HIFI Continuum Intensity repeatability from Mars observations

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Abstract

We investigate the repeatability of the continuum intensity calibration from the Herschel-HIFI instrument, using multi-epoch analysis of Mars measurements obtained in the framework of calibration and science observations. The repeatability is checked both on the short term, using close frequency tunings of Spectral Scans, and on the long term by combining observations at close frequency tunings obtained by any observing mode. Overall, the continuum repeatability ranges from a couple of percents in the lowest bands (1-2) up to typically 10% in the higher bands (6-7). Larger values reaching as high as a factor of two uncertainty can, however, be observed at isolated frequencies where the instrument stability is worse than usual.

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1 Scope of the study

The Heterodyne Instrument for the Far-Infrared (HIFI), on board the Herschel Space Observatory, carried out dedicated observations of Solar System Objects (SSOs) devoted to both regular beam calibration measurements and science programmes (see also Sect. 5.9 of the HIFI Handbook[1], or Hartogh et al. (2009)). Most of these targets exhibit continuum emission that can be detected within the HIFI sensitivity, and they could therefore be used to study the repeatability of the continuum calibration over measurements performed multiple times throughout the mission. Table 1 compiles the SSO targets observed at least once by HIFI, together with the observing mode used.

Source	P	M	S	Total
Mars	54	61	12	127
Jupiter	14	9	0	23
Saturn	25	16	0	41
Uranus	7	0	0	7
Neptune	2	4	0	6
Titan	6	0	0	6
Ceres	7	0	0	7
Cybele	1	0	0	1
Themis	1	0	0	1

Table 1: Compilation of HIFI observations towards SSOs. The observing modes are denoted as "P" (Single Point), "M" (Spectral Mapping) and "S" (Spectral Scan). Note that asteroids Cybele and Themis were observed in Frequency Switching mode, and as such could not deliver any reliable continuum measurement.

Because Mars was used as prime calibrator, it was extensively observed in various observing modes throughout the mission, and covered a broad range of frequency tunings, as is illustrated in Fig. 1. No other planet or asteroid offers a similar coverage, both in frequency, and repetition number. We will therefore focus here on observations of this planet in order to derive continuum repeatability figures at various frequency tunings over the HIFI operational range.

It should be noted, however, that the main-belt asteroid Ceres was observed multiple times at a particular frequency tuning in band 1a. The repeatability figure was analysed by (Müller et al. 2014), and is of a couple of percent, consistent with results found with Mars at this frequency (see Section 3). Beside, the measured continuum and the modelled one agree within 5%.

[1] http://herschel.esac.esa.int/twiki/pub/Public/HifiDocsEditableTable/hifi_handbook.pdf

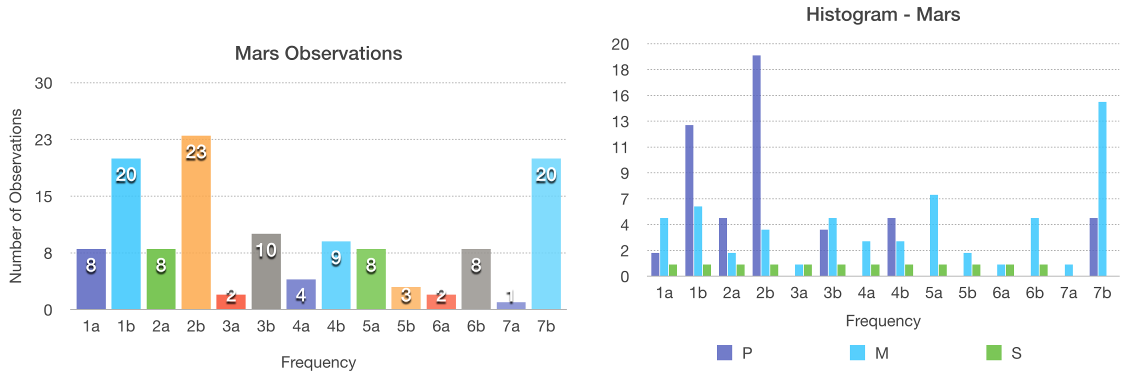

Figure 1: Number of HIFI Mars observations per sub-bands (left - histogram colours are arbitrary), and observing modes (right)

2 Continuum estimate sample

2.1 Continuum derivation from HIFI observations

Estimates of the double-sideband continuum levels were performed for every individual Level 2 spectrum obtained in a Mars observation (for a description of the HIFI products and their processing level, please refer to the HIFI Products Explained document[2]). For both single point and spectral scan observations, this corresponds to one unique measurement per frequency tuning and polarisation. For spectral maps, however, there are as many spectra as pixels sampled on the sky. In order to compare measurements towards the same line-of-sight, only the central pixels of spectral maps were therefore considered. In case of even numbers of rows or columns in the map, an average of the central two (in case of an even $\times$ uneven pixel map dimension) or four (in case of an even $\times$ even pixel map dimension) pixels was considered, leading to a slightly under-estimate of the expected peak intensity at the map geometrical centre. The pixel number(s) used for each map is compiled in Table 4. Note that no attempt was made to correct for pointing error in the Mars maps (this is in contrast with what was performed in similar studies of spectral line repeatability – see Olberg 2014[3]).

