in a FITS header or in a FITS binary table. FITS names are case sensitive.

CLASS	Type	Value	Default	Description
obsid	I*8	Card OBS_ID	0	Observation id
instrument	C*8	Card INSTRUME	Blank	Instrument name
proposal	C*24	Card PROPOSAL	Blank	Proposal name
aor	C*68	Card AOR	Blank	Astronomical Observation Request
operday	I*4	Card ODNUMBER	0	Operational day number
dateobs	C*28	Card DATE-OBS	Blank	Start date
dateend	C*28	Card DATE-END	Blank	End date
obsmode	C*40	Card OBS_MODE	Blank	Observing mode
vinfo	R*4	Metacard vlsr if card REDSHFT is "optical" or "radio"	0.0	Informative source velocity in LSR
zinfo	R*4	Metacard vlsr if card REDSHFT is not "optical" or "radio", else 0.0	0.0	Informative target redshift
posangle	R*8	Card POSANGLE	0.d0	Spacecraft pointing position angle
reflam	R*8	Card RAOFF	0.d0	Sky reference (a.k.a. OFF) lambda
refbet	R*8	Card DECOFF	0.d0	Sky reference (a.k.a. OFF) beta
hifavelam	R*8	Metacard longitude_cmd (level 2.5) or Column longitude_cmd (level 2.0)	0.d0	HIFI ON average H and V lambda
hifavebet	R*8	Metacard latitude_cmd (level 2.5) or Column latitude_cmd (level 2.0)	0.d0	HIFI ON average H and V beta
etamb	R*4	Card ETAMB	0.0	Main beam efficiency used when applying doAntennaTemp
etal	R*4	Card ETAL	0.0	Forward efficiency used when applying doAntennaTemp
etaa	R*4	Card ETAA	0.0	Telescope aperture efficiency
hpbw	R*4	Card HPBW	0.0	Azimuthally-averaged HPBW
tempscal	C*8	Card TEMPSCAL	Blank	Temperature scale in use
lodopave	R*8	Card LODOPPAV	lofreq (Table 2)	Average LO frequency Doppler corrected to freqFrame (SPECSYS)
gim0	R*4	Metacard *sbGain_0 (usb or lsb)	0.0	Sideband gain polynomial coeff 0
gim1	R*4	Metacard *sbGain_1 (usb or lsb)	0.0	Sideband gain polynomial coeff 1
gim2	R*4	Metacard *sbGain_2 (usb or lsb)	0.0	Sideband gain polynomial coeff 2
gim3	R*4	Metacard *sbGain_3 (usb or lsb)	0.0	Sideband gain polynomial coeff 3
mixercurh	R*4	Metacard MJC_Hor (level 2.5) or Column MJC_Hor (level 2.0)	0.0	Calibrated mixer junction current (horizontal polarization)
mixercurv	R*4	Metacard MJC_Ver (level 2.5) or Column MJC_Ver (level 2.0)	0.0	Calibrated mixer junction current (vertical polarization)
datehcss	C*28	Card DATE	Blank	Processing date
hcssver	C*24	Card CREATOR	Blank	HCSS version
calver	C*16	Card CALVERS	Blank	Calibration version
level	R*4	Card LEVEL	0.	Pipeline level

3 Technical details

3.1 Detecting an Herschel-HIFI FITS

A FITS file fed as input of the command `LAS\FITS` is assumed to be an Herschel-HIFI FITS if the Primary HDU:

1. contains the card `HCSS____`, and
2. the value of the card `TYPE` is not `HICLASS`.

The 2nd rule discriminates Herschel-HIFI FITS and **CLASS** FITS produced by `HICLASS`.

3.2 FITS level

The command `LAS\FITS` traverses one by one all the HDUs in the FITS file *independently of their names*. If a binary table is found and:

- if it contains a column `frequency` or `wave`, it is assumed to be a level 2.5 Herschel-HIFI FITS and the specific decoding is started.
- if if contains at least one column `lsbfrequency_*` or `usbfrequency_*`, it is assumed be a level 2.0 Herschel-HIFI FITS and the specific decoding is started.

The levels 2.0 and 2.5 refer to the reduction pipeline level in HCSS. The resulting FITS provides (almost) the same data but under a different form. For our needs, the main differences come from values which are found in columns of the binary table in level 2.0, and in metacards (see below) of the header in level 2.5.

3.3 Cards and metacards

In this document, we refer to 2 concepts in the FITS context:

- header *cards*. In the FITS standard, an header card has the form:

  ```
  CALVERS = 'HIFI_CAL_22_0'      / HIFI calibration version
  ```

  with an 8-characters key, a value, and a comment. In this document, we abusively refer to *e.g.* "the card `CALVERS`" as "the value in the card which key is `CALVERS`".

- header *metacards*. Not in the FITS standard, we refer as metacards when encoutering in the FITS header a pair of lines (contiguous or not, ordered or not) with the form:

  ```
  META_10 =     62.39999999999999 / [s]
  HIERARCH  key.META_10='integrationTime'
  ```

  i.e. a standard card and a `HIERARCH` (free-form) line. We can see that these 2 lines provide an indirection through a `META_XX` key (`XX` being a non-ambiguous number). In this case, we abusively refer to *e.g.* "the metacard `integrationTime`" as "the value in the card which key (`META_10`) has the value `integrationTime` in the associated `HIERARCH` line". Thanks to the metacards, case-sensitive keywords not limited to 8 characters can be used. There is also no need to refer to the exact `META_XX` name in the subsequent specifications, *i.e.* `XX` can vary from one file to another.

4 Acknowledgements

This work was partly founded by CNES. We thanks Claudia Comito and Jonathan Braine for useful comments during this work.

Test report for the HCSS FITS input into Gildas/CLASS

D. Teyssier, ESAC/ESA – 24-09-2015 – v3.0

Summary:

This document summarizes the systematic sanity and validation checks performed on the HIFI FITS filler in Class. The approach consists in systematically ingesting a collection of representative FITS files covering various instrument modes and configurations. Metadata being populated in the Class headers are being compared to the original ones, and contrasted for different processing versions of the HCSS FITS. Overall all ingestion tests are successful. We also perform a handful of data manipulation showing that most Class functionalities behave as expected on the ingested data. In particular the use of the newly introduced associated data array is demonstrated for two test cases.

Test file sample:

The following files have been considered in the testing:

	Obs. Type	Level	HCSS Obsid	Stitch	Band	File name
1a	Single point	2.5	1342271259	YES	1a	HIFI_Point_Spec1d.fits
1b	Spectral Scan	2.5	1342196516	N/A	1a	HIFI_SScan_Spec1d.fits
1c	Single pt FSW	2.5	1342256427	YES	1a	HIFI_Point_FSW_Spec1d.fits
1d	Single point	2.5	1342271259	YES	1a	HIFI_Point_Spec1d_dataset_product.fits
1e	Spectral Scan	2.5	1342196516	N/A	1a	HIFI_SScan_Spec1d_ssb_product.fits
1f	Single pt FSW	2.5	1342256427	YES	1a	HIFI_Point_FSW_Spec1d_dataset_produc
2a	Single point	2	1342271259	YES	1a	HIFI_Point_Lev2.fits
2b	Single point	2	1342271259	NO	1a	HIFI_Point_Lev2_nonStitched.fits
2c	Spectral Scan	2	1342196516	YES	1a	HIFI_SScan_Lev2.fits
2d	Map	2	1342269948	YES	1a	HIFI_Map_Lev2.fits
2e	Single point	2	1342271220	NO	7b	HIFI_Point_Lev2_HEB_nonStitched.fits
2f	Single point	2	1342271259	NO	1a	HIFI_Point_Lev2_HRSV_nonStitched.fits
2g	Map	2	1342233894	NO	2a	HIFI_Map_Lev2_nonStitched_SSO.fits
2h	Single pt FSW	2	1342256427	YES	1a	HIFI_Point_FSW_Level2.fits
2i	Single pt FSW	2	1342256427	YES	1a	HIFI_Point_FSW_Level2_Folded.fits
2j	Single pt FSW	2	1342256427	NO	1a	HIFI_Point_FSW_Level2_HRSH_nonStitch olded.fits
2k	Single pt FSW	2	1342256427	NO	1a	HIFI_Point_FSW_Level2_HRSH_nonStitch d.fits

For each of the above, three versions have been considered:

- HCSS v12.1.0 (user release)
- HCSS v13.0.0 (user release)
- HCSS v14.0.3006 (developer build)

Test plan:

1. Systematic sanity check import of the various file categories

Bulk import of all above files, checking any warning or error message in the console. This should confirm that none of the files/versions breaks. A compilation of warnings/errors should help weighting the pros and cons of letting the code cope with e.g. HIPE 12 data.

2. Systematic comparison of the various variable section entries

A reference table is generated inside HIPE when generating the FITS files. An equivalent file is generated from the Class-imported data and a simple diff is run between the two files. Additionally, diff's are generated between the output from the various HCSS versions.

3. Dedicated tests
    a. Basic data processing tasks
        i. Deconvolution
        ii. Cube generation (in Class)
        iii. Baseline fitting
        iv. Folding
    b. Inspection of blanked flags
        i. Visual inspection of flags vs those from the HCSS data
        ii. Run deconvolution once flagged data channels are converted to the blanking value
    c. Inspection of line flags
        i. Visual inspection of flags vs those from the HCSS data
        ii. Run baseline fitting and confirm the flags are honoured

Test results:

1. Systematic sanity check import of the various file categories

The import is successful for all files, and numerous warnings are being raised in the event of metadata missing in the headers. This is especially true for data processed with the now old HIPE 12 version, and significantly reduced in data processed with HIPE 13 data. Overall, however, import of data as old as HIPE 12 is still meaningful and this should be supported.

