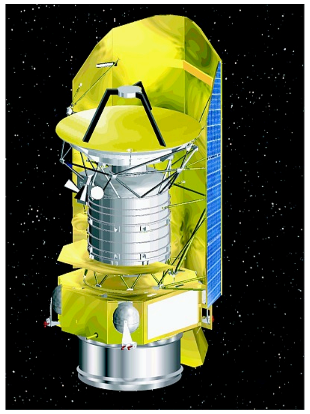

HIFI Wavelength calibration

Fabrice Herpin

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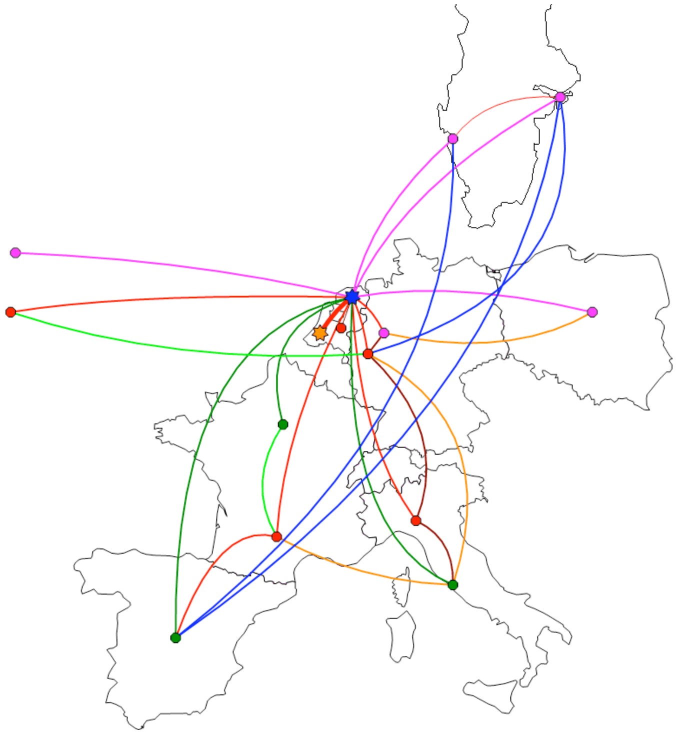
on behalf of all the people involved:

C. Vastel, E. Caux, N. Whyborn, V. Ossenkopf, M. Olberg, D. Teyssier, J. Braine ....



Overview

A. Introduction : HIFI design

B. HIFI frequency calibration approach on ground

    1. strategy

    2. results

C. HIFI frequency calibration approach in space :

    1. normal strategy

    2. backup (rescue) strategy

    3. Astronomical calibration sources

    requirements, source list / visibilities

D. ISO and SWAS experience

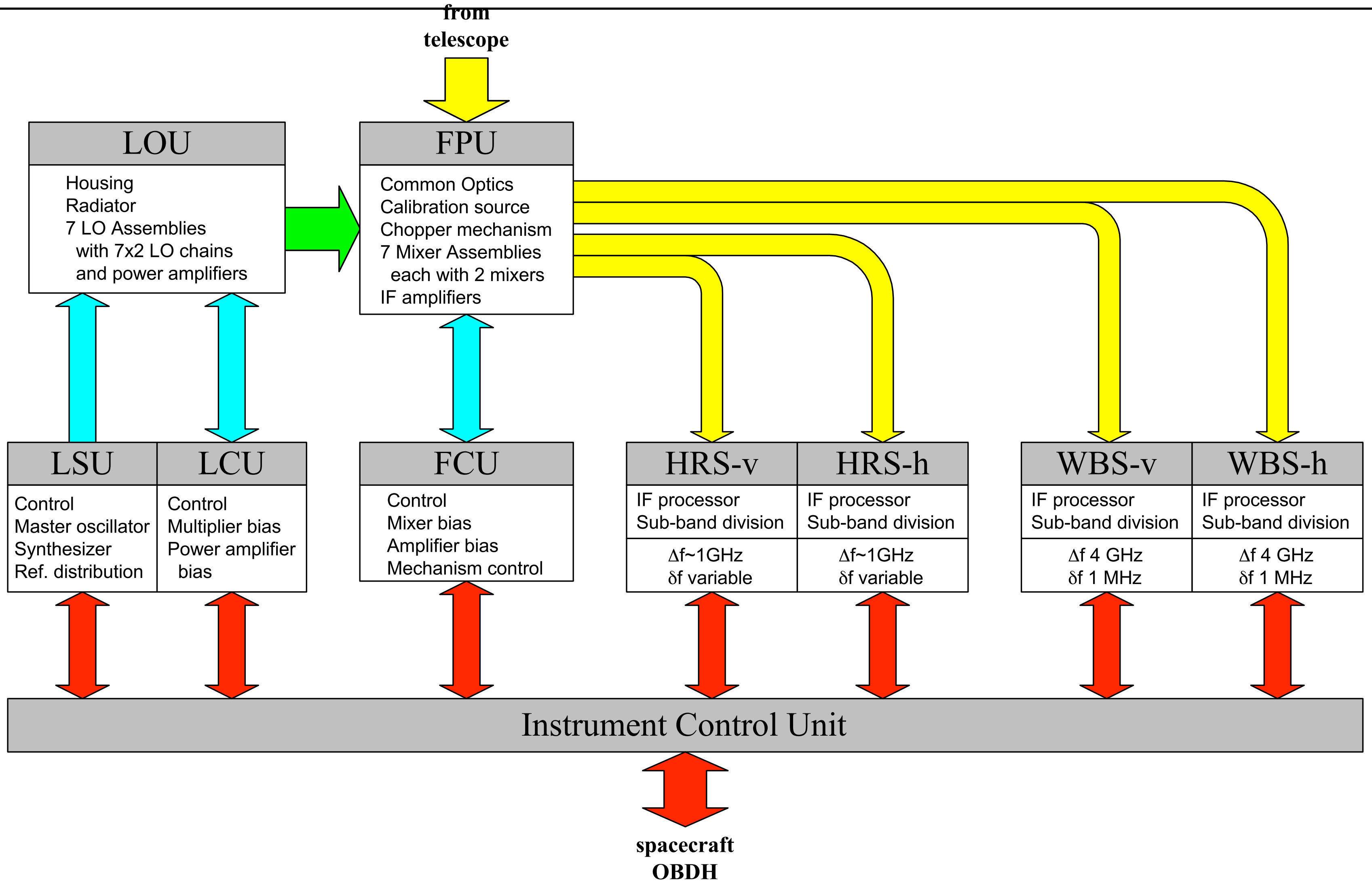
A- Introduction : HIFI design

Frequency calibration measurements address both the calibration of the frequency itself and of the frequency resolution (also called here line profile)