Although Mars observations were often performed at frequency tunings chosen such that no spectral lines would be covered by the instantaneous frequency coverage of the Wide-band Spectrometer, this was not the case of observations belonging to the science programme. For those, dedicated line masking was required. The continuum is then computed as the mean of the intensities over all unmasked channels. Further details about

[2] http://herschel.esac.esa.int/twiki/pub/Public/HifiDocsEditableTable/HIFI_Products_Explained_v1.pdf

[3] http://herschel.esac.esa.int/twiki/pub/Public/HifiDocsEditableTable/Continnum_Repeatiblity_AGB_Monitoring.pdf

continuum derivation on HIFI spectra are given in Rodriguez & Teyssier 2015[4].

2.2 Mars model

The Mars continuum model used to calculate the flux densities at the HIFI reference wavelengths for the mid-time of each observation, and in the Herschel-centric reference system, was provided by Raphael Moreno, and is based on the work of Rudy et al. (1987). The initial model was developed by E. Lellouch and H. Amri, and it is available in its version 1.3 to the community[5]. Modelled flux densities, which are averaged over the surface of the planet, can be directly compared to observations. A possible refinement consists in using the full 2D representation of the HIFI beam and compute beam weighted flux densities (Mueller et al. 2014[6]). However, it is not considered here.

2.3 Pseudo-light curves

Because no dedicated observing programme was designed and performed in order to specifically perform multi-epoch measurements of the same continuum target at the same frequency tunings, one needs to find groups of observations of Mars that match a certain frequency tuning window. The assumption here is that the continuum can be considered constant within a given frequency span when compared to the typical calibration precision. To estimate this span, one can directly use the Mars model at some representative frequencies, and check how large the span can be until the continuum variation exceeds a pre-defined threshold. Preliminary tests on multi-epoch measurements done at low frequency tunings show that the repeatability can be as low as 1% when the instrument performs well. We therefore assumed that the frequency span should not imply intrinsic source continuum variation by more than 0.1%. This threshold translates into a maximum frequency span of 4 GHz.

With this assumption, we considered that any group of measurements taken towards Mars at frequencies falling within a common range of 4 GHz could be considered as multi-epoch measurements of the same target and frequency. When this criterion is applied to the sample of Mars observations, a total of 254 frequency groups of at least two measurement points (or "epochs") is found. We, however, enforced that the time series should consist of at least 3 measurements. This restricts the number of pseudo-light curves to 153. Of these, we distinguished those comprised solely of frequency tunings belonging to a same spectral scan and therefore comparing measurements taken very close in time (within minutes), from those mixing various observations, potentially taken months apart.

[4] `http://herschel.esac.esa.int/twiki/pub/Public/HifiDocsEditableTable/HIFI_StWv_Study_FinalReport_GRodriguez.pdf`

[5] `http://www.lesia.obspm.fr/perso/emmanuel-lellouch/mars/`

[6] `http://herschel.esac.esa.int/twiki/pub/Public/HifiDocsEditableTable/HifiBeamReleaseNote_Sep2014.pdf`

The first group amounts to 125 individual frequency points while the second one is limited to 28. In the following section we analyse those groups separately, and interpret the reproducibility figures they reveal as short-term and long-term respectively.

3 Continuum repeatability results

3.1 Long-term repeatability

The continuum intensity repeatability on the long-term is assessed based on the analysis of time series formed by measurements belonging to different observations. This implies in most cases that different observing modes are mixed in the time series. Because the Mars brightness temperature as seen from Herschel will vary with time, each continuum measurement is normalised to the modelled value. The standard deviation of the time series at a given frequency tuning is then computed, and it is considered to provide a measure of the 1-σ uncertainty on the continuum repeatability. In this process, we note the existence of obvious outliers in the time series, which are representative of instrument sub-optimal configuration, rather than intrinsic to the instrument performance at the studied frequency. In order to filter out those outliers from our analysis, we applied the method described in Appendix A. We also filtered out measurements affected by saturation or anomalous tuning.

The 28 time series considered for this sub-sample are shown in Figures 2 to 4. They sample frequencies covering the whole of the HIFI operational range, however, no measurement was available in bands 6a and 7a. The extracted repeatability figures are shown in function of tuning frequency in Fig. 5, and the mean of measurements belonging to the same HIFI band are summarised in Table 2.

Overall, the repeatability performance is degrading with increasing tuning frequency, which is in line with the fact that instrument stability is worse typically in bands 6 and 7. Repeatability figures as low as a couple of percents can be achieved at stable frequency spots in the lower bands, increasing to 5-8% when reaching bands 4-5. In bands 6 and 7, the repeatability is in slight excess of 10%. On top of that, much worse repeatability performances can be observed at spot frequencies due to local instability in the instrument tuning. The granularity of the long-term repeatability sample is, however, not fine enough to derive a clean picture of those. This is improved in the sample described in the following section.