2. Systematic comparison of the various variable section entries

    a. **Class vs Class at different versions:**
        i. **12 *vs* 13:**

As expected, many differences show up between the two versions. In 12 a lot of fields later on identified as needed for the import into Class were not filled in and so they appear with value zero in Class. This is basically limited to items belonging to the new HER sections. Other numbers differ, but this is either because of numerical rounding, or because the pointing product slightly changed between 12 and 13, leading to slightly different astrometry and therefore Doppler-corrected frequencies. These are no show-stoppers.

ii. **13 *vs* 14:**

Only three differences were observed between the 13 and 14 products:

- **As expected**, HCSSVER and DATAHCSS are different
- In the cases of Spec1d in point mode, the temperature of the hot and cold load is informed in 14, while it was missing (in HIPE) in 13, so this was **expected**
- In the spectral scan Spec1d, the values of LAMOFF and BETAOFF have changed. This is an **expected** effect: in 13, the co-ordinates of spectral scan data were the H+V averaged position irrespective of the polarization in use, while in 14 we differentiate between the polarisations

b. **HIPE vs Class:**

With the above in mind it is sufficient to compare the Class parameters with those from 14. Since the algorithm is basically the same for many types of observations, we focus on the following cases:

- **HIFI_Point_Spec1d**.
- **HIFI_SScan_Spec1d**
- **HIFI_SScan_Lev2** (look at one spectrum only)
- **HIFI_Map_Lev2** (look at one spectrum only)

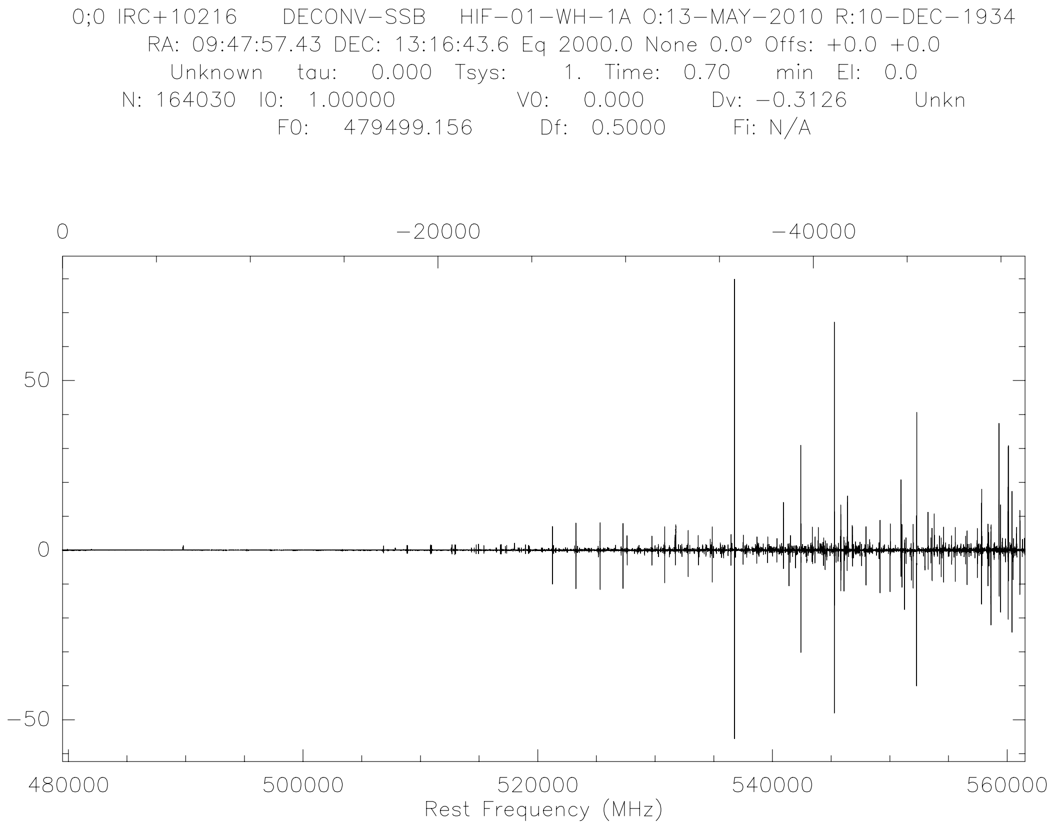
There were no particular issues noted. Some expectedly missing metadata are being converted into specific defaults.

3. <u>Dedicated tests</u>
   a. Basic data processing tasks
      i. Deconvolution

I take the data from **HIFI_SScan_Lev2.fits** and run the following:

init
decon 1e-5 100

The output spectrum is shown as follows. **As expected the numerous spurs prevent a decent deconvolved result – *garbage-in – garbage-out***

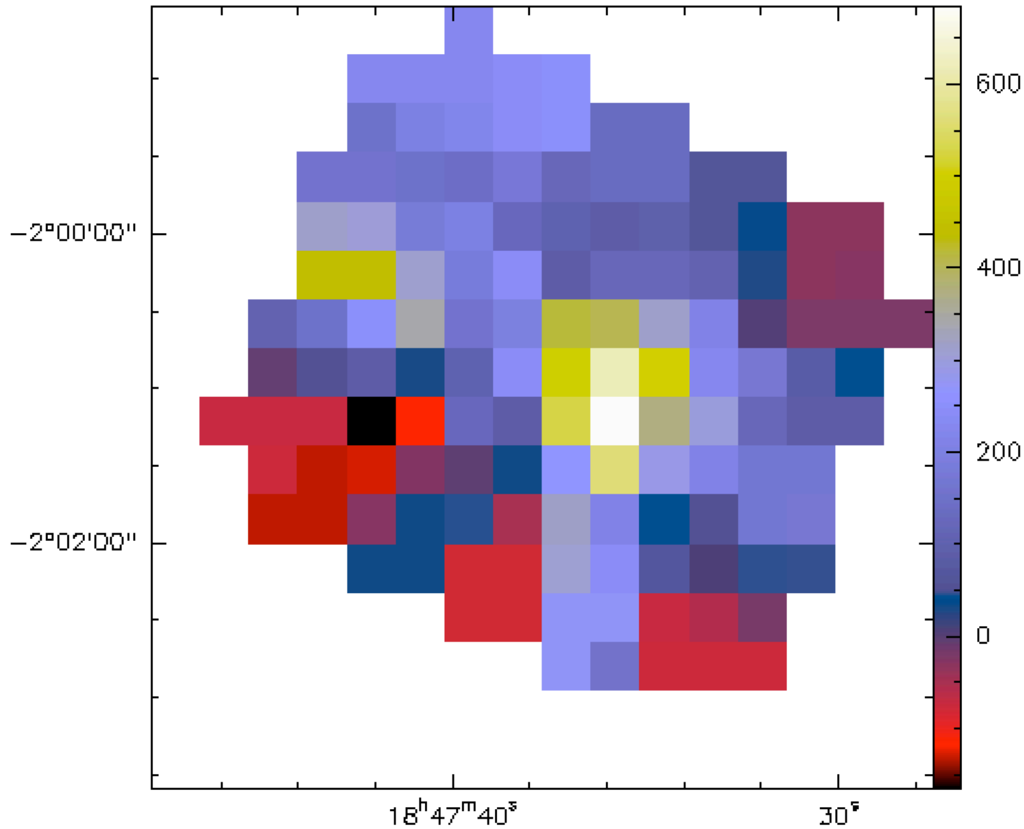


ii. Cube generation (in Class)

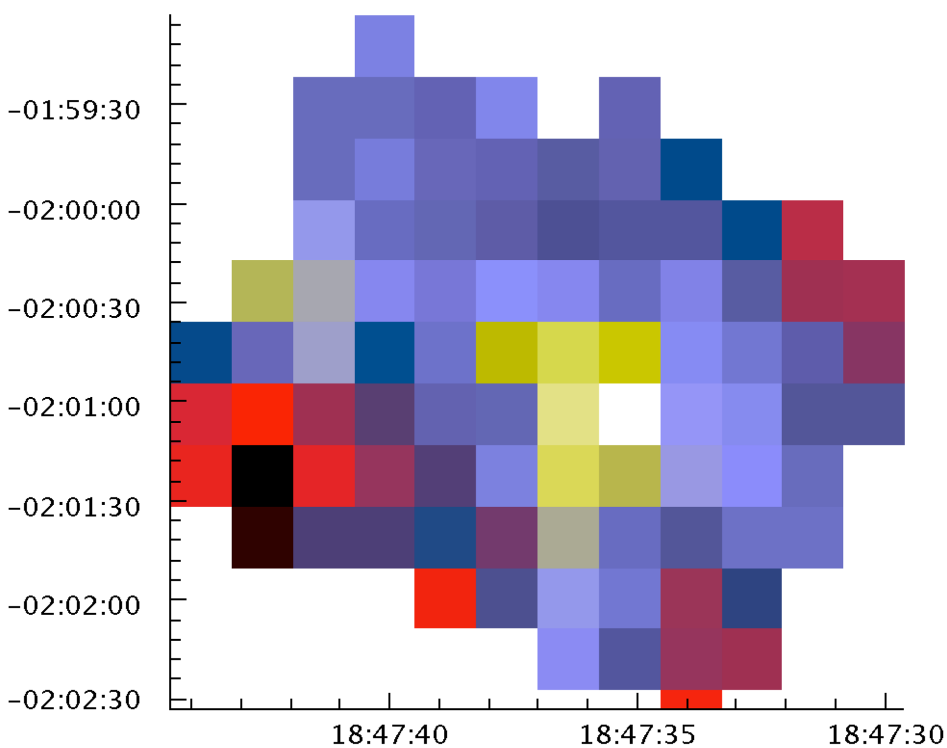
I take the data from **HIFI_Map_Lev2.fits** and run the following:

let map%beam 38
table HIFI_Map_lev2 new /math TDV(-500,+500) /nocheck
xy_map HIFI_Map_lev2

I get the following continuum map:



As a matter of comparison this what HIPE would create for a similar integration:



iii. Baseline fitting

Successfully tried various options of the baseline command.

iv. Folding

When trying to fold a spectrum I get the following message: "W-FOLD, Section Associated Array can not be folded. Removed. We note that this is an expected behavior for the associated array data, as is explained in the dedicated documentation.