HIFI instrument = *Focal Plane subsystem* (FPU) + *Local Oscillator subsystem* (LO) + *Wide Band Spectrometer* (WBS) + *High Resolution Spectrometer* (HRS) + *Instrument Control Unit* (ICU)

⇒ **Effective instrument spectral response**

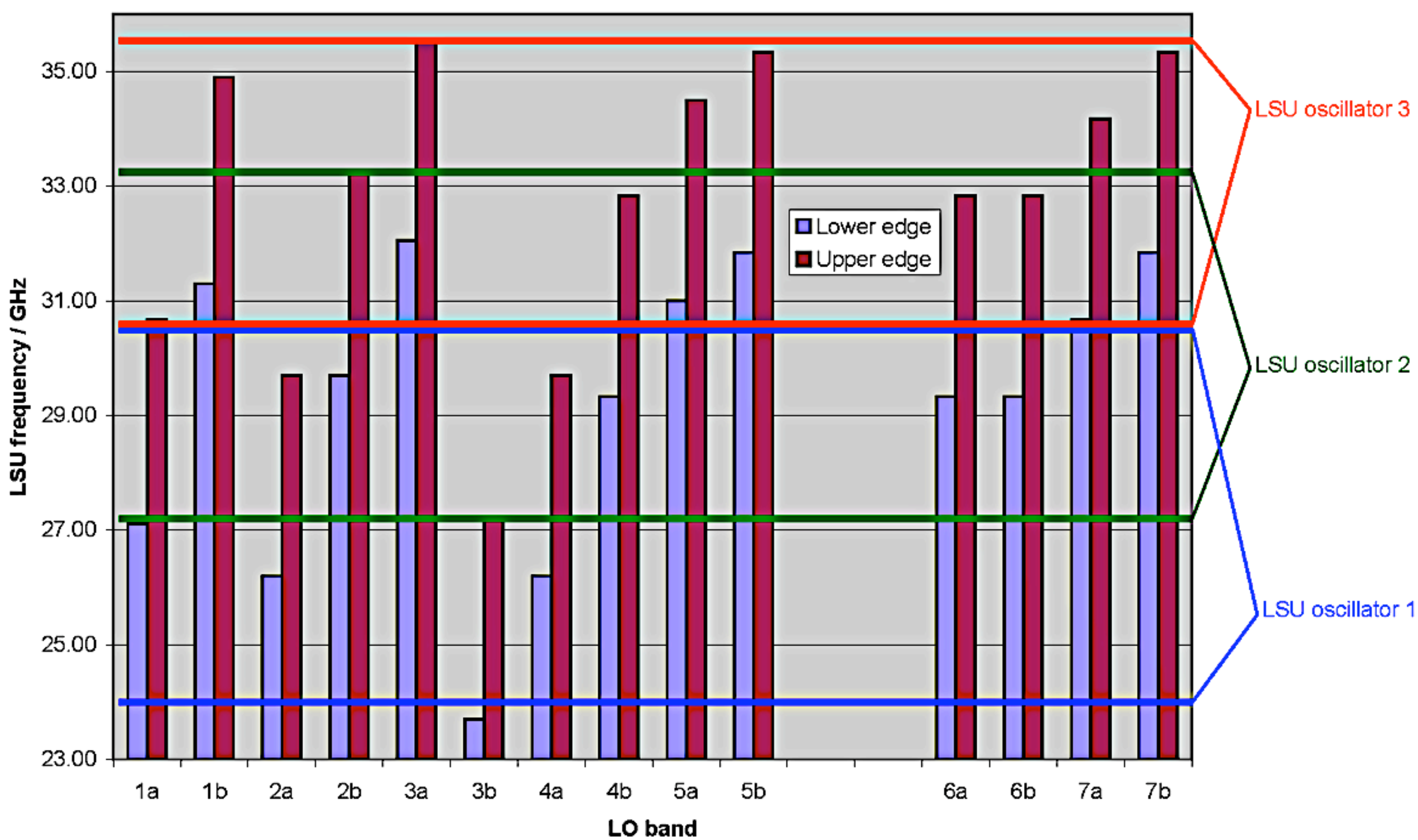
= combination of several spectral element responses along the detection chain.