3.2 Short term repeatability from Spectral Scan measurements

Assuming that the continuum does not vary by more than 0.1% over frequency bins of 4 GHz (Section 2.3), one can consider that subsequent frequency tunings of a given spectral scan provide short term (of the order of 10 minutes) time series of identical

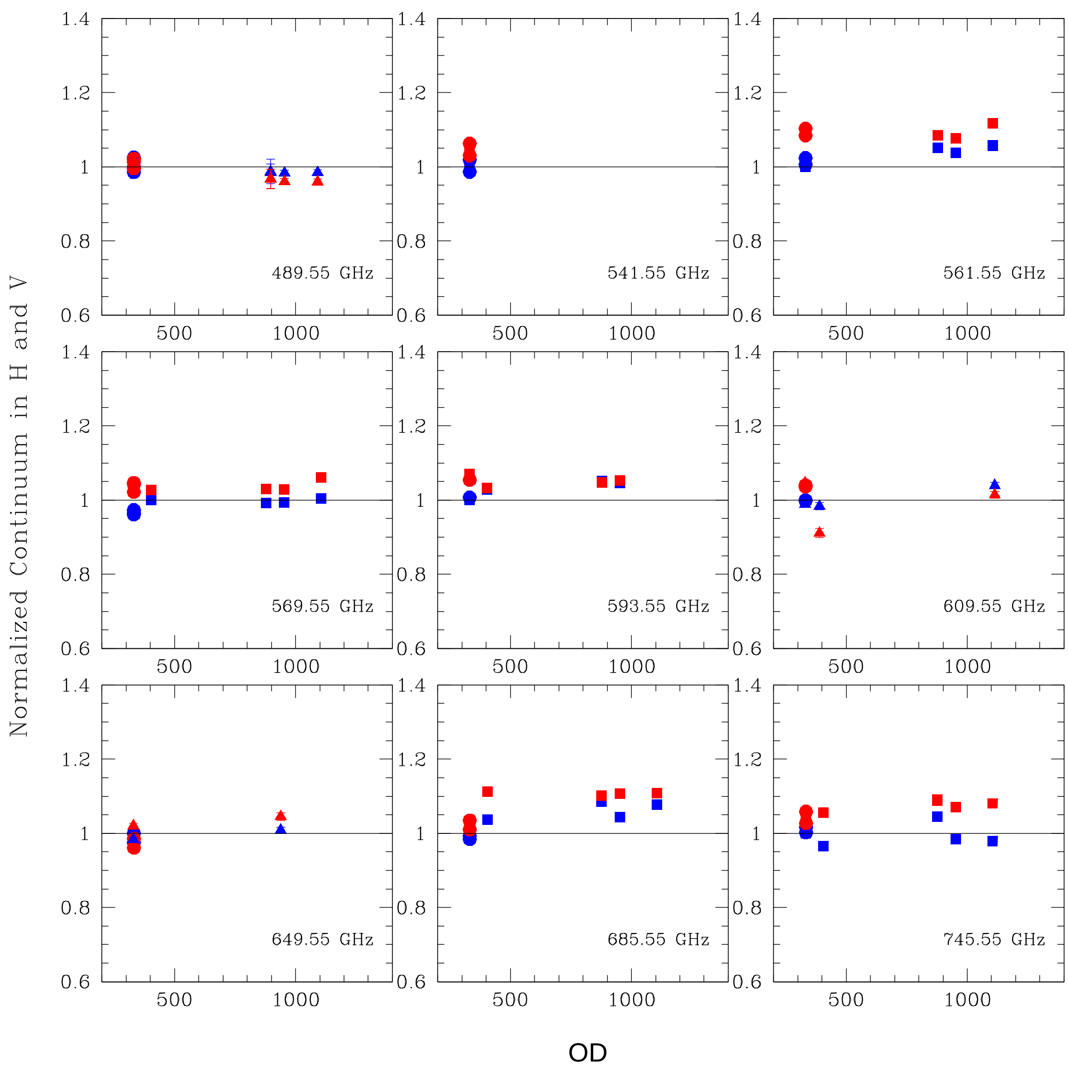

Figure 2: Continuum levels normalised by Mars model as a function of Herschel Observational Day (OD) for each tuning frequency bin centre. H and V polarisation measurements are shown in blue and red symbols respectively. Circles, triangles and squares are used respectively for Spectral Scan, Single Point and Spectral Map observations. Error bars correspond to the 1-sigma noise measured over the individual spectra, and is sometimes smaller than the symbols.

