International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R RA.1860

(01/2010)

Preferred frequency bands for radio astronomical measurements in the range 1-3 THz

RA Series

Radio astronomy

International Telecommunication Union

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Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R RA.1860

Preferred frequency bands for radio astronomical measurements in the range 1-3 THz

(Question ITU-R 145/7)

(2010)

Scope

This Recommendation describes spectral line and continuum radio astronomical observations conducted in the frequency range between 1 000 and 3 000 GHz and recommends that administrations provide assistance in the coordination of radio astronomy observations in this frequency range.

The ITU Radiocommunication Assembly,

considering

a) that radio astronomers study radio emissions from cosmic sources at higher and higher frequencies;

b) that the frequencies of observation are often determined by the spectral line frequencies of atoms and molecules that exist in astrophysical environments and that such frequencies are determined by nature;

c) that the possibility of carrying out observations from the surface of the Earth depends on the "windows" at which the atmosphere is sufficiently transparent;

d) that the development of radio astronomy at THz frequencies is leading to technological advances, particularly in receiving techniques, and promises further important results;

e) that frequency bands of importance to the radio astronomy service below 1 000 GHz are addressed in Recommendation ITU-R RA.314;

f) that astronomical use of frequencies between 10 THz and 1 000 THz are addressed in Recommendation ITU-R RA.1630;

g) that there is increasing interest in the use of the range 1 000-3 000 GHz by the radio astronomy service;

h) that the International Astronomical Union (IAU) is maintaining and updating the list of spectral lines of the greatest importance to radio astronomy at frequencies up to 3 000 GHz;

j) that account should be taken of the Doppler shifts of the lines, due to the relative motion of cosmic source and observer;

k) that radio astronomers also have a need to make continuum observations at frequencies above 1 000 GHz, and that the bands used for such observations from the ground are determined by the atmospheric windows where lower attenuation occurs;

l) that the use of radio telescopes from space platforms, conducted under the space research service (passive), provides access to the entire radio spectrum, including portions of the spectrum not accessible from the Earth due to absorption in the atmosphere;

m) that protections are afforded to the radio astronomy service in bands below 275 GHz by virtue of the Table of Frequency Allocations and in bands between 275 and 1 000 GHz by virtue of No. 5.565 of the Radio Regulations (RR),

recommends

1 that administrations provide assistance in the coordination of radio astronomy observations in bands between 1 000 GHz and 3 000 GHz, particularly those listed in Table 1 (for space-based observations) and Table 3 (for ground-based observations).

Annex 1

1 Spectral lines of astronomical interest

Table 1 lists the non-Doppler-shifted ("rest") frequencies of the spectral lines emitted by a variety of molecules of astrophysical interest. From the rest frequency, an approximate range of frequencies over which the lines may be observed is provided, based upon typical Doppler shifts that are observed due to radial motion of the cosmic source toward or away from the observer. In the table, an assumed Doppler range of ±300 km/s is used. The ranges listed in Table 1 are suggested minimum bands.

It should be noted that because of high sensitivities of the radio astronomical observations so many spectral lines have been observed from extragalactic objects, up to $z \sim 6$ or higher (here, z denotes the "red-shift", defined by $z = (\lambda_{obs} - \lambda_0)/\lambda_0$, where λ_{obs} is the observed wavelength and λ_0 is the non-Doppler shifted wavelength). Therefore highly red-shifted spectral line observations need to be taken care of.

The source data for Table 1, which was approved by the General Assembly of the International Astronomical Union (IAU) in 2009, were derived from observational studies of submillimetre spectral line emission towards two molecule-rich regions of the Milky Way Galaxy[1,2]; from the JPL Molecular Spectroscopy database[3]; and from a web-based catalogue of molecular spectral lines (the Cologne Database for Molecular Spectroscopy) maintained by the University of Cologne, Germany[4].

2 Atmospheric absorption

At millimetre and submillimetre wavelengths, an important factor for ground-based observing is the degree to which the atmosphere attenuates radio signals. Attenuation of signals in the 1 000-3 000 GHz frequency range is due mainly to absorption by water vapour, and to a lesser extent by oxygen, nitrogen and ozone.

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1 POLEHAMPTON, E. T. *et al*. [2007] The ISO LWS high-resolution spectral survey towards Sagittarius B2*. *Monthly Notices of the Royal Astronomical Society (MNRAS)*, Vol. 377, p. 1122.

2 LERATE, M. R. *et al.* [2006] A far-infrared molecular and atomic line survey of the Orion KL region. *Monthly Notices of the Royal Astronomical Society (MNRAS)*, Vol. 370, p. 597.