Other than that we can confirm that it is not possible fold when it's not authorized, e.g.:

- Non-FSW data: "*Cannot fold a single phase spectrum*"
- Already folded FSW data: "*Spectrum has already been folded*"

b. Inspection of blanked flags

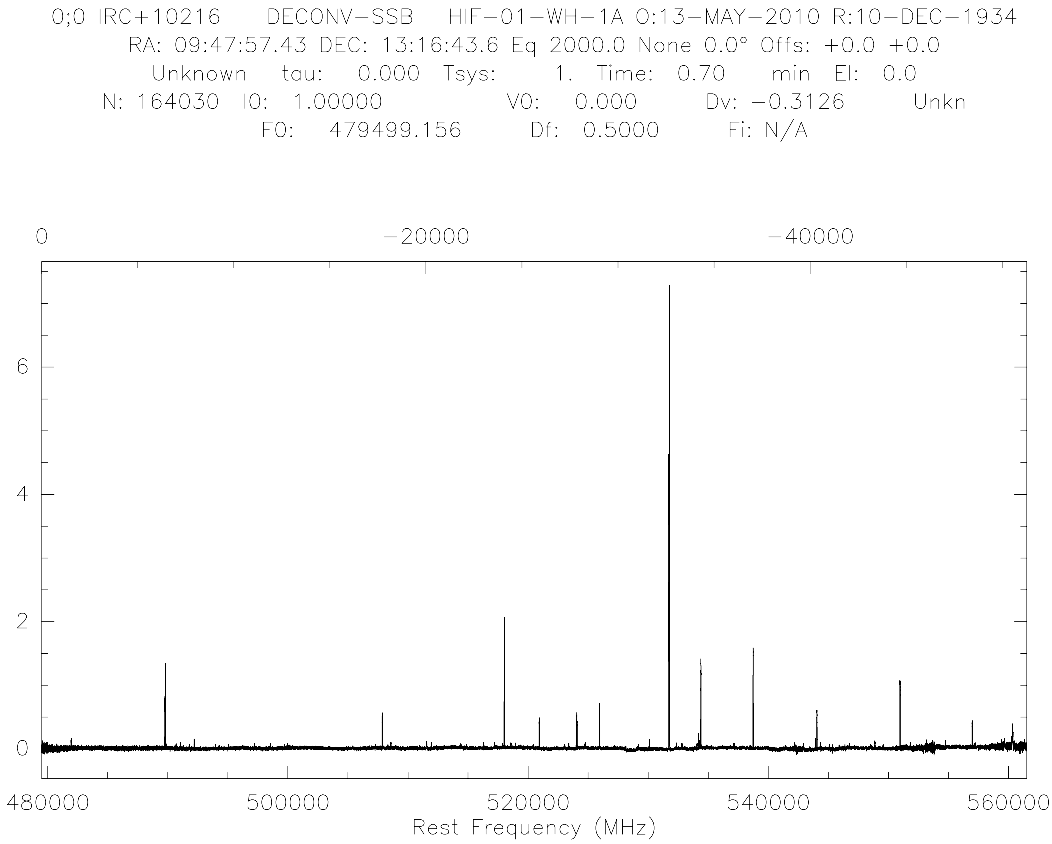
i. Visual inspection of flags vs those from the HCSS data

I checked the content of R%ASSOC%BLANKED%DATA in the data imported from **HIFI_SScan_Lev2.fits**

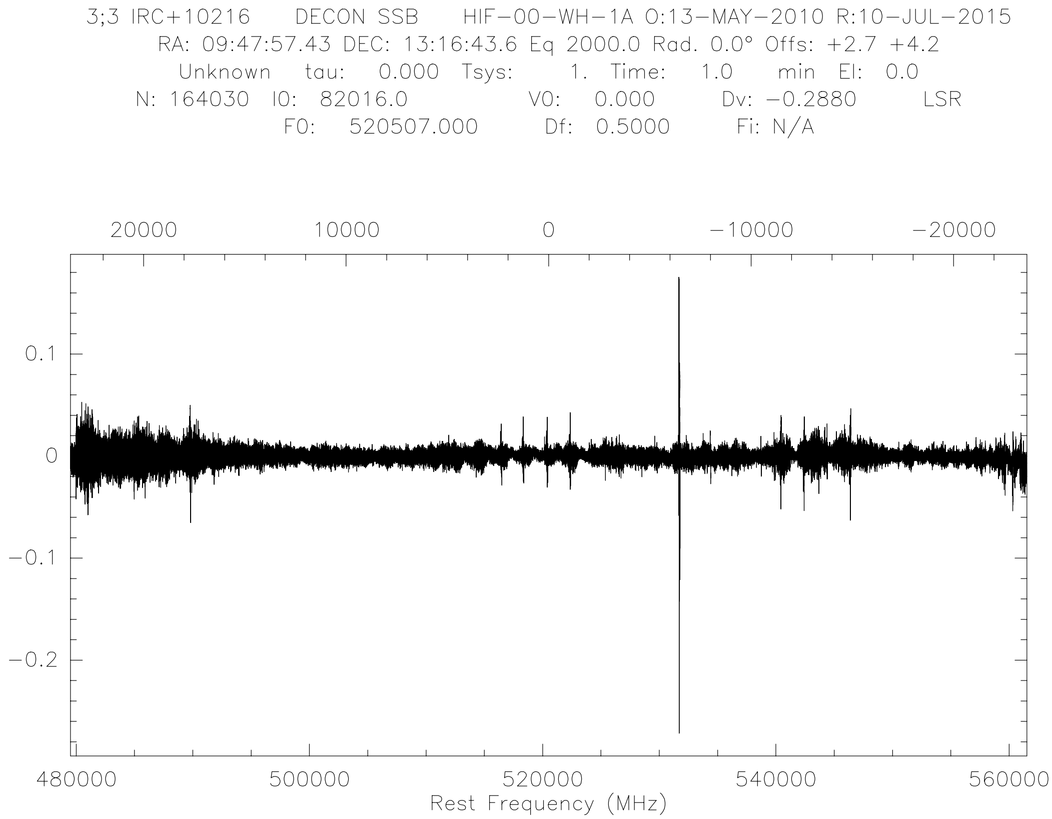
- Scan#60 is expected to have all channels blanked: **OK**
- Scan#90 has portion of the spectrum as blanked – I applied the following to get rid of the blanked data:
  let ry = -1000 /where R%ASSOC%BLANKED%DATA.eq.1
  and it resulted in the expected blanked regions: **OK**

ii. Run deconvolution once flagged data channels are converted to the blanking value

I flagged all the applicable channels and re-ran the deconvolution as in the previous point *a.i.* The output spectrum is shown as follows. **This time the flagged channels have not entered into the SSB solution and the result is good**.



As a matter of comparison this is the residual with the deconvolution from HIPE. Typically the noise in the deconvolved spectrum is around 10 mK, so the residual are for the majority below or within this, with some exception near to the strongest lines. The largest discrepancy is at one of the HCN lines, with a residual of order ~3% of the line peak.



c. Inspection of line flags

i. Visual inspection of flags vs those from the HCSS data

I checked the content of R%ASSOC%LINE%DATA in the data imported from **HIFI_SScan_Lev2.fits**

- Scan#20 has some lines masked – they appear as such: **OK**

ii. Run baseline fitting and confirm the flags are honoured

I ran the following:

set window /associated

show window

Results in:

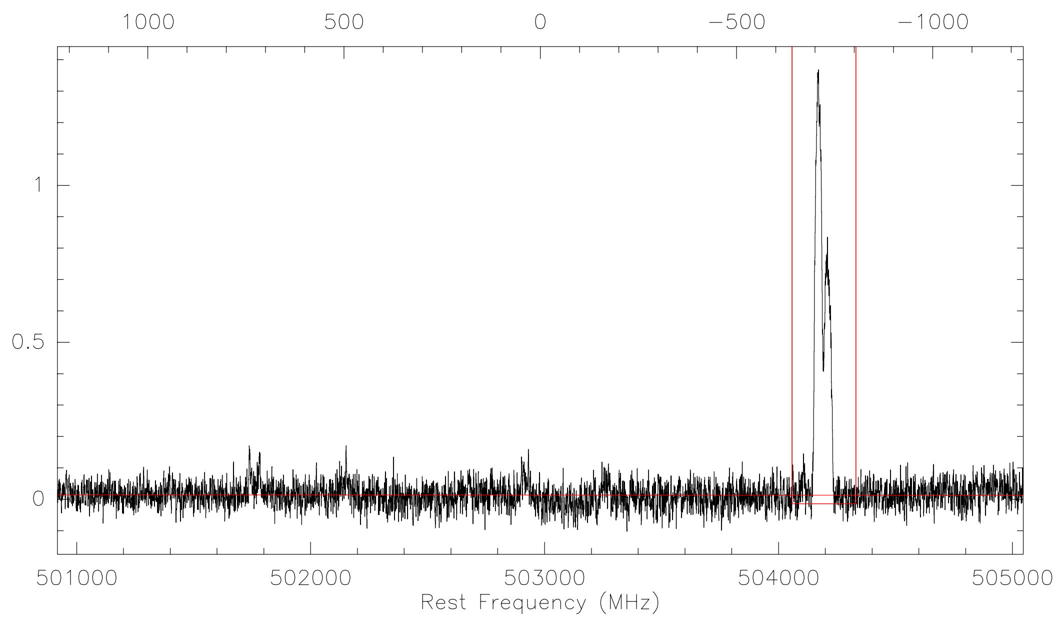
WINDOW Defined from LINE Associated Array