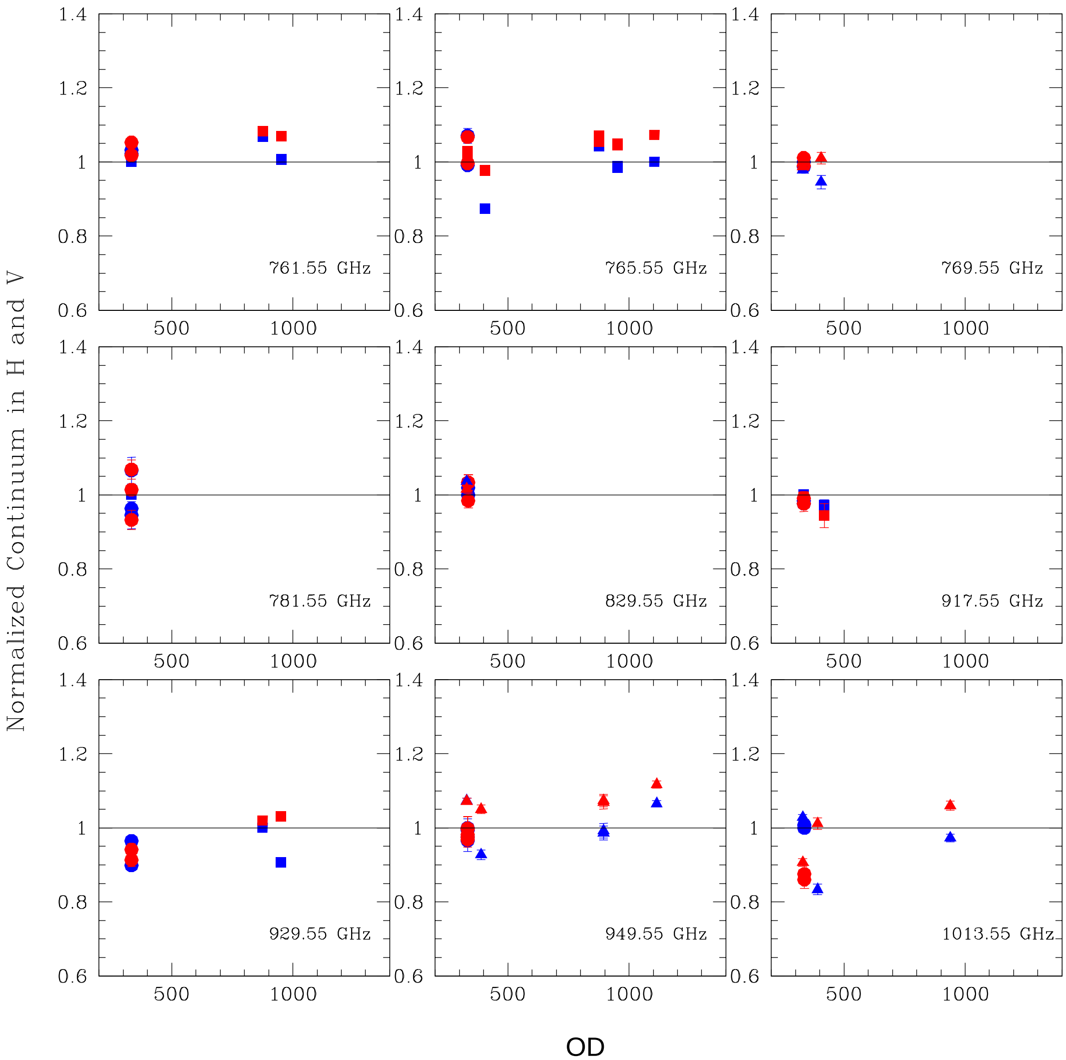

Figure 3: Continued from Fig. 2

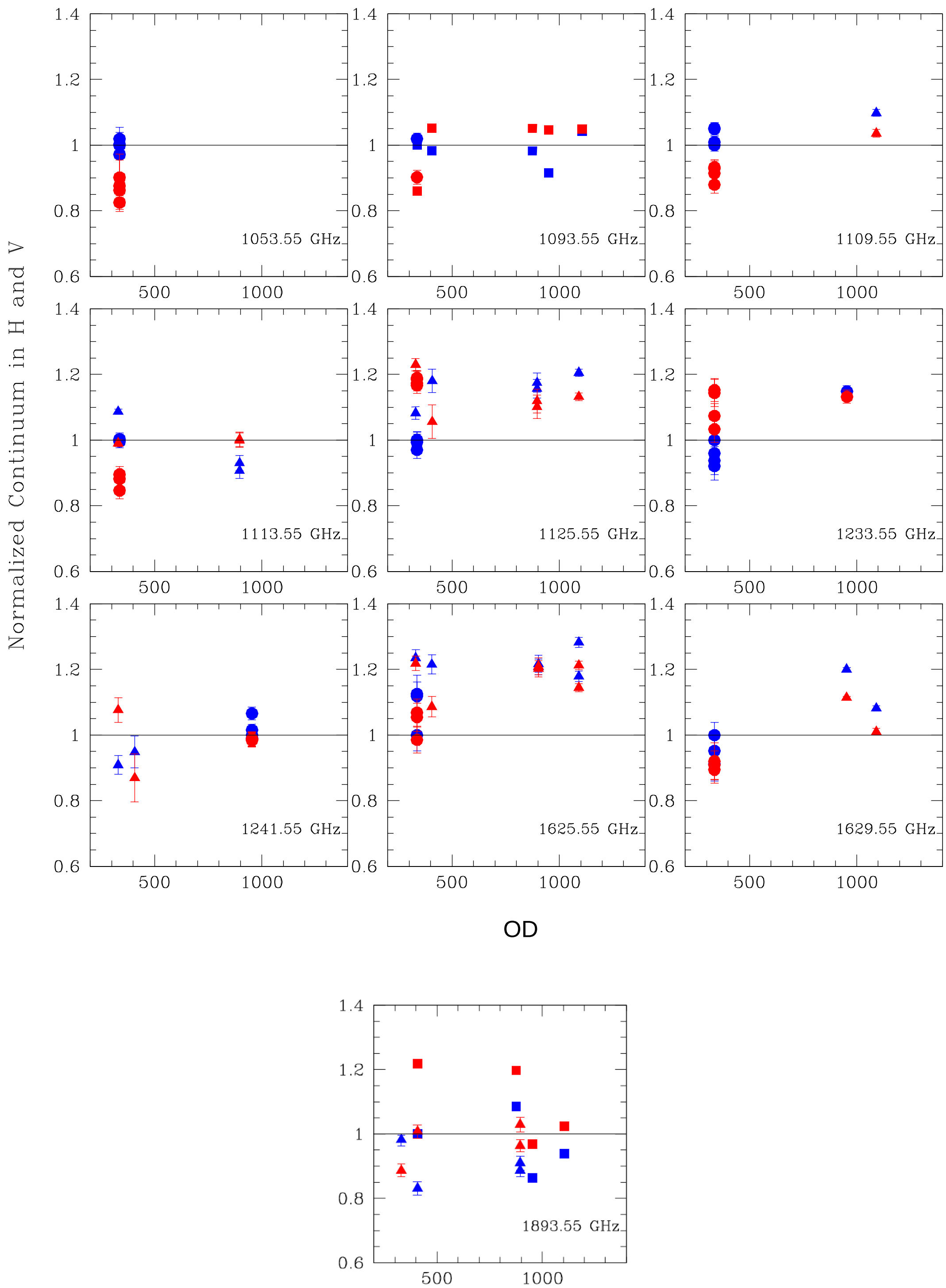

Figure 4: Continued from Fig. 3

Table 2: Continuum repeatability results averaged per HIFI band for the multi-Obsid sample

Band	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b
Repeatability H	1.7	2.4	2.9	3.0	1.7	4.4	5.2	5.8	8.4	5.7	–	8.5	–	8.3
Repeatability V	2.5	1.5	4.2	2.9	3.3	6.0	6.4	7.3	4.7	6.9	–	7.6	–	11.5
Repeatability H/V	2.1	1.9	3.6	3.0	2.5	5.2	5.8	6.5	6.5	6.3	–	8.0	–	9.9

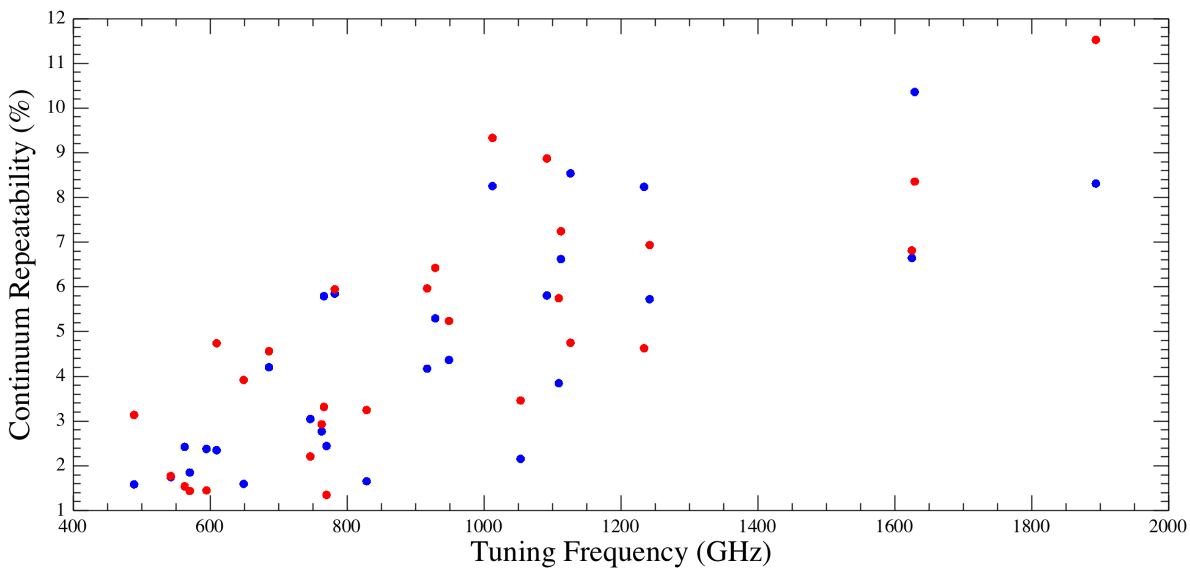

Figure 5: Continuum repeatability as a function of tuning frequency for the multi-Obsid sub-sample. Blue dots correspond to the H polarisation, while red dots represent the V polarisation.

continuum measurements from which some statistic can be derived. We applied that same approach as the one described in the previous section to the Spectral Scans performed on Mars from bands 1a to 6b. Because the Mars continuum model is virtually identical for any measurement involved in a given time series, normalisation by the mean of all measurements is enough here.

The derived standard deviation derived from this process on all available time series are summarised in Fig. 6, while the corresponding means per HIFI band are given in Table 3. Fig. 6 illustrates the very good performance in the frequency range 480–950 GHz with repeatability figures below 3%. Above this frequency, spot frequencies appear where the instrument instability drives the performance and leads to continuum fluctuation that can reach 50-80% even for the short term period we are sampling here. On average, however, the short term repeatability is better than 5% up to band 5, but only slight higher than than in bands 6 and 7. This is in contrast with longer-term repeatability where performances are worst in the higher bands. This is also expected since the instrument performance benefits greatly from the thermalised system achieved while scanning over closeby frequencies of a Spectral Scan.