3 http://spec.jpl.nasa.gov/.

4 http://www.astro.uni-koeln.de/cdms/.

For ground-based observatories, atmospheric attenuation reduces the observed signal level of emission coming from cosmic sources and adds thermal noise to the received signal. For this reason, millimetre and submillimetre radio astronomy stations are located at high, dry sites. Despite optimizing the observing location, the level of attenuation is so high over portions of the 1 000-3 000 GHz range that, with the exception of a few "windows", many observations in this spectral region can only be conducted from space. Table 1 notes those spectral lines that would only be observable from space due to high atmospheric attenuation within the suggested minimum band.

Figure 1 is an example of the transmittance on a vertical path through the atmosphere (i.e. looking straight up along the shortest line of sight through the atmosphere), over the frequency range 1 000-3 000 GHz, at a good astronomical observing site. The data were calculated using the *am* atmospheric model[5], assuming the following inputs[6]:

– Site location: Cerro Sairecabur, approximately 35 km north-northwest of the location of the Atacama Large Millimeter/submillimeter Array (ALMA) site at Chajnantor, Chile.

– Elevation: 5 525 m.

– Barometric pressure at ground: 532 mbar.

– Ground temperature: 285 K.

– Atmospheric pressure/temperature profile: Based on data acquired over 187 radiosonde flights in the area over the period 1998-2002. The ozone profile was based on NASA ozone-sonde flights over Galapagos, Ecuador, during the same period.

– Total precipitable water vapour (PWV) content: 0.25 mm. Based on extended measurement campaigns, this site was determined to have a PWV at or below this value approximately 25% of the time.

The calculated transmittance curve agrees well with observed atmospheric brightness temperatures obtained with Fourier transform spectrometer (FTS) measurements at the site.

Table 2 lists the frequency ranges over which the atmospheric transmittance of Fig. 2 exceeds 20%, 10%, 5%, and 1% (Fig. 2 is a graphical representation of the data in Table 2). Lower transmittances will decrease the received signal strength from cosmic sources due to atmospheric absorption, and increase the radio astronomy system noise temperature due to thermal emission from the atmosphere. Therefore, larger transmittances are highly desirable for ground-based radio astronomical measurements, although useful ground-based observations of relatively strong cosmic emissions may be made for transmittances as low as 5%, and possibly lower.

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5 See http://www.cfa.harvard.edu/~spaine/am/ (queried June 2008).

6 Specifically, the calculations employed the Sairecabur profile of Example 4 of: PAINE, S. [2004] The am Atmospheric Model. Submillimeter Array Technical Memo #152 (Revision 3). Available at http://sma-www.harvard.edu/private/memos/tech_no.html (queried June 2008).

TABLE 1

Astrophysically most important spectral lines in the frequency range between 1 000 and 3 000 GHz