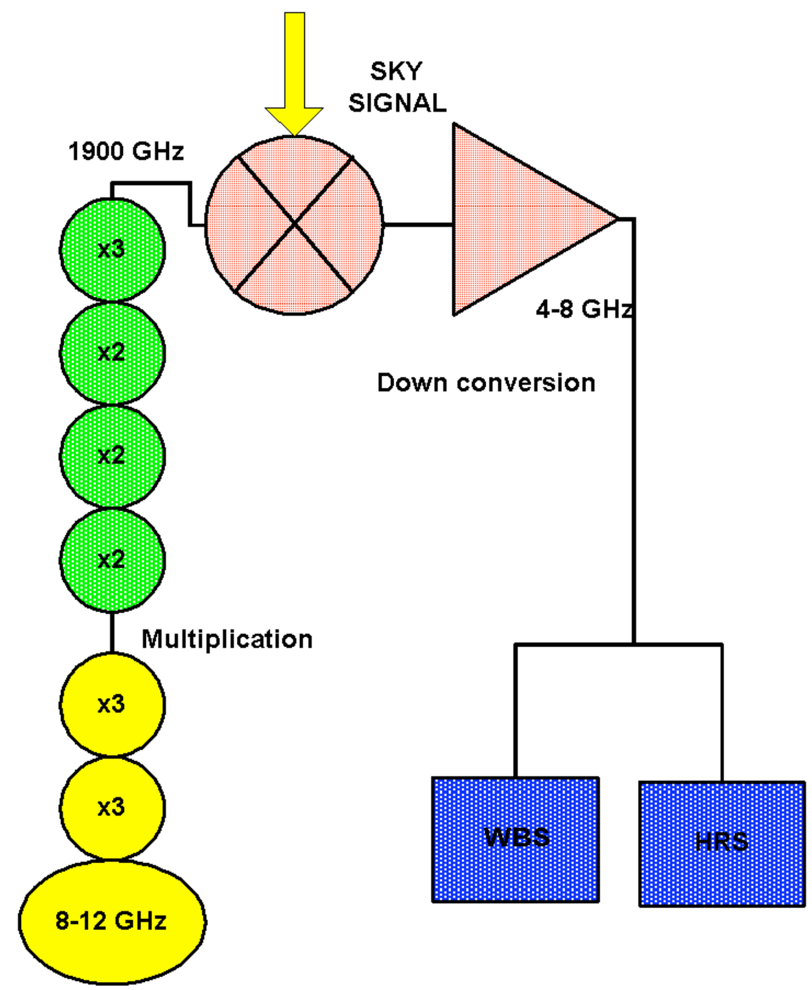


Heterodyne process

L.O. band	first stage [GHz]	up-converter	amplifier [GHz]	multiplier	ν_{LO}-output [GHz]
Ia	27.11-30.67	×3	81-92	×2 × 3	488-552
Ib	31.27-34.88	×3	94-105	×2 × 3	563-628
IIa	26.75-29.58	×3	80-89	×2 × 2 × 2	642-710
IIb	30.17-33.04	×3	90-99	×2 × 2 × 2	724-793
IIIa	33.63-35.46	×3	101-106	×2 × 2 × 2	807-851
IIIb	24.05-26.47	×3	72-79	×2 × 2 × 3	866-953
IVa	26.86-28.94	×3	81-87	×2 × 2 × 3	967-1042
IVb	29.33-30.92	×3	88-93	×2 × 2 × 3	1056-1113
Va	31.00-32.72	×3	93-98	×2 × 2 × 3	1116-1178
Vb	33.11-34.50	×3	99-103	×2 × 2 × 3	1192-1242
VIa	29.41-32.81	×3	88-99	×2 × 2 × 2 × 2	1412-1575
VIb	32.62-35.33	×3	98-106	×2 × 2 × 2 × 2	1566-1696
VIIa	31.33-34.17	×3	94-103	×2 × 3 × 3	1692-1845
VIIb	31.83-35.33	×3	95-106	×2 × 3 × 3	1719-1908

LSU output frequency ranges





HRS

Mode	normal	high resolution	low resolution	wide band
resolution, FWHM	0.27 MHz	0.14 MHz	0.54 MHz	1.1 MHz
lags per sub-band (min.)	2030	4060	1015	1015
sub-band bandwidth (min.)	250 MHz	250 MHz	250 MHz	500 MHz
number of sub-bands (min.)	2	1	4	8

Due to its digital nature, the **HRS frequency calibration is entirely relying on the master oscillator frequency** (HRS is directly locked to the MO).

But band 6 IF up-converter oscillator is not locked to the MO ⇒ to be determined

- ***frequency accuracy = 5 kHz***.
- ***optimal resolution available ≈ 125 kHz*** (not varying from band to band !)

The only degradation is due to the LSU: for HRS observations it is the dominant term.

WBS = 2 acousto-optical 4-channel array-spectrometers.

- WBS amplifies and conditions the two IF signals from the FPU.
- It divides the IF band into 4 sub-bands per polarisation
- it down-converts the IF-signal to a lower frequency suitable for injection into a Bragg cell.

The total bandwidth is 4 GHz (made of 7650 valid frequency pixels).

The ***overall spectral calibration of the AOS makes use of a COMB measurement*** providing lines at known IF frequencies (between 3.9 and 8.1 GHz by steps of 100 MHz).

B- HIFI frequency calibration approach on ground

Frequency accuracy and frequency response function for HIFI/WBS and HIFI/HRS

+ band 6 IF up-converter LO frequency.

- **For HRS observations**, the dominant term is the **degradation due to the LSU**

⇒ to be determined (deconvolve the frequency response function)

- **For the WBS**, the uncertainty sources are:

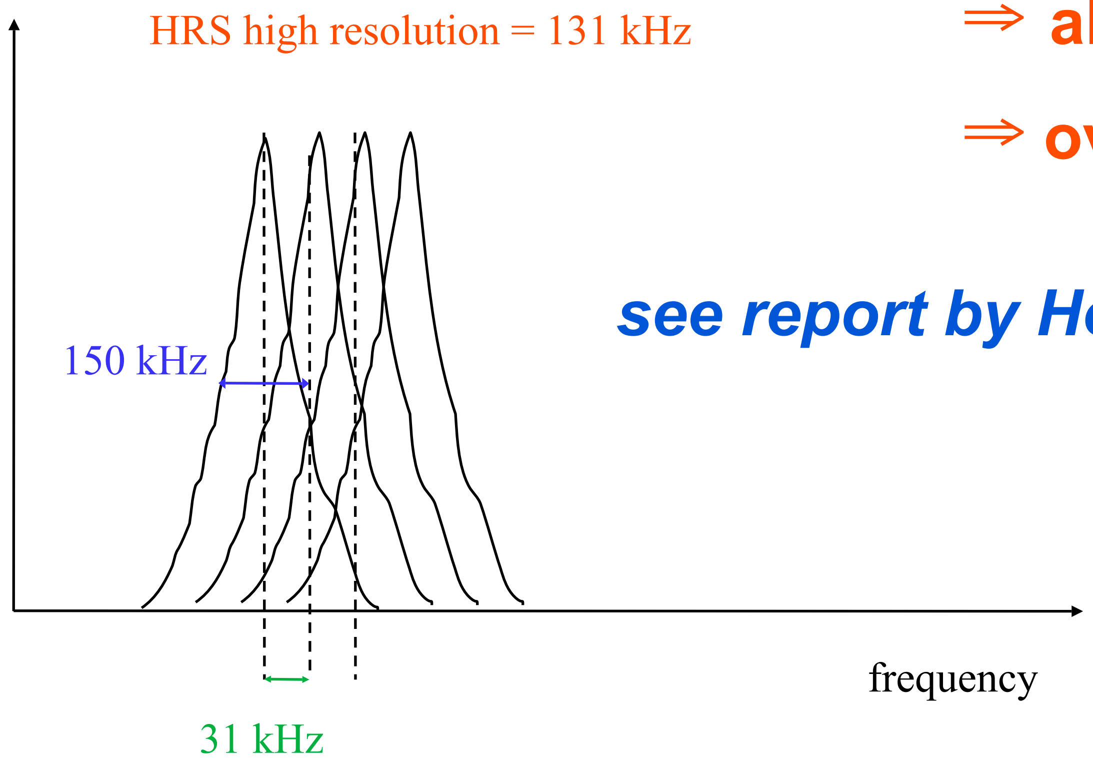
1) ***precision of the frequency reference signal*** (± 0.1 Hz)
2) ***frequency calibration of the AOS scans*** (using the comb scans)
3) ***frequency drift*** of the AOS (internal temperature drift ~ 0.1°/hr ⇒ ~ 0.01 MHz)
4) ***velocity determination of the spacecraft*** (common to the HRS) ~ kHz
5) ***data processing***, e.g. measured 2s scans are calibrated in the HIFI pipeline and are reduced to 3 min co-adds ⇒ frequency uncertainty in the final spectra. Spectral shifting is performed in the software to compensate the spacecraft movement relative to the source while observing ⇒ negligible

1- Strategy

Combine spectra with different test source (spectral line laboratory source**) frequencies to form a composite (oversampled) spectrum**