Table 3: Continuum repeatability results averaged per HIFI band for the Spectral Scan sample

Band	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b
Repeatability H	1.4	0.6	0.9	3.4	1.4	2.8	3.9	3.0	2.7	1.2	4.8	2.7
Repeatability V	1.4	0.8	1.1	2.7	1.9	2.7	2.3	2.0	3.2	2.8	7.2	4.5
Repeatability H/V	1.4	0.7	1.0	3.0	1.7	2.8	3.1	2.5	3.0	2.0	6.0	3.6

4 Acknowledgement

This work benefited from a lot of interaction with experts from the HIFI Instrument Control Centre. We wish to thank in particular Michael Mueller (RuG, The Netherlands) who initiated this study, Willem Jellema (NOVA, The Netherlands) for his work on the HIFI spatial response, and Raphael Moreno (LESIA-Observatoire de Paris, France) for providing detailed Mars models at frequencies of interest. We also thank Michael Olberg (OSO) for his review and comments on the document.

References

Hartogh, P., Lellouch, E., Crovisier, J., et al. 2009, Planetary and Space Science, 57, 1596

Müller, T., Balog, Z., Nielbock, M., et al. 2014, Experimental Astronomy, 37, 253

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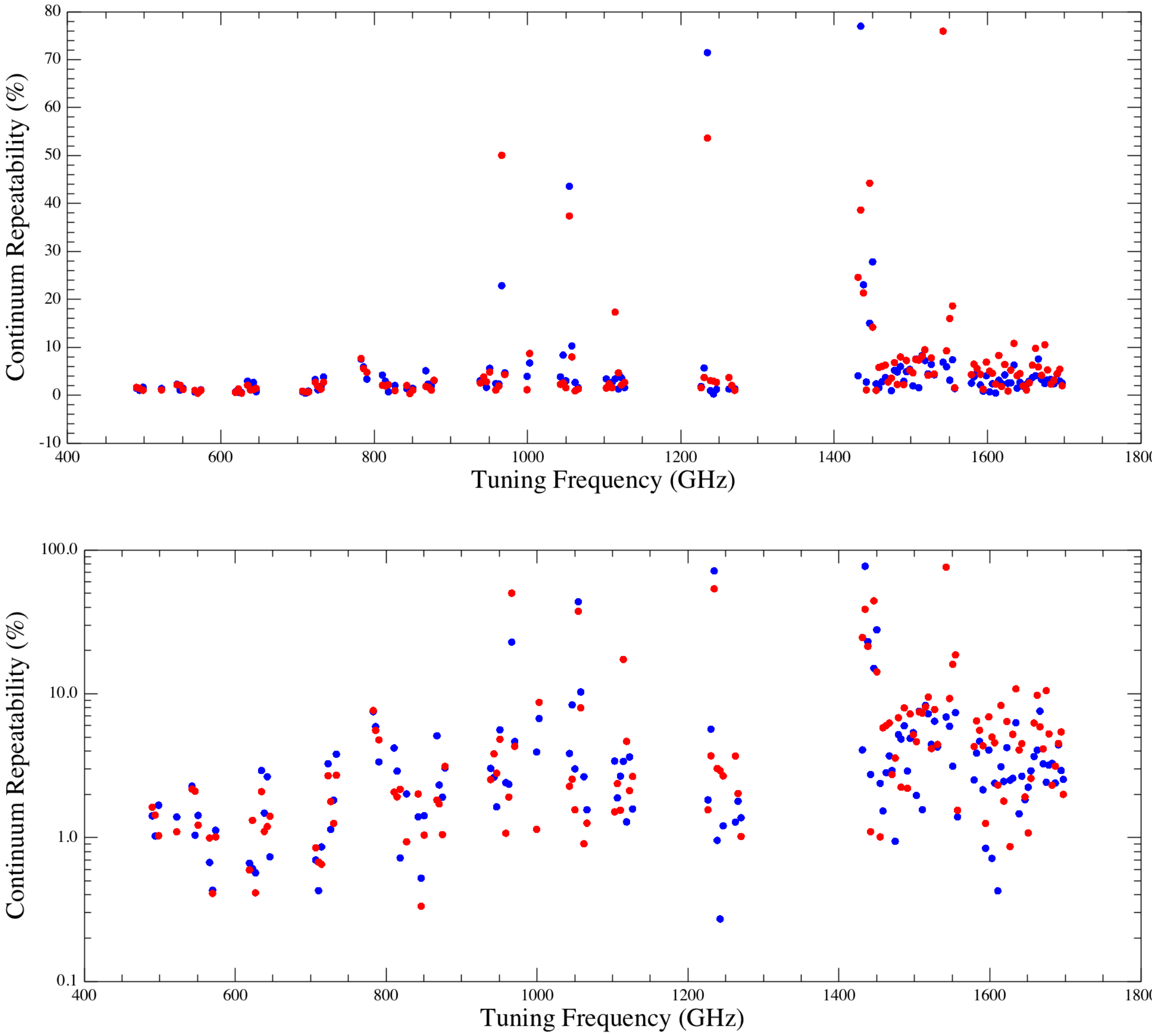

Figure 6: Continuum repeatability as a function of tuning frequency for the Spectral Scan sample. Blue dots correspond to the H polarisation, while red dots represent the V polarisation. The upper panel shows the data in linear scale, while the lower panel uses a logarithmic scale.