draw window

base 1 /pl

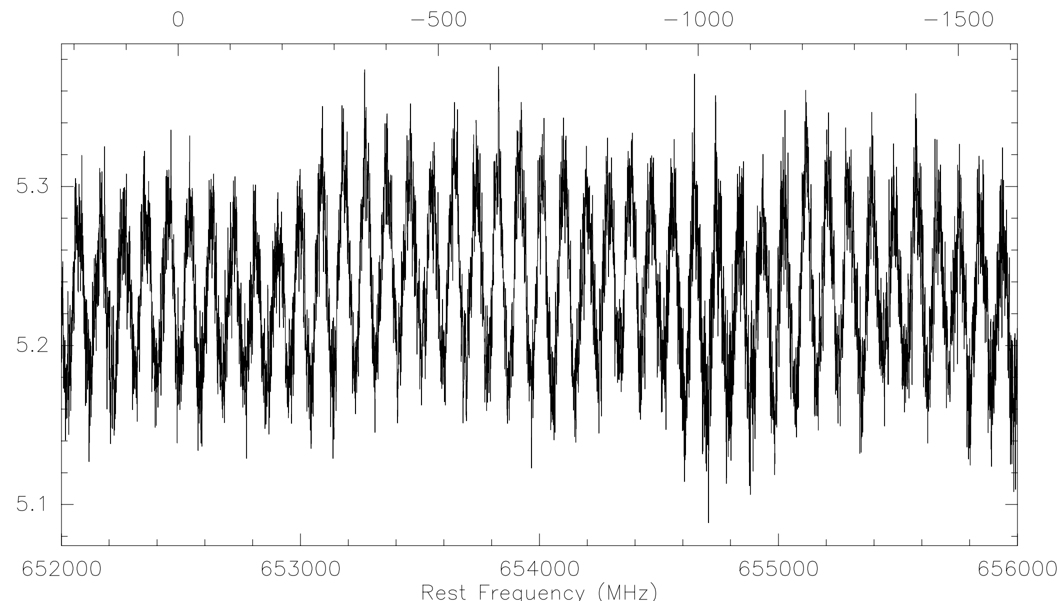
Results in the attached plot.

20;1 IRC+10216 0496.982 USB HIF−01−WH−1A O:13−MAY−2010 R:21−JUL−2015
RA: 09:47:57.43 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.8 +4.3
Unknown tau: 0.000 Tsys: 96. Time: 0.70 min El: 0.0
N: 8257 I0: 4129.00 V0: 0.000 Dv: −0.2980 LSR
F0: 502981.500 Df: 0.5000 Fi: 490982.966

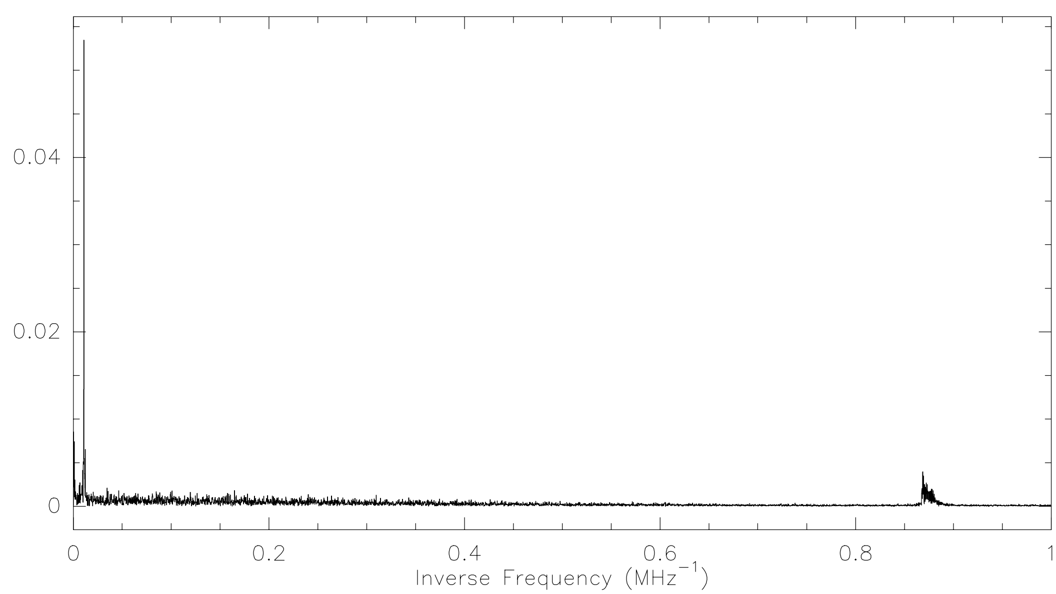


d. Additional ad hoc checks
    i. Headers in SSO observations: the inspection of the position offsets in HIFI_Map_Lev2_nonStitched_SSO.fits shows, as expected, the tracking of the moving target. In the HCSS cubes would be built in the commoving frame (i.e. the ephemerids at the time of the observation are part of the product and are used to compute offsets with respect to the moving target rather than with respect to a fixed RA/Dec position – typically the one at the start of the observation) – this will be warned against in the documentation.
    ii. In the same file I also note at importing: “Unsupported velocity type 'source', use Unknown”. This is because for SSO the velocity scale is not LSR, but the one in the commoving frame (i.e. v=0 km/s is for an observer sitting on the moving body). Again this will be explained in the documentation.
    iii. In the same file, there is a very strong optical standing wave, that can be seen typically when averaging all spectra in the map, see below. I used the FFT command and could indeed see a very nice component around 100 MHz

0;0 Mars 0647.999 USB HIF-0--WH-2A O:09-DEC-2011 R:12-JUL-2015
RA: 11:00:41.86 DEC: 08:45:39.9 Eq 2000.0 Rad. 0.0° Offs: −16.4 −19.8
Unknown tau: 0.000 Tsys: 115. Time: 12. min El: 0.0
N: 8257 I0: 1134.00 V0: 0.000 Dv: −0.2297 Unkn
F0: 652488.500 Df: 0.5000 Fi: 643509.059

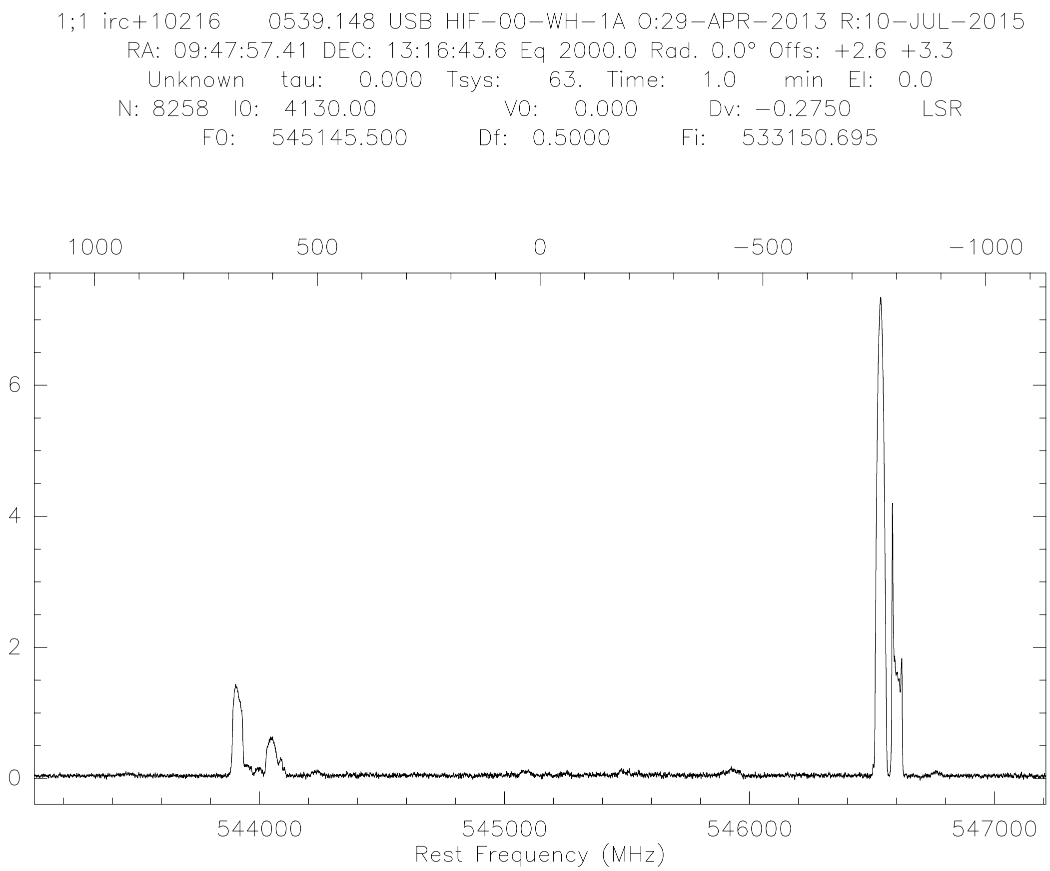


0;0 Mars 0647.999 USB HIF-0--WH-2A O:09-DEC-2011 R:12-JUL-2015
RA: 11:00:41.86 DEC: 08:45:39.9 Eq 2000.0 Rad. 0.0° Offs: −16.4 −19.8
Unknown tau: 0.000 Tsys: 115. Time: 12. min El: 0.0
N: 8257 I0: 1134.00 V0: 0.000 Dv: −0.2297 Unkn
F0: 652488.500 Df: 0.5000 Fi: 643509.059