Band 1a : RF step size = 1 kHz * Int (490/15.64) = 31 kHz

⇒ 196 spectra with injected line shifted by 31 kHz for each



⇒ all spectra realigned in frequency

⇒ oversampled spectra

see report by Herpin & Vastel SRON-G/HIFI/PR/2007-102

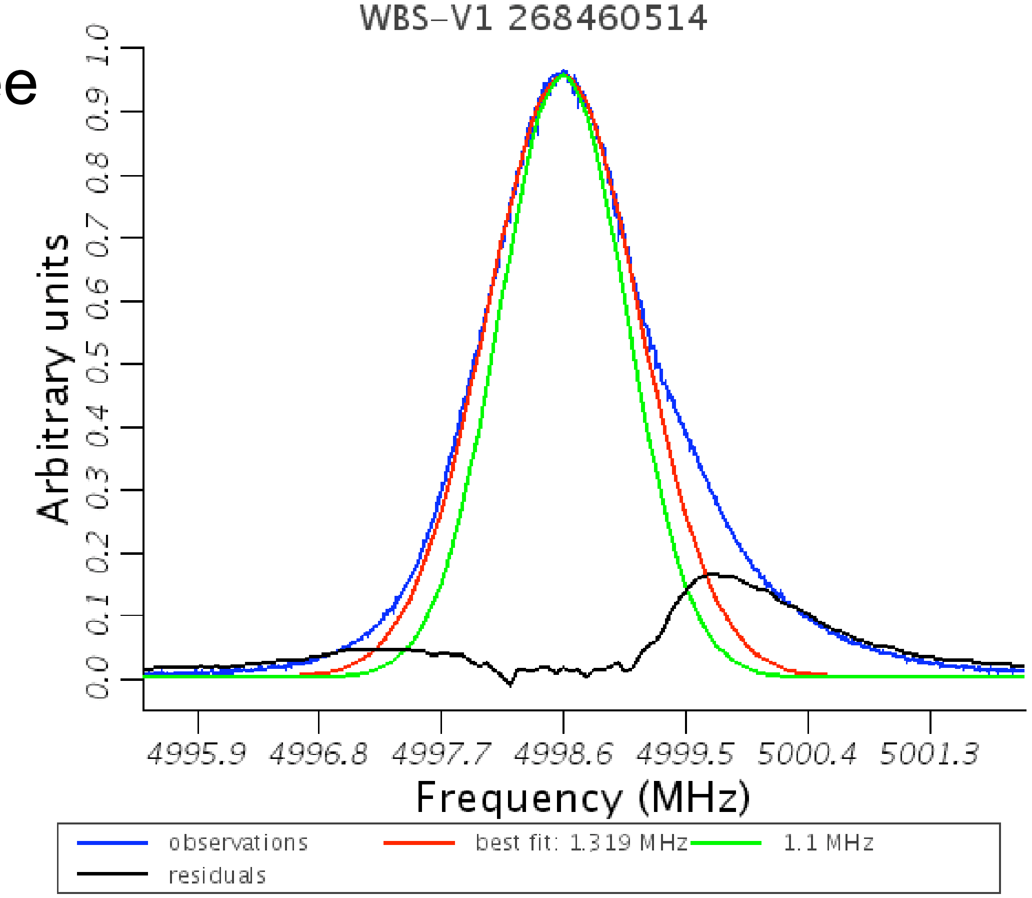
2- Results

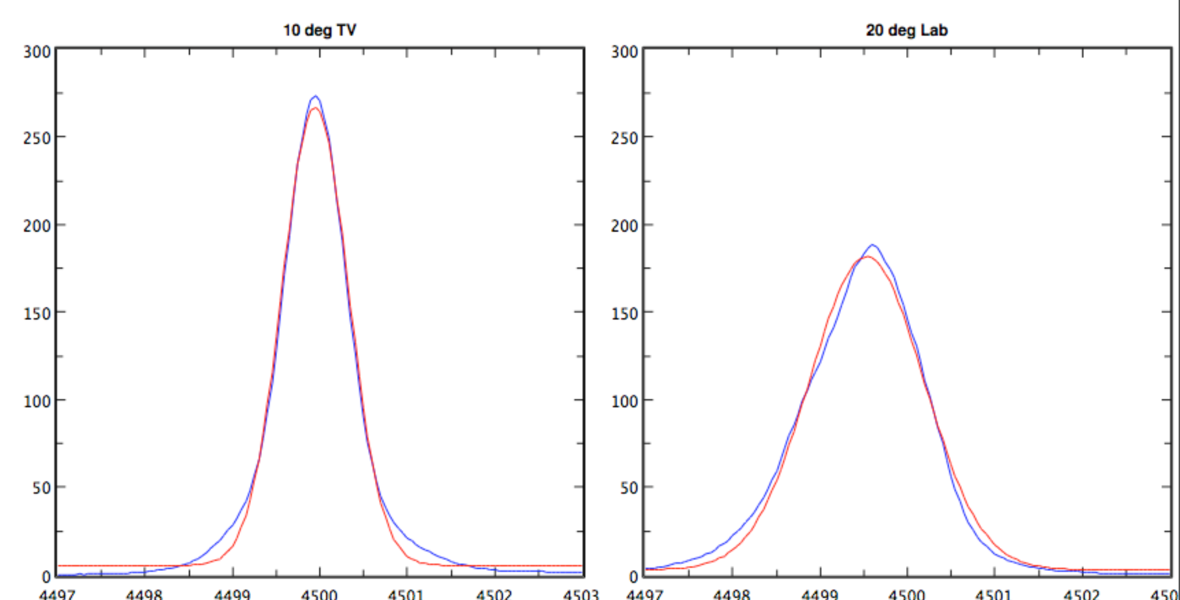
WBS

Lab conditions (normal air pressure, 20°C) out of WBS spec

The shape of the line can be described to a large degree by a Gaussian function but with Lorentzian wings.

- **B_{res} = resolution bandwidth** or equivalent width of a CCD pixel = width of an equivalent boxcar filter, which transmits the identical power. ***Spec = 1.1 MHz***
- **B_{flu} = fluctuation bandwidth B_{flu}** = filter noise characteristic of the spectrometer. ***Spec = 1.6 MHz***





Schieder, Schmülling & Siebertz (Köln)

- Resolution different from one subband to another
- Resolution different between polar H and V
- B_{flu}/B_{res} ratio between 1.45 and 1.58 as expected.
- B_{res} varies between 1.310 and 1.797 MHz

Band	**1a**		**2a**		**2b**		**3a**		**4b**		**6b**	
Freq (GHz)	**490H**	**490V**	**715H**	**715V**	**725H**	**725V**	**840H**	**840V**	**1109H**	**1109V**	**1600H**	**1600V**
	Freq. Accuracy (MHz)								**Freq. Accuracy (MHz)**			
Spec	**0.15**		**0.17**		**0.17**		**0.18**		**0.21**		**0.31**	
Result/sb												
1	0.05		0.02	0.04	0.05	0.07	0.10	0.10	0.10	0.11		
2	0.10		0.10	0.05	0.10	0.08	0.16	0.10	0.17	0.12		
3	0.05		0.09	0.10	0.05	0.08	0.09	0.09	0.07	0.10		
4	0.09		0.10	0.09	0.07	0.07	0.13	0.09	0.10	0.07		
Result/sb	**B_{res} (MHz)**								**B_{res} (MHz)**			
1	1.43		1.48	1.54	1.31	1.61	1.58	1.71	1.48	1.68		
2	1.73		1.65	1.58	1.54	1.51	1.79	1.65	1.70	1.60		
3	1.46		1.46	1.67	1.39	1.65	1.56	1.80	1.53	1.70	1.43-1.48	1.65-1.71
4	1.52		1.53	1.43	1.45	1.42	1.64	1.44	1.58	1.45	1.48-1.54	1.42-1.46