A Statistical approach to outliers detection

In rare cases, outlying continuum measurements apply to certain time series. While most of those represent intrinsic continuum fluctuation due to poor instrument stability at the studied frequencies, other are related to anomalous tunings or configuration of the instrument at the time of observation, and therefore not representative of the performance we are trying derive here. We are filtering out outliers by the statistical box plot method. We calculate the lower quartile (Q_1) and upper quartile (Q_3) along with the median for the respective H and V polarisation continuum measured. The lower quartile is the 25th percentile, and the upper quartile is the 75th percentile. The upper and lower fences usually are set a fixed distance from the interquartile range (Q_3 - Q_1):

$$lowerfence = Q_3 + (Q_3 - Q_1) \times 1.5 \quad (1)$$

$$upperfence = Q_1 - (Q_3 - Q_1) \times 1.5 \quad (2)$$

As a general rule, we removed any continuum whose absolute value was above 1000 K. We then applied the box plot method separately to the multi-Obsid (Section 3.1) and Spectral Scan (Section 3.2) sub-samples.

B Parameters for Spectral Map observations

Table 4: Map dimensions and centre pixels indices for each mapping observation

ObsId	Map dimension	Center
1342231522	3×20	30,31
1342231523	3×20	30,31
1342245592	3×20	30,31
1342245593	3×20	30,31
1342197927	10×11	65,66
1342197928	10×11	65,66
1342199668	10×11	65,66
1342194165	7×7	25
1342197931	7×7	25
1342231437	3×20	30,31
1342231438	3×20	30,31
1342246541	3×3	5
1342194146	7×7	25
1342197950	7×7	25
1342233896	5×5	13
1342194167	7×7	25
1342231497	3×20	30,31
1342231498	3×20	30,31

1342194144	7×7	25
1342199664	7×7	25
1342231515	3×20	30,31
1342231516	3×20	30,31
1342245619	3×20	30,31
1342245620	3×20	30,31
1342194175	7×7	25
1342199105	7×7	25
1342231769	3×20	30,31
1342231772	3×20	30,31
1342245622	3×20	30,31
1342245623	3×20	30,31
1342194157	7×7	25
1342199674	7×7	25
1342231461	3×20	30,31
1342231462	3×20	30,31
1342197938	10×11	65,66
1342197939	10×11	65,66
1342199671	10×11	65,66
1342199672	10×11	65,66
1342199673	10×11	65,66
1342194179	7×7	25
1342245592	3×20	30,31
1342245593	3×20	30,31
1342194154	7×7	25
1342246525	3×3	5
1342194152	7×7	25
1342233894	5×5	13
1342194150	7×7	25
1342199101	7×7	25
1342231533	20×20	33
1342194148	7 x7	25
1342194169	7×7	25
1342199666	7×7	25
1342235060	3×1	2
1342245624	3×1	2
1342231462	3×20	30,31
1342231461	3×20	30,31
1342197929	7×7	25

C Values of continuum repeatability in function of tuning frequency

Table 5: Values of continuum repeatability (standard deviation from time series) for the Spectral Scan sample

Frequency (GHz)	H	V
490.0742644	1.413179215	1.625982114
494.0333491	1.023387506	1.431711548
498.5463007	1.677173326	1.030096163
522.550422	1.388277158	1.095983757
542.7677429	2.276470228	2.171747029
546.8605221	1.038089333	2.099018576
550.8882355	1.424682382	1.218870669
566.0973566	0.67053692	0.992049333
570.0384404	0.429916889	0.408453537
574.0526531	1.122328145	1.010218412
618.9087792	0.662703787	0.594880003
622.8661764	0.609888399	1.315605984
626.8995151	0.568110166	0.412472382
634.8642511	2.923899622	2.085909936
638.597349	1.479349703	1.100821464
642.556059	2.646262365	1.192118062
646.045244	0.733266443	1.405163227
706.6284559	0.698028689	0.848500815
710.4069063	0.427321343	0.674741754
714.4151189	0.860124865	0.651637678
723.079349	3.259476027	2.689919304
726.6070362	1.137203456	1.778675332
730.5657462	1.818168992	1.255019578
734.0549313	3.794547108	2.713570487
782.9443248	7.497395433	7.651473808
786.1232935	5.900980565	5.5597114
790.4219215	3.358815695	4.780641917
810.624306	4.196552256	2.06889947
814.5657654	2.896955918	1.918011721
818.5792286	0.721175418	2.164593724
827.1124318	2.012130462	0.933388849
842.4627472	1.392237355	2.009168355
846.4192074	0.522171282	0.333365767
850.4019189	1.417065679	1.039513892
867.352382	5.098836382	1.821790057
870.2944131	2.319681236	1.713285843