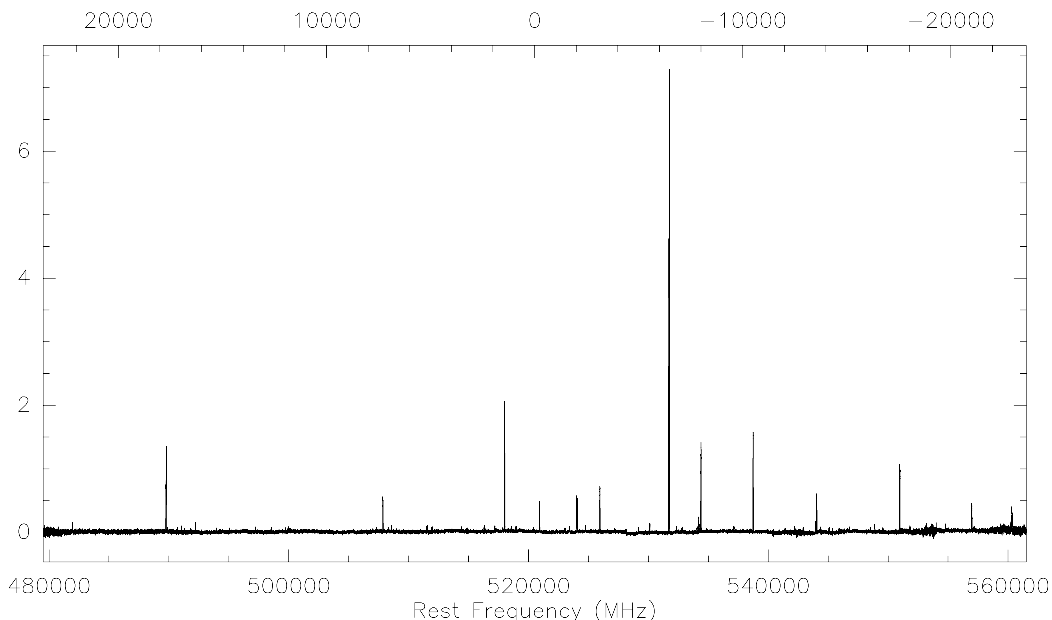


<u>APPENDIX</u>: sample plots of all spectra for all considered files

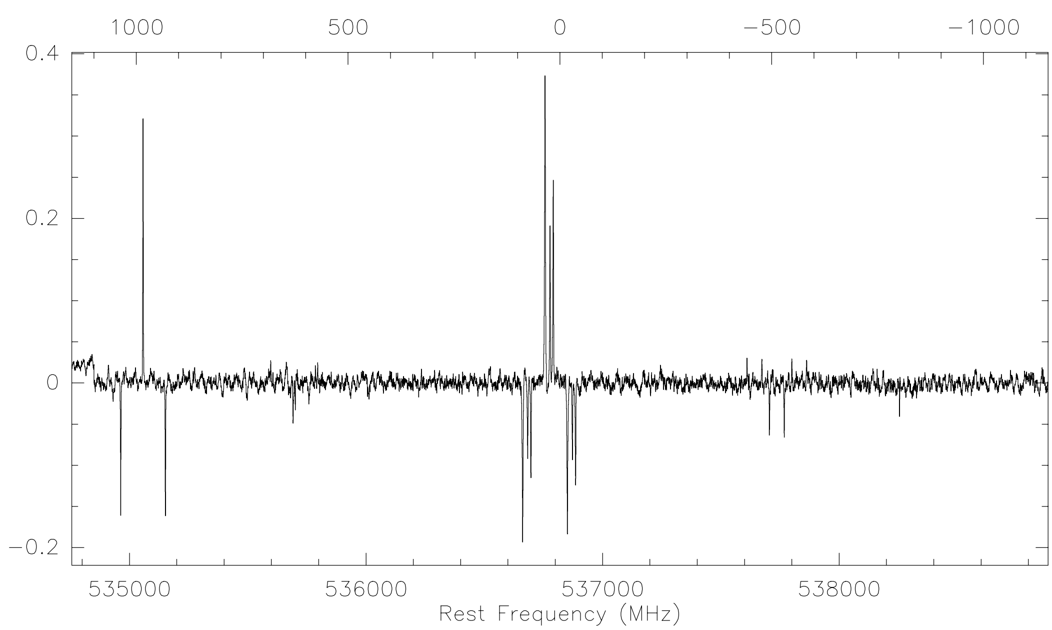
The plots appear in the same order as in Table 1. The frequency scale is the only one to be fixed. Different colors are used for different entries in the spectra list, with a rotating order (0 to 7 modulo 7).



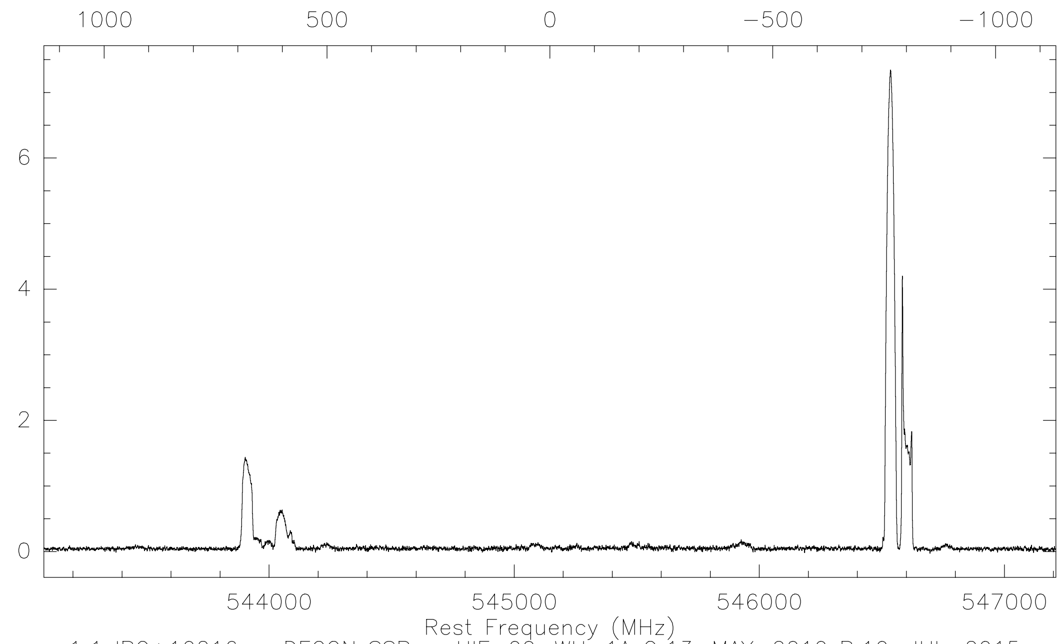
1;1 IRC+10216 DECON SSB HIF−00−WH−1A O:13−MAY−2010 R:10−JUL−2015
RA: 09:47:57.43 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.7 +4.2
Unknown tau: 0.000 Tsys: 1. Time: 1.0 min El: 0.0
N: 164030 I0: 82016.0 V0: 0.000 Dv: −0.2880 LSR
F0: 520507.000 Df: 0.5000 Fi: N/A



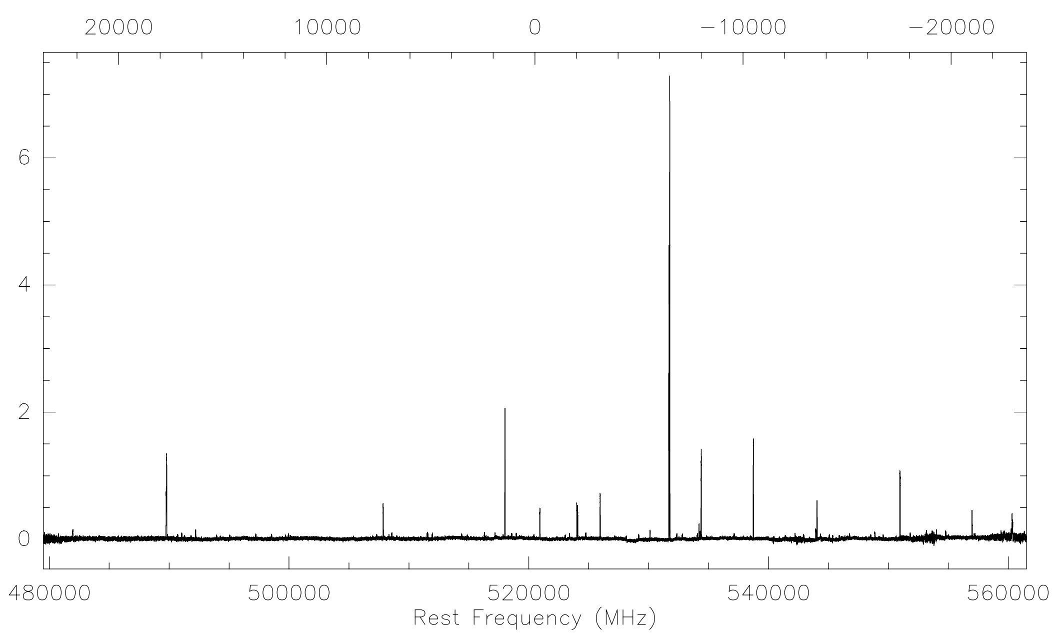
1;1 N7023−H2peak 0530.821 USB HIF−00−WH−1A O:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +3.0
Unknown tau: 0.000 Tsys: 65. Time: 18. min El: 0.0
N: 8254 I0: 4128.00 V0: 0.000 Dv: −0.2792 LSR
F0: 536819.500 Df: 0.5000 Fi: 524821.712