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Water vapour ($H_2{}^{18}O$)	1 003.278	1 002.274	1 004.281	G	1 002.274	1 004.281
Heavy water (HDO)	1 009.945	1 008.935	1 010.955	G	1 008.935	1 010.955
Azanylidenium (NH^+)	1 012.524	1 011.511	1 013.537	G	1 011.511	1 013.537
Carbon monosulphide (CS)	1 027.314	1 026.287	1 028.341	G	1 026.287	1 028.341
Hydroxylium (OH^+)	1 033.119	1 032.085	1 034.152	G	1 032.085	1 034.152
Carbon monoxide (CO)	1 036.912	1 035.875	1 037.949	G	1 035.875	1 037.949
Hydrogen cyanide (HCN)	1 062.983	1 061.920	1 064.046		1 061.920	1 064.046
Formylium (HCO^+)	1 069.694	1 068.624	1 070.764		1 068.624	1 070.764
Carbon monosulphide (CS)	1 076.078	1 075.002	1 077.154		1 075.002	1 077.154
Sulfhydrylium (SH^+)	1 082.909	1 081.826	1 083.993		1 081.826	1 083.993
Water vapour ($H_2{}^{18}O$)	1 095.627	1 094.532	1 096.723		1 094.532	1 098.462
Carbon monoxide ($C^{18}O$)	1 097.163	1 096.066	1 098.260			
Water vapour (H_2O)	1 097.365	1 096.267	1 098.462			
Carbon monoxide (^{13}CO)	1 101.350	1 100.248	1 102.451		1 100.248	1 102.800
Water vapour ($H_2{}^{18}O$)	1 101.698	1 100.597	1 102.800			
Water vapour (H_2O)	1 113.343	1 112.230	1 114.456		1 112.230	1 116.175
Water cation (H_2O^+)	1 115.059	1 113.943	1 116.175			
Carbon monosulphide (CS)	1 124.820	1 123.696	1 125.945		1 123.696	1 125.945
Water vapour ($H_2{}^{18}O$)	1 136.704	1 135.567	1 137.840		1 135.567	1 137.840
Hydrogen cyanide (HCN)	1 151.452	1 150.301	1 152.603		1 150.301	1 154.280
Carbon monoxide (CO)	1 151.985	1 150.833	1 153.137			
Water vapour (H_2O)	1 153.127	1 151.974	1 154.280			
Water vapour (H_2O)	1 158.324	1 157.165	1 159.482		1 157.165	1 159.886
Formylium (HCO^+)	1 158.727	1 157.568	1 159.886			
Heavy water (HDO)	1 161.953	1 160.791	1 163.115		1 160.791	1 165.935
Water vapour (H_2O)	1 162.912	1 161.749	1 164.075			
Heavy water (HDO)	1 164.770	1 163.605	1 165.935			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Ammonia (NH_3)	1 168.452	1 167.283	1 169.620		1 167.283	1 169.620
Carbon monosulphide (CS)	1 173.539	1 172.366	1 174.713		1 172.366	1 174.713
Heavy water (HDO)	1 180.324	1 179.143	1 181.504		1 179.143	1 182.575
Water vapour ($H_2{}^{18}O$)	1 181.394	1 180.213	1 182.575			
Water vapour ($H_2{}^{18}O$)	1 188.863	1 187.674	1 190.052		1 187.674	1 190.052
Water vapour ($H_2{}^{18}O$)	1 199.006	1 197.807	1 200.205		1 197.807	1 200.205
Carbon monoxide ($C^{18}O$)	1 206.725	1 205.519	1 207.932		1 205.519	1 208.846
Water vapour (H_2O)	1 207.639	1 206.431	1 208.846			
Carbon monoxide (^{13}CO)	1 211.330	1 210.118	1 212.541		1 210.118	1 212.541
Ammonia (NH_3)	1 214.859	1 213.644	1 216.073		1 213.644	1 218.476
Ammonia (NH_3)	1 215.245	1 214.030	1 216.460			
Water vapour ($H_2{}^{18}O$)	1 216.850	1 215.634	1 218.067			
Heavy water (HDO)	1 217.258	1 216.041	1 218.476			
Carbon monosulphide (CS)	1 222.234	1 221.012	1 223.456		1 221.012	1 223.456
Water vapour (H_2O)	1 228.789	1 227.560	1 230.018		1 227.560	1 231.633
Heavy water (HDO)	1 230.403	1 229.173	1 231.633			
Hydrogen cyanide (HCN)	1 239.895	1 238.655	1 241.134		1 238.655	1 241.134
Formylium (HCO^+)	1 247.735	1 246.487	1 248.982		1 246.487	1 248.982
Heavy water (HDO)	1 259.072	1 257.813	1 260.331	G	1 257.813	1 262.731
Heavy water (HDO)	1 261.469	1 260.208	1 262.731	G		
Carbon monoxide (CO)	1 267.014	1 265.747	1 268.282	G	1 265.747	1 268.310
Heavy water (HDO)	1 267.043	1 265.776	1 268.310	G		
Carbon monosulphide (CS)	1 270.903	1 269.632	1 272.174	G	1 269.632	1 272.174
Heavy water (HDO)	1 277.676	1 276.398	1 278.954	G	1 276.398	1 278.954
Heavy water (HDO)	1 291.642	1 290.351	1 292.934	G	1 290.351	1 294.666
Heavy water (HDO)	1 293.372	1 292.079	1 294.666	G		
Heavy water (HDO)	1 297.805	1 296.507	1 299.103	G	1 296.507	1 299.103