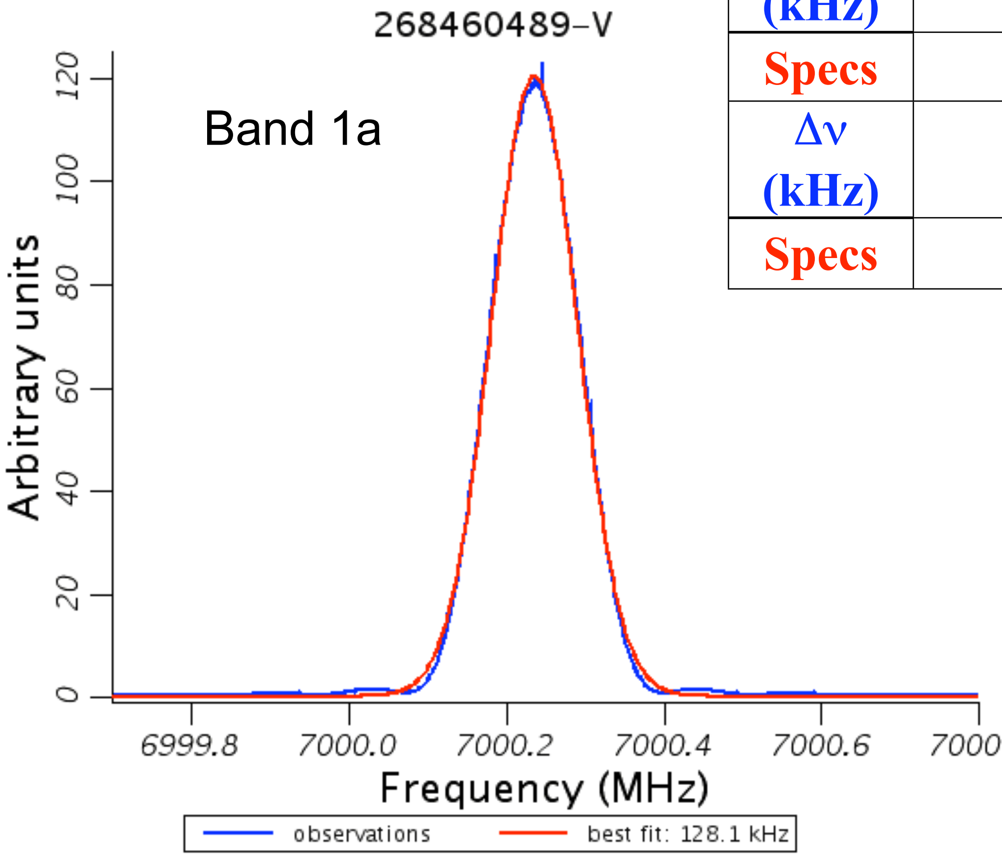
WBS resolution is out of specification

BUT test conditions were out of specification too.

see report by Herpin & Vastel SRON-G/HIFI/PR/2007-102

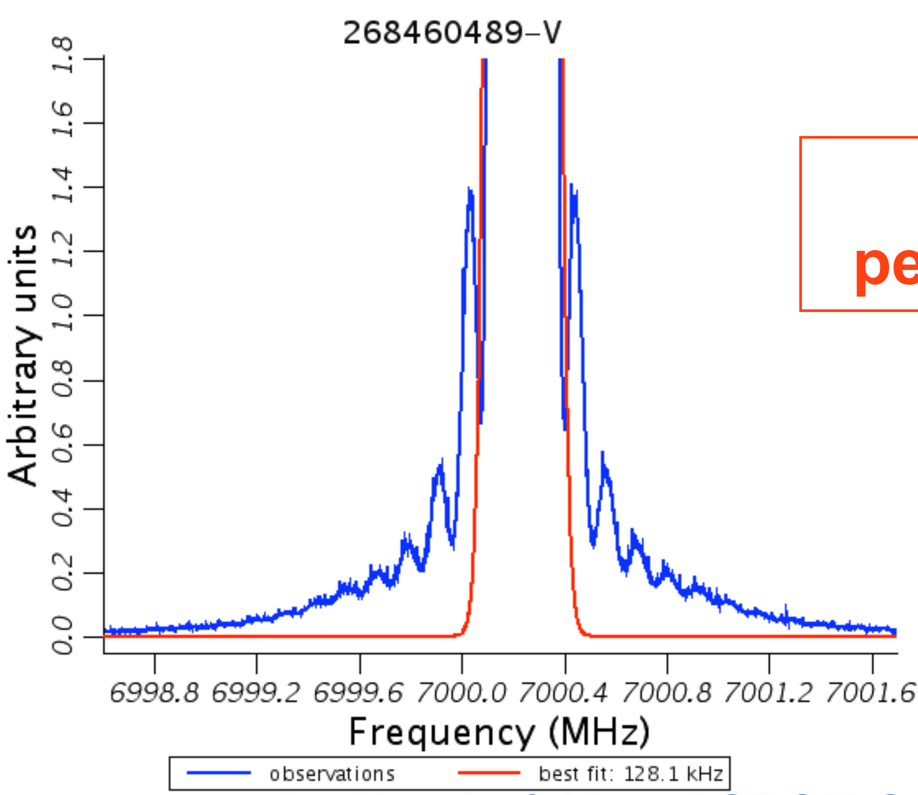
HRS

	Band 1a		Band 2a		Band 2b		Band 3a		Band 4b		Band 6b	
	H	V	H	V	H	V	H	V	H	V	H	V
FWHM (kHz)	125.8	127.6	216.4	215.7	171.2	170.4	155.5	157.7	157.2	153.4	185.9	184.4
Specs	160		180		180		190		230		280	
Δν (kHz)	21		31.4		31.6		37.6		40.5			
Specs	53		69		69		85		117			



	LSU1 Lower (Band2a)		LSU2 Lower (Band 1a)		LSU2 Upper (Band 4b)		LSU3 Lower (Band 2b)		LSU3 Upper (Band 3a)	
	H	V	H	V	H	V	H	V	H	V
FWHM (kHz)	180	180	50	53	100	100	105	105	100	100
Measured	173		92		145		131		205	
Specs	110		80		190		110		130	

+ resolutions for the other bands (1b, 3b, 4a, 5a, 5b, 6a) interpolated assuming a linear behaviour



Conclusions:
perfect, except for bands 2a, 3b, 4a out of specifications

The IF up-converter LO frequency (f_{LO2}) are :

- 10404.6 MHz in H polarization
- 10403.2 MHz in V polarization

see report by Herpin & Vastel SRON-G/HIFI/PR/2007-102

CSIC CAMK NUI MAYNOOTH LERMA KOSMA ipac CESR CAISMI SRON

C- HIFI frequency calibration approach in space

Performance Verification Phase will not allow to add to the characterisation of the spectral properties of HIFI done during ILT on ground because:

- ***HIFI/HRS*** frequency accuracy and resolution /frequency response measured on ground and reliable ⇒ ***not in space***.

  Moreover : impossible in space because we do not have any source emitting a line narrow enough !

- ***HIFI/WBS*** frequency resolution and line profile not properly checked on ground because the lab test conditions were out of spec.

  ⇒ in space ?

  The difficulty is that the WBS theoretical resolution is 1.1 MHz, hence less that 1km/s at 500 GHz.

  \+ fixed astronomical line will not help much to get the proper spectral channel response.

  But we have the comb...

1- normal strategy

WBS freq. calibration

- ***What do we expect ?***

e.g., based on the experience with the AOS on board of Odin (M. Olberg) or on the CSO, the frequency scale of an AOS can change because of mode jumps of the laser diode = **sudden jumps in frequency / mode-hopping** which can occur with temperature changes (seen in ILT!).