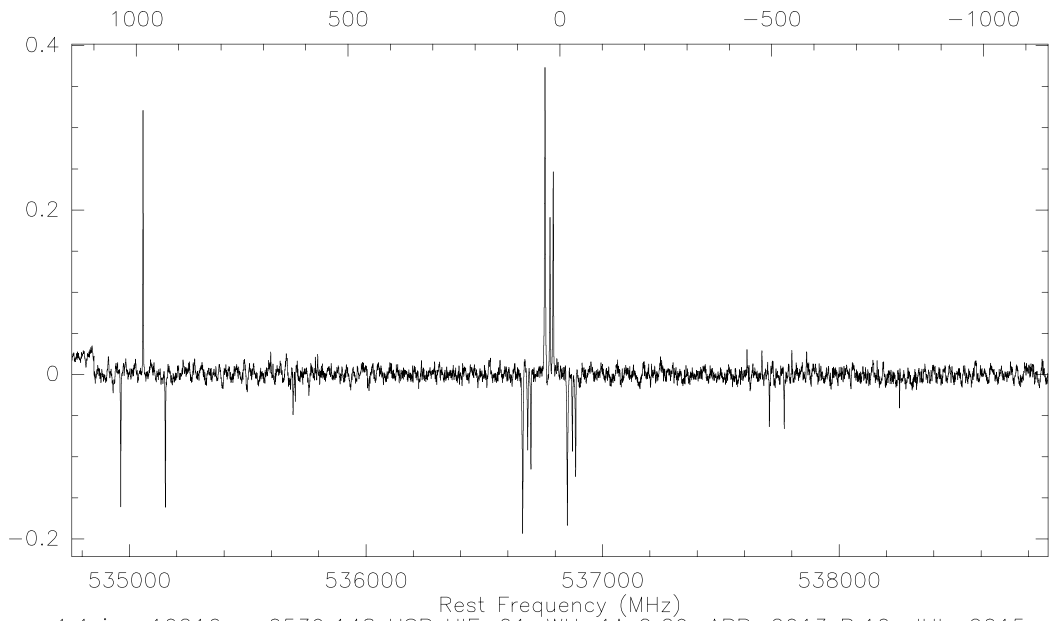
1;1 irc+10216 0539.148 USB HIF-00-WH-1A O:29-APR-2013 R:10-JUL-2015
RA: 09:47:57.41 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.6 +3.3
Unknown tau: 0.000 Tsys: 63. Time: 1.0 min El: 0.0
N: 8258 I0: 4130.00 V0: 0.000 Dv: −0.2750 LSR
F0: 545145.500 Df: 0.5000 Fi: 533150.695



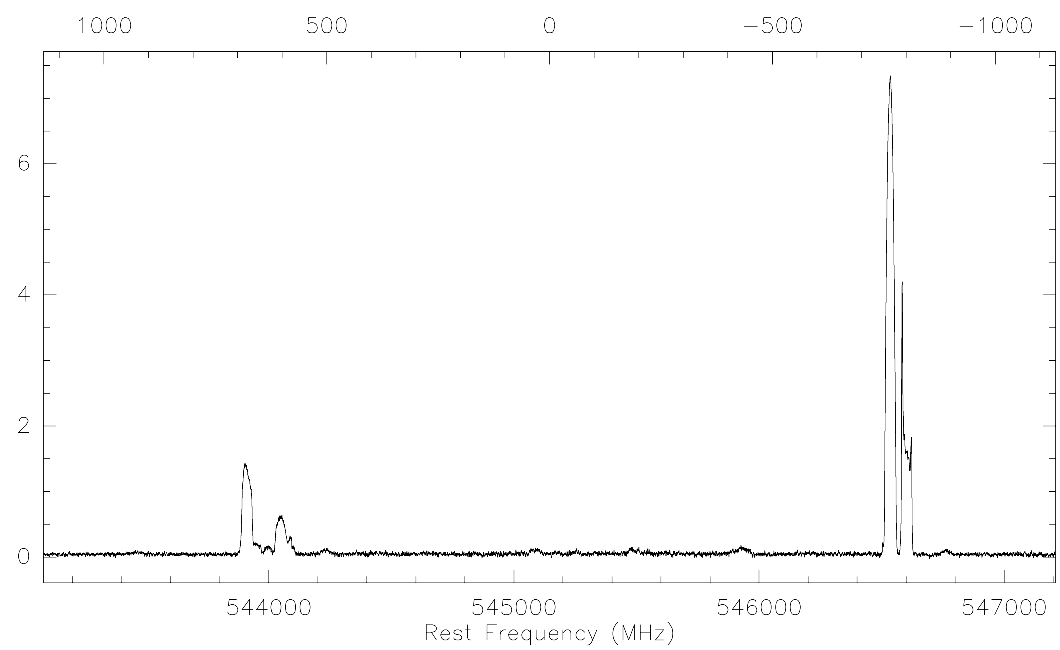
1;1 IRC+10216 DECON SSB HIF-00-WH-1A O:13-MAY-2010 R:10-JUL-2015
RA: 09:47:57.43 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.7 +4.2
Unknown tau: 0.000 Tsys: 1. Time: 1.0 min El: 0.0
N: 164030 I0: 82016.0 V0: 0.000 Dv: −0.2880 LSR
F0: 520507.000 Df: 0.5000 Fi: N/A



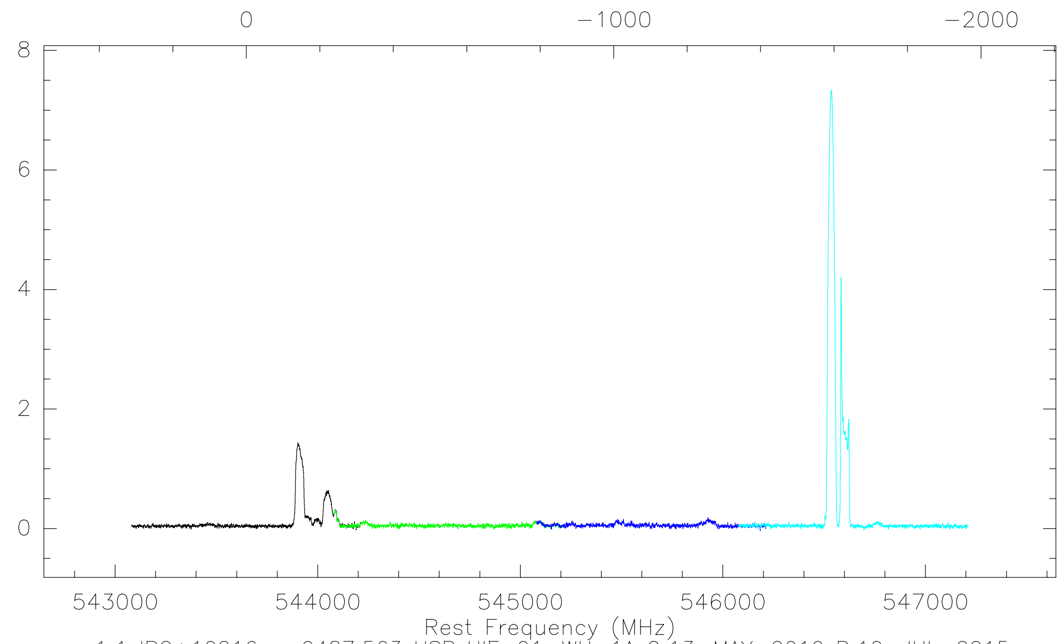
1;1 N7023−H2peak 0530.821 USB HIF−00−WH−1A O:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +3.0
Unknown tau: 0.000 Tsys: 65. Time: 18. min El: 0.0
N: 8254 I0: 4128.00 V0: 0.000 Dv: −0.2792 LSR
F0: 536819.500 Df: 0.5000 Fi: 524821.712



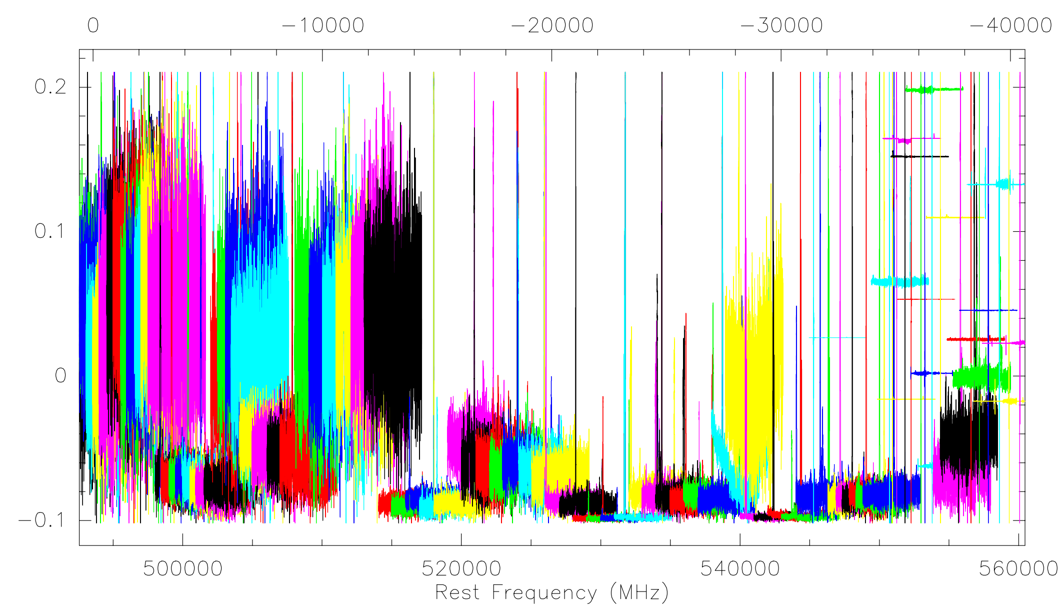
1;1 irc+10216 0539.148 USB HIF−01−WH−1A O:29−APR−2013 R:10−JUL−2015
RA: 09:47:57.41 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.6 +3.3
Unknown tau: 0.000 Tsys: 63. Time: 1.0 min El: 0.0
N: 8258 I0: 4130.00 V0: 0.000 Dv: −0.2750 LSR
F0: 545145.500 Df: 0.5000 Fi: 533150.695