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Carbon monoxide ($C^{18}O$)	1 316.244	1 314.928	1 317.560	G	1 314.928	1 317.560
Carbon monosulphide (CS)	1 319.545	1 318.226	1 320.865		1 318.226	1 323.387
Carbon monoxide (^{13}CO)	1 321.266	1 319.944	1 322.587			
Water vapour (H_2O)	1 322.065	1 320.743	1 323.387			
Hydrogen cyanide (HCN)	1 328.308	1 326.980	1 329.637	G	1 326.980	1 329.637
Formylium (HCO^+)	1 336.714	1 335.378	1 338.051	G	1 335.378	1 338.051
Water vapour ($H_2{}^{18}O$)	1 340.739	1 339.398	1 342.080	G	1 339.398	1 342.080
Heavy water (HDO)	1 353.777	1 352.423	1 355.130	G	1 352.423	1 355.130
Carbon monosulphide (CS)	1 368.160	1 366.792	1 369.528	G	1 366.792	1 371.455
Trihydrogen (H_2D^+)	1 370.085	1 368.715	1 371.455	G		
Carbon monoxide (CO)	1 381.995	1 380.613	1 383.377	G	1 380.613	1 383.377
Heavy water (HDO)	1 385.216	1 383.831	1 386.601		1 383.831	1 386.601
Heavy water (HDO)	1 392.919	1 391.526	1 394.312		1 391.526	1 394.312
Water vapour ($H_2{}^{18}O$)	1 402.966	1 401.563	1 404.369		1 401.563	1 404.369
Water vapour (H_2O)	1 410.618	1 409.207	1 412.029		1 409.207	1 412.029
Hydrogen cyanide (HCN)	1 416.691	1 415.275	1 418.108		1 415.275	1 418.162
Carbon monosulphide (CS)	1 416.745	1 415.329	1 418.162			
Formylium (HCO^+)	1 425.664	1 424.238	1 427.090		1 424.238	1 427.141
Carbon monoxide ($C^{18}O$)	1 425.715	1 424.289	1 427.141			
Carbon monoxide (^{13}CO)	1 431.153	1 429.722	1 432.584		1 429.722	1 434.310
Heavy water (HDO)	1 432.877	1 431.444	1 434.310			
Water vapour ($H_2{}^{18}O$)	1 438.649	1 437.210	1 440.087		1 437.210	1 442.222
Water vapour (H_2O)	1 440.782	1 439.341	1 442.222			
Heavy water (HDO)	1 444.829	1 443.384	1 446.274	G	1 443.384	1 448.460
Sulfhydryl (SH)	1 447.012	1 445.564	1 448.460	G		
Nitrogen ion (N II)	1 461.130	1 459.669	1 462.591	G	1 459.669	1 462.591
Trihydrogen (D_2H^+)	1 476.606	1 475.128	1 478.083	G	1 475.128	1 478.083
Heavy water (HDO)	1 491.927	1 490.435	1 493.419	G	1 490.435	1 493.419
Carbon monoxide (CO)	1 496.923	1 495.426	1 498.420	G	1 495.426	1 498.420