874.5808906	1.907645796	1.048347998
878.0715759	3.046815415	3.122652741
938.4902814	3.025527857	2.527649515
942.9590185	2.624094721	3.818141258
946.4395783	1.633795261	2.80334642
950.7939344	5.607995938	4.823133226
958.6161661	2.409180878	1.071280773
962.6033779	2.346774984	1.910500452
966.3974009	22.85876951	50.04163981
970.4000421	4.65034631	4.305717617
999.405583	3.929178846	1.141468818
1002.815264	6.722449549	8.709191292
1042.967897	3.840410287	2.272918214
1046.483334	8.365941663	2.546977149
1050.157779	3.0020285	1.558893163
1054.659818	43.59114902	37.39878253
1057.938049	10.27792585	7.97650378
1062.090162	2.647063166	0.904747121
1066.102125	1.558653368	1.258363197
1102.788074	3.400222023	1.509083355
1106.420892	1.885491181	2.372321298
1110.447481	2.671671001	1.54984825
1114.325186	3.385065542	17.3205061
1118.642415	1.284326811	4.659324923
1122.601501	3.631811601	2.116607283
1126.623589	1.57981802	2.658049474
1226.463643	1.827457905	1.55793332
1230.426103	5.671494267	3.69772555
1234.706264	71.46117249	53.63689744
1238.669701	0.955322177	3.022542177
1242.609243	0.271455188	2.918452749
1246.621906	1.206148683	2.680539525
1262.787676	1.28056367	3.688650793
1266.342113	1.788862492	2.024068435
1270.319903	1.371753512	1.016958227
1431.16501	4.067498588	24.59738881
1434.664862	76.97889122	38.63464965
1438.331591	23.03129896	21.32620387
1441.980584	2.744240285	1.098530282
1446.340816	15.0138913	44.23262821
1450.205022	27.81511118	14.18113555
1454.725262	2.379794489	1.010045487
1458.343454	1.528685727	5.797195203

1462.568678	2.826309284	6.006231262
1466.765901	3.695540054	6.262825714
1470.32209	2.922746562	2.744261482
1474.561816	0.94168086	3.569049289
1478.752538	5.195664188	6.809016044
1482.334728	4.839352996	2.2386963
1486.539952	5.979576237	7.974113832
1490.757176	2.896706415	2.199542925
1494.349367	4.893237431	7.236325866
1498.575092	5.364225255	5.187644149
1502.755814	1.961645883	4.64007744
1506.378006	7.553954589	7.466366924
1510.551728	1.564092193	7.330343877
1514.74045	8.289802336	8.086878944
1518.362642	7.237885327	9.469135182
1522.558366	4.444333552	4.151170604
1526.77909	6.434960338	7.76518304
1530.588892	4.261362853	4.438689347
1542.060902	6.886334201	75.94438915
1546.576142	5.936384817	9.260075521
1550.86337	3.129710403	15.99940114
1554.417059	7.389380157	18.61809894
1557.236709	1.390865393	1.546303648
1579.079307	2.512854656	4.292904644
1582.357329	3.858094716	6.479399602
1586.346406	4.663980471	5.569563322
1590.791742	2.148272917	4.349436133
1594.358181	0.842331106	1.2542957
1598.574343	4.057884594	6.899088109
1602.742127	0.716285342	4.996338829
1606.360319	2.388009643	4.557902769
1610.583231	0.425474564	2.31568586
1614.780266	3.109075475	8.287162473
1618.337705	2.454534144	1.791199549
1622.57693	4.223050713	6.403963921
1626.768903	2.504449226	0.864913658
1630.351093	2.58004252	5.218148731
1634.555442	6.284057338	10.80991167
1638.77104	1.46275261	4.062018708
1642.366731	2.670744358	4.494968628
1646.591331	1.830729106	1.917173882
1650.773178	2.235992199	1.076225153
1654.39362	2.908711389	2.575126639

1658.569842	3.655963942	6.259899063
1662.755065	4.05207618	9.767960724
1666.377757	7.562583201	5.883306438
1670.575355	3.254968814	4.137610337
1674.793204	2.42128933	10.51214753
1678.368644	3.18605489	5.255095508
1682.575806	3.271554013	2.308325616
1686.77284	2.392243589	3.132875202
1690.925999	4.405050519	4.509447464
1694.467125	2.923275683	5.423316987
1697.34559	2.536039398	1.994795953

Table 6: Values of continuum repeatability (standard deviation from time series) for the multi-Obsid sample

Frequency (GHz)	H	V
488.806083338	1.58529091904	3.13625298307
542.271217474	1.74756495554	1.77157923656
562.749630398	2.42360752864	1.54061264762
570.221741718	1.84940694776	1.43740284405
594.609057255	2.37612071055	1.44992740161
609.435416378	2.34910224499	4.74059831763
649.003479471	1.59548864049	3.91814686597
685.934695916	4.20369554383	4.56299382113
746.31343066	3.04724904895	2.20793128542
762.908133254	2.76887020752	2.92855368248
766.241303482	5.7925947509	3.31628561419
770.03039234	2.44220386222	1.34932272515
782.06947916	5.84800026439	5.94756909417
828.544945857	1.65515901126	3.24577760095
916.956656136	4.17279633378	5.96643878784
928.858132413	5.29659948501	6.42418193597
948.876020332	4.36649594308	5.23888688122
1012.45709436	8.25387489184	9.33100139879
1053.53745809	2.1555423336	3.45988014455
1091.91050899	5.8089127456	8.87182189338
1109.29377936	3.84728403382	5.7471969432
1112.46370127	6.62140432471	7.2455492668
1126.38824112	8.53917789374	4.74940179887
1233.9442591	8.23662818449	4.62886049731
1242.07576462	5.72595959669	6.93541903609
1625.19188057	6.64539360698	6.81700778659
1629.31312594	10.3573394314	8.35524465876

1894.02033026	8.31097546866	11.5242395394