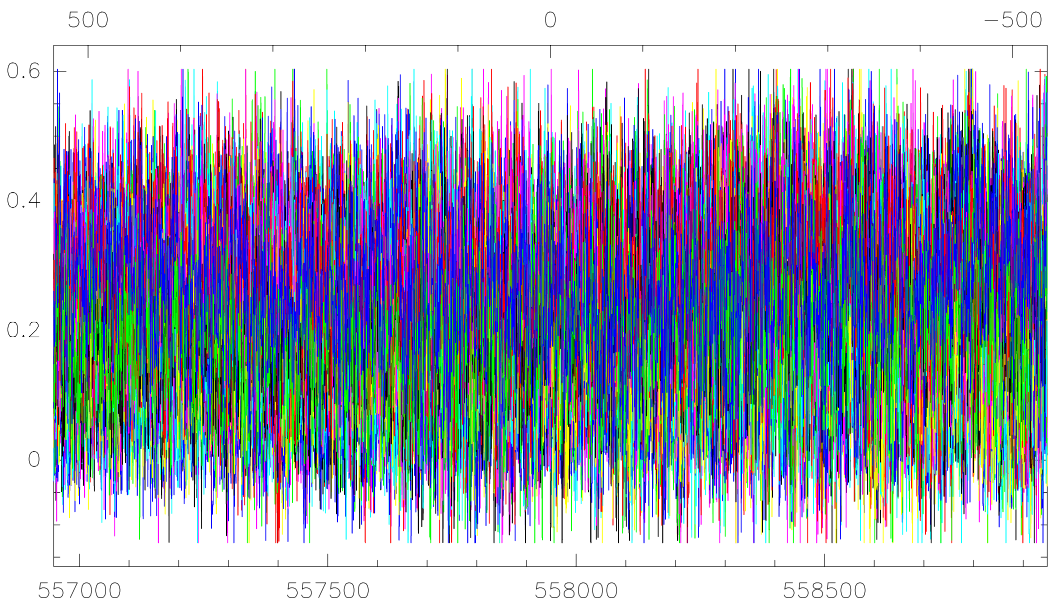
1;1 irc+10216 0539.148 USB HIF-01-WH-1A 0:29-APR-2013 R:10-JUL-2015
RA: 09:47:57.41 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.6 +3.3
Unknown tau: 0.000 Tsys: 63. Time: 1.0 min El: 0.0
N: 2266 I0: 1134.00 V0: 0.000 Dv: −0.2757 LSR
F0: 543647.500 Df: 0.5000 Fi: 534648.695



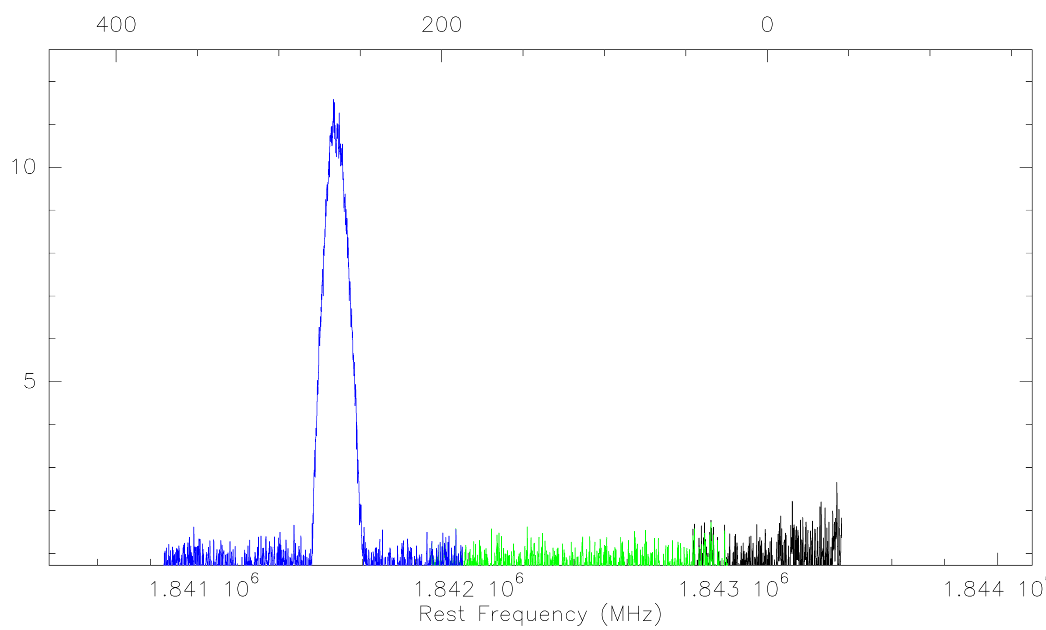
1;1 IRC+10216 0487.563 USB HIF-01-WH-1A 0:13-MAY-2010 R:10-JUL-2015
RA: 09:47:57.43 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: +2.5 +4.1
Unknown tau: 0.000 Tsys: 93. Time: 0.70 min El: 0.0
N: 8257 I0: 4129.00 V0: 0.000 Dv: −0.3037 LSR
F0: 493562.000 Df: 0.5000 Fi: 481563.162



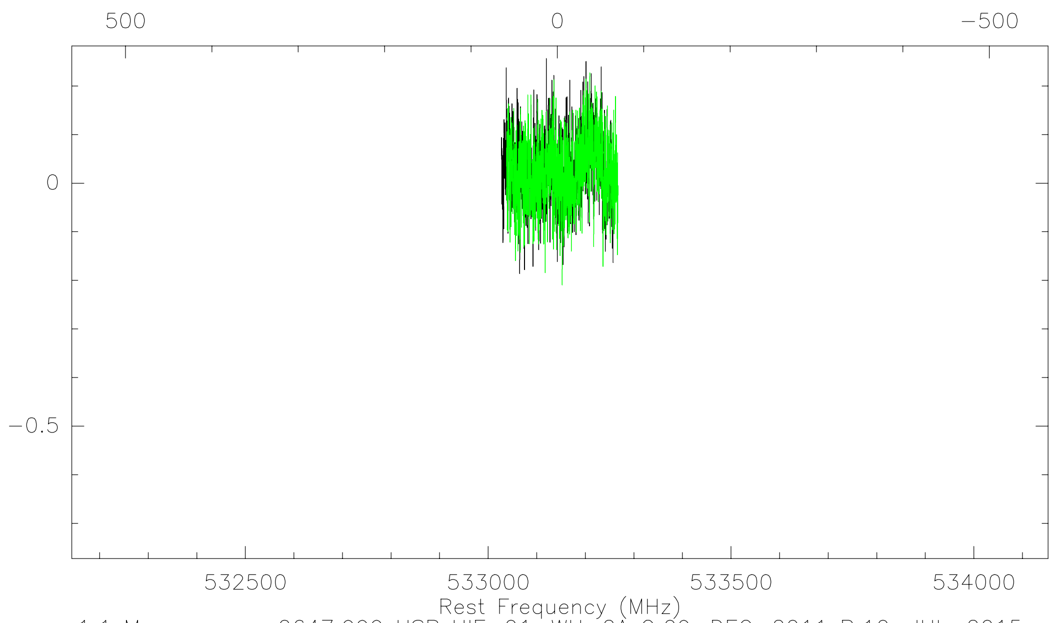
1;1 W43-SiOMM2-1 0551.952 USB HIF-01-WH-1A O:13-APR-2013 R:10-JUL-2015
RA: 18:47:37.00 DEC: −02:00:50.0 Eq 2000.0 Rad. 0.0° Offs: +45.9 +93.3
Unknown tau: 0.000 Tsys: 79. Time: 4.87E−02min El: 0.0
N: 8255 I0: 4128.00 V0: 0.000 Dv: −0.2687 LSR
F0: 557948.000 Df: 0.5000 Fi: 545955.327



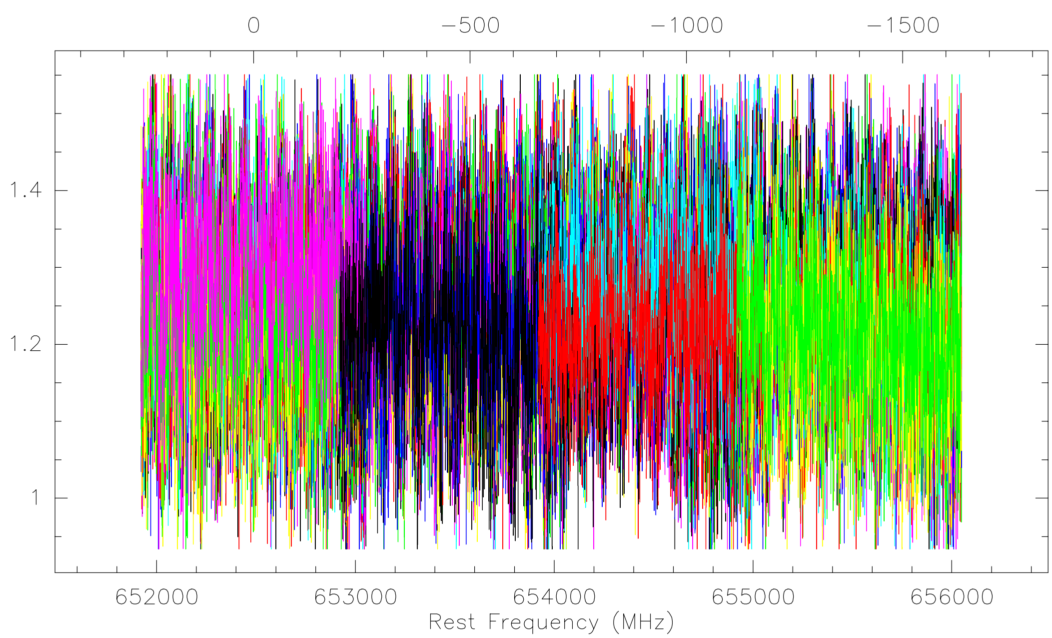
1;1 irc+10216 1838.506 USB HIF−02−WH−7B O:29−APR−2013 R:10−JUL−2015
RA: 09:47:57.41 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: −0.6 +0.5
Unknown tau: 0.000 Tsys: 1167. Time: 1.1 min El: 0.0
N: 1128 I0: 565.000 V0: 0.000 Dv: −8.1327E−02 LSR
F0: 1843129.50 Df: 0.5000 Fi: 1833882.21