- ***How to check that ?***

- using the **internal combs** to provide the frequency accuracy

$\Rightarrow$ no need to schedule extra time for this

- very well known lines from AGB stars or star forming regions. Calibration lines in any LO band.

2- backup (rescue) strategy

Algorithms developped by V. Ossenkopf

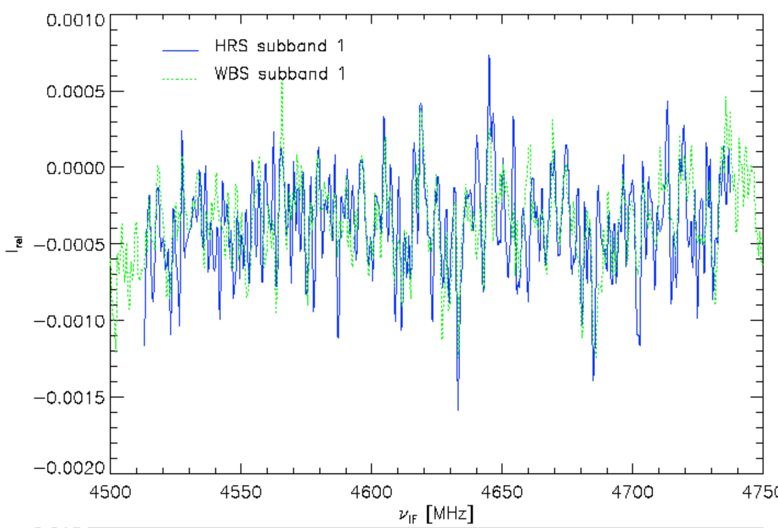
- **in case of one comb failure**

  (e.g. problem detected in comb generator of the WBS-V; subsystem is being replaced)

⇒ ***"bootstrap" the V polarization frequency scaling from the H polarization comb***

= cross calibration to the WBS-H on an astronomical signal.

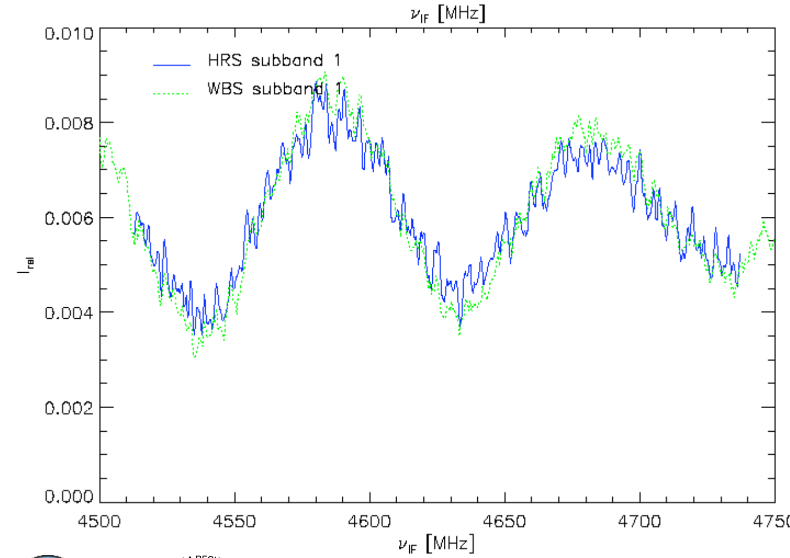
⇒ observe the same spectrum with both AOSs and determine the shift required for the uncalibrated AOS to make it line-up with the calibrated one.



The cross-calibration works even better for broader lines with an internal structure. With many significantly different points across the line, we can even recover the original accuracy goal of 0.1MHz.

- **in case of both combs failure**

⇒ ***noise correlation technique to determine the relative frequency scaling between HRS and WBS*** based on a standard load measurement.



3- Astronomical calibration sources requirements/source list

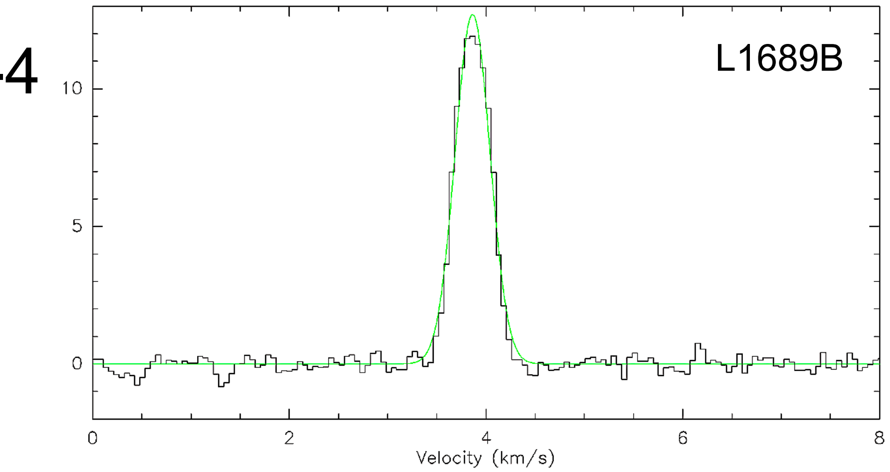
- **narrow strong lines:**
  - ***pre-stellar core*** (e.g., L1689B) in band 1.

According to *CASSIS* model for the *HS3F* GT-KP, the CO 5-4 line at 576 GHz could be strong (1.3 K) and narrow enough (less than 0.5 km/s).

  - ***upper atmosphere of e.g. Uranus***.