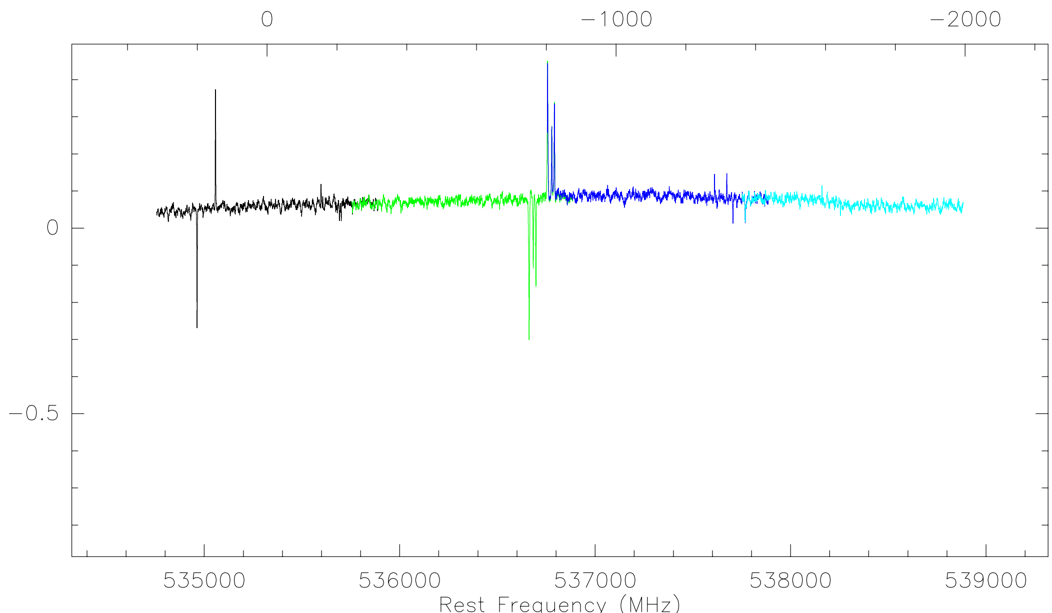
1;1 irc+10216 0539.148 LSB HIF−01−HV−1A O:29−APR−2013 R:10−JUL−2015
RA: 09:47:57.41 DEC: 13:16:43.6 Eq 2000.0 Rad. 0.0° Offs: −1.6 −1.8
Unknown tau: 0.000 Tsys: 77. Time: 1.0 min El: 0.0
N: 1914 I0: 958.000 V0: 0.000 Dv: −6.7533E−02 LSR
F0: 533142.458 Df: 0.1201 Fi: 545153.739



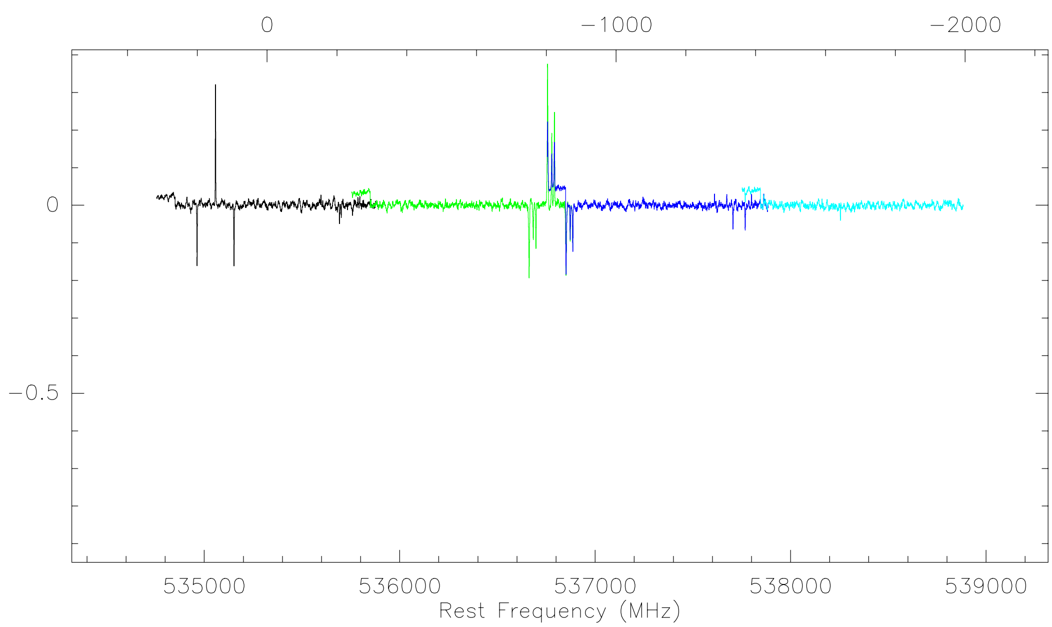
1;1 Mars 0647.999 USB HIF−01−WH−2A O:09−DEC−2011 R:10−JUL−2015
RA: 11:00:41.86 DEC: 08:45:39.9 Eq 2000.0 Rad. 0.0° Offs: −16.4 −19.8
Unknown tau: 0.000 Tsys: 115. Time: 0.12 min El: 0.0
N: 2266 I0: 1134.00 V0: 0.000 Dv: −0.2297 Unkn
F0: 652488.500 Df: 0.5000 Fi: 643509.059



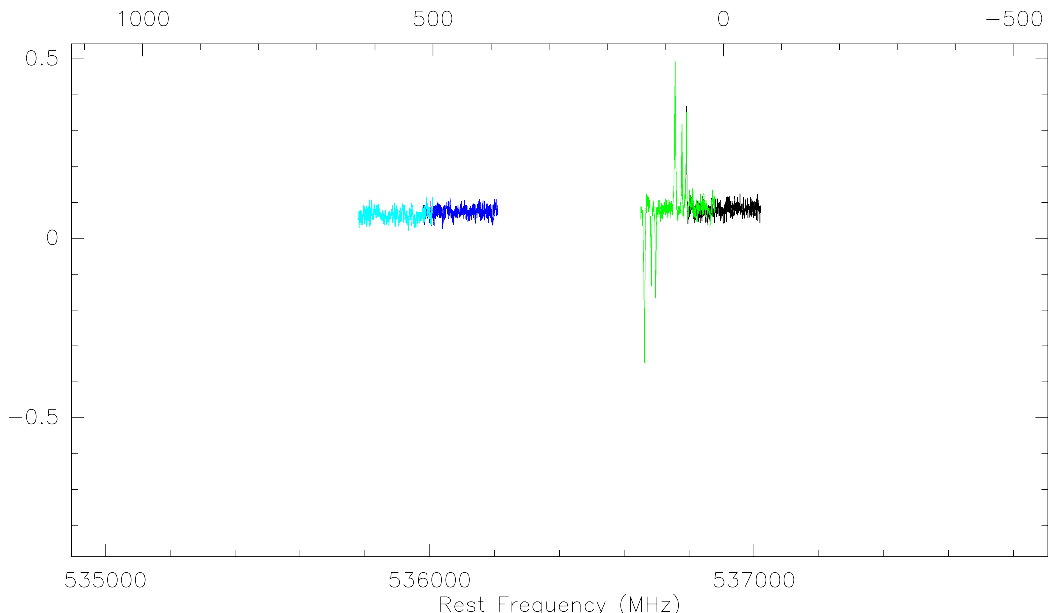
1;1 N7023−H2peak 0530.821 USB HIF−01−WH−1A 0:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +3.0
Unknown tau: 0.000 Tsys: 65. Time: 9.1 min El: 0.0
N: 2263 I0: 1132.00 V0: 0.000 Dv: −0.2800 LSR
F0: 535321.500 Df: 0.5000 Fi: 526319.712



1;1 N7023−H2peak 0530.821 USB HIF−01−WH−1A 0:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +3.0
Unknown tau: 0.000 Tsys: 65. Time: 18. min El: 0.0
N: 2263 I0: 1132.00 V0: 0.000 Dv: −0.2800 LSR
F0: 535321.500 Df: 0.5000 Fi: 526319.712



1;1 N7023−H2peak 0530.821 USB HIF−01−HH−1A 0:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +2.9
Unknown tau: 0.000 Tsys: 67. Time: 9.3 min El: 0.0
N: 956 I0: 479.000 V0: 0.000 Dv: −0.1341 LSR
F0: 536905.730 Df: 0.2402 Fi: 524735.481



1;1 N7023−H2peak 0530.821 USB HIF−01−HH−1A 0:04−DEC−2012 R:10−JUL−2015
RA: 21:01:32.40 DEC: 68:10:25.0 Eq 2000.0 Rad. 0.0° Offs: −0.5 +2.9
Unknown tau: 0.000 Tsys: 67. Time: 19. min El: 0.0
N: 956 I0: 479.000 V0: 0.000 Dv: −0.1341 LSR
F0: 536905.730 Df: 0.2402 Fi: 524735.481