98; 4 L1689B   13CO(1−0)   IRAM−30M−B42 O: 27−NOV−1998 R: 19−OCT−2007
RA: 16:31:46.103 DEC: −24:31:54.00 (1950.0) Offs: 0.0 −120.000 Eq
Unknown Tau: .1180 Tsys: 233.1 Time: 2.000 El: 27.81
N: 896 I0: 433.6 V0: 2.500 Dv: −5.3234E−02 LSR
F0: 110201.370 Df: 1.9531E−02 Fi: 112778.129

13CO (1-0) line at 110 GHz (HPLW = 0.417 km/s)



- **broader lines with an internal structure:**

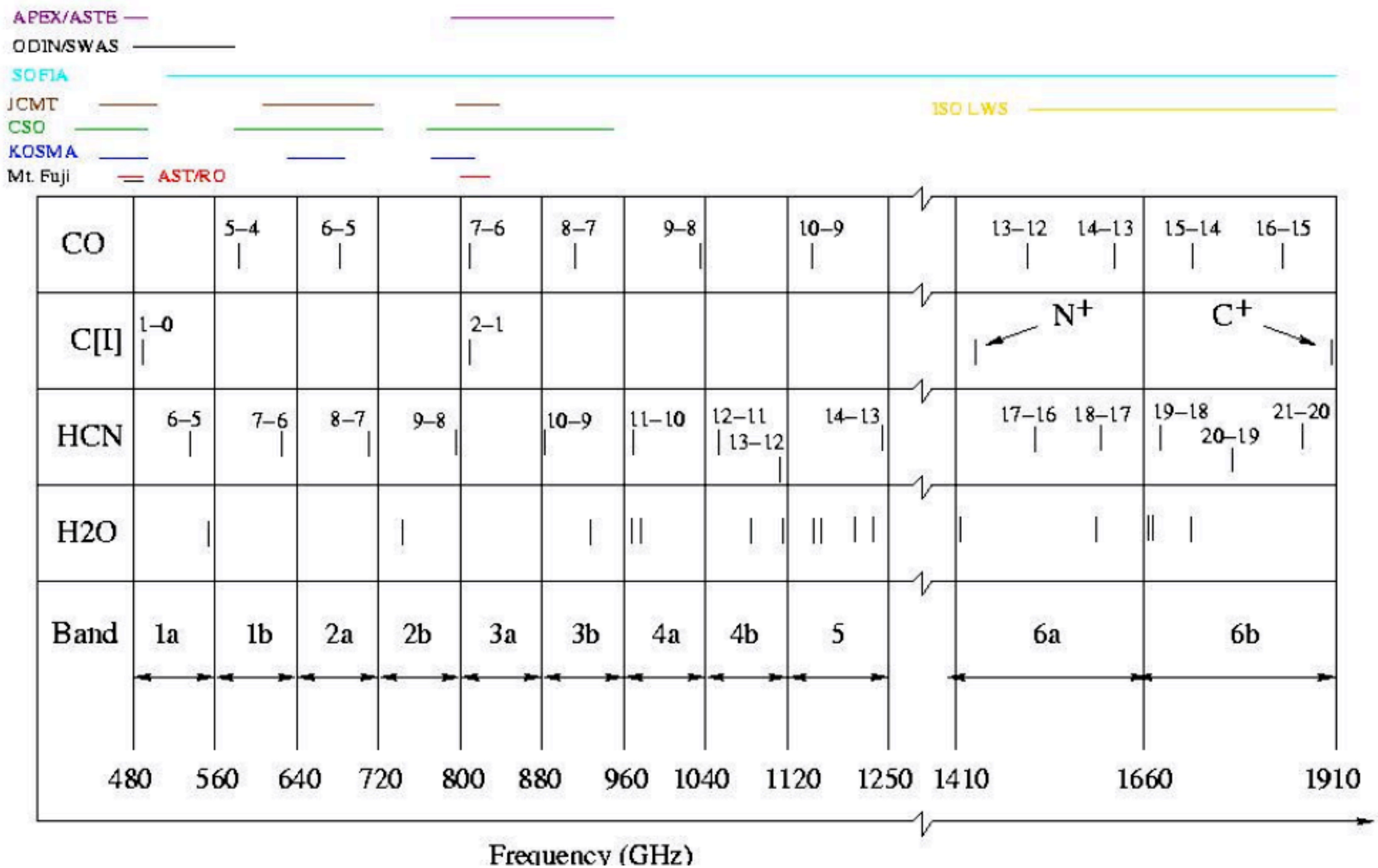
UCHII regions, hot cores, and PDRs = CO(5-4) (band 1b) or CO(6-5) (band 2a), strong water lines (bands 1,2,3).

The CO and H2O lines in the HIFI frequency range arise in warm gas (~100 K) which broadens them to 5 km/s at least, and more typically to 10 km/s. Some of these spectra show narrow absorption features of just 1-2 km/s wide superposed on broad emission lines.

e.g. Orion IRC2 or W49N

- **Visibilities:** at least 1 source visible at any moment of the year. Usually these sources will be our science targets, so they even will be consistent with the mission planning schedule for a given period.

HiFi ICC


APEX/ASTE
ODIN/SWAS
SOFIA
JCMT
CSO
KOSMA
Mt. Fuji
AST/RO
ISO LWS
CO
5–4
6–5
7–6
8–7
9–8
10–9
13–12
14–13
15–14
16–15
C[I]
1–0
2–1
N+
C+
HCN
6–5
7–6
8–7
9–8
10–9
11–10
12–11
13–12
14–13
17–16
18–17
19–18
20–19
21–20
H2O
Band
1a
1b
2a
2b
3a
3b
4a
4b
5
6a
6b
480
560
640
720
800
880
960
1040
1120
1250
1410
1660
1910
Frequency (GHz)

D- ISO & SWAS

- **ISO SWS and LWS** = ***grating spectrometers + Fabry-Pérot***

  ⇒ different !!

  Wavelengths standards were planetary nebulae and HII regions (large number of lines, cf. Vastel thesis). Done weekly.

- **SWAS** = ***heterodyne receivers + AOS*** built by Köln University; selected frequencies around 500 GHz (H_2O, O_2...)

  ⇒ comb calibration

  - final uncertainty = 0.22 MHz.
  - drift of 0.2°/hr ⇒ ± 0.06 MHz in 6 min
  - spectral resolution and fluctuation bandwidth were measured on ground.