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	1 500.990	1 499.489	1 502.491	G	1 499.489	1 502.491
Hydrogen cyanide (HCN)	1 505.042	1 503.537	1 506.547	G	1 503.537	1 508.768
Heavy water (HDO)	1 507.261	1 505.754	1 508.768	G		
Formylium (HCO^+)	1 514.582	1 513.067	1 516.096	G	1 513.067	1 516.096
Heavy water (HDO)	1 522.926	1 521.403	1 524.449	G	1 521.403	1 524.449
Carbon monoxide ($C^{18}O$)	1 535.134	1 533.599	1 536.669	G	1 533.599	1 536.669
Carbon monoxide (^{13}CO)	1 540.989	1 539.448	1 542.530		1 539.448	1 543.509
Water vapour (H_2O)	1 541.967	1 540.425	1 543.509			
Heavy water (HDO)	1 577.178	1 575.600	1 578.755		1 575.600	1 578.755
Hydrogen cyanide (HCN)	1 593.357	1 591.764	1 594.951		1 591.764	1 594.951
Water vapour (H_2O)	1 602.219	1 600.617	1 603.821		1 600.617	1 607.568
Formylium (HCO^+)	1 603.466	1 601.862	1 605.069			
Water vapour ($H_2{}^{18}O$)	1 605.962	1 604.356	1 607.568			
Carbon monoxide (CO)	1 611.794	1 610.182	1 613.405		1 610.182	1 617.242
Heavy water (HDO)	1 614.294	1 612.679	1 615.908			
Heavy water (HDO)	1 615.626	1 614.010	1 617.242			
Water vapour ($H_2{}^{18}O$)	1 620.852	1 619.231	1 622.472		1 619.231	1 622.472
Heavy water (HDO)	1 625.408	1 623.783	1 627.033		1 623.783	1 627.033
Sulfhydrylium (SH^+)	1 632.518	1 630.884	1 634.151		1 630.884	1 636.274
Water vapour ($H_2{}^{18}O$)	1 633.484	1 631.850	1 635.117			
Heavy water (HDO)	1 634.639	1 633.005	1 636.274			
Carbon monoxide ($C^{18}O$)	1 644.497	1 642.852	1 646.141		1 642.852	1 646.141
Heavy water (HDO)	1 648.801	1 647.153	1 650.450		1 647.153	1 652.418
Carbon monoxide (^{13}CO)	1 650.768	1 649.117	1 652.418			
Oxonium (H_3O^+)	1 655.813	1 654.158	1 657.469		1 654.158	1 657.858
Water vapour ($H_2{}^{18}O$)	1 655.868	1 654.212	1 657.523			
Water vapour ($H_2{}^{18}O$)	1 656.202	1 654.546	1 657.858			
Water vapour (H_2O)	1 661.008	1 659.347	1 662.669		1 659.347	1 665.247
Oxonium (H_3O^+)	1 663.584	1 661.920	1 665.247			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Methylidynium (CH^+)	1 669.170	1 667.499	1 670.840		1 667.499	1 673.021
Water vapour (H_2O)	1 669.905	1 668.235	1 671.575			
Water vapour ($H_2{}^{18}O$)	1 671.350	1 669.679	1 673.021			
Heavy water (HDO)	1 678.578	1 676.899	1 680.256		1 676.899	1 686.290
Hydrogen cyanide (HCN)	1 681.636	1 679.955	1 683.318			
Heavy water (HDO)	1 684.606	1 682.921	1 686.290			
Formylium (HCO^+)	1 692.313	1 690.621	1 694.006		1 690.621	1 694.006
Water vapour (H_2O)	1 713.883	1 712.169	1 715.597		1 712.169	1 721.701
Water vapour (H_2O)	1 716.770	1 715.053	1 718.486			
Water vapour (H_2O)	1 716.957	1 715.240	1 718.674			
Water vapour ($H_2{}^{18}O$)	1 719.250	1 717.531	1 720.969			
Water vapour ($H_2{}^{18}O$)	1 719.981	1 718.261	1 721.701			
Carbon monoxide (CO)	1 726.603	1 724.876	1 728.329		1 724.876	1 728.329
Carbon monoxide ($C^{18}O$)	1 753.800	1 752.046	1 755.554		1 752.046	1 755.554
Heavy water (HDO)	1 759.978	1 758.218	1 761.738		1 758.218	1 765.585
Carbon monoxide (^{13}CO)	1 760.486	1 758.726	1 762.247			
Water vapour (H_2O)	1 762.043	1 760.281	1 763.805			
Ammonia (NH_3)	1 763.525	1 761.762	1 765.289			
Heavy water (HDO)	1 763.558	1 761.795	1 765.322			
Ammonia (NH_3)	1 763.602	1 761.838	1 765.365			
Ammonia (NH_3)	1 763.821	1 762.058	1 765.585			
Hydrogen cyanide (HCN)	1 769.877	1 768.107	1 771.647		1 768.107	1 771.647
Formylium (HCO^+)	1 781.123	1 779.342	1 782.904		1 779.342	1 782.904
Water vapour (H_2O)	1 794.789	1 792.994	1 796.584		1 792.994	1 796.584
Water vapour ($H_2{}^{18}O$)	1 800.475	1 798.674	1 802.275		1 798.674	1 802.275
Ammonia (NH_3)	1 808.936	1 807.127	1 810.744		1 807.127	1 812.188
Ammonia (NH_3)	1 810.378	1 808.567	1 812.188			
Water vapour ($H_2{}^{18}O$)	1 815.853	1 814.038	1 817.669		1 814.038	1 820.348
Heavy water (HDO)	1 818.530	1 816.711	1 820.348			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Water vapour ($H_2{}^{18}O$)	1 824.554	1 822.729	1 826.378		1 822.729	1 826.378
Hydroxyl (OH)	1 834.745	1 832.911	1 836.580		1 832.911	1 843.187
Hydroxyl (OH)	1 837.741	1 835.903	1 839.578			
Hydroxyl (OH)	1 837.812	1 835.974	1 839.649			
Carbon monoxide (CO)	1 841.346	1 839.504	1 843.187			
Water vapour ($H_2{}^{18}O$)	1 846.872	1 845.025	1 848.719		1 845.025	1 850.154
Heavy water (HDO)	1 848.306	1 846.458	1 850.154			
Heavy water (HDO)	1 853.873	1 852.019	1 855.727		1 852.019	1 855.727
Hydrogen cyanide (HCN)	1 858.077	1 856.219	1 859.935		1 856.219	1 859.935
Carbon monoxide ($C^{18}O$)	1 863.039	1 861.176	1 864.902		1 861.176	1 864.902
Water vapour (H_2O)	1 867.749	1 865.881	1 869.616		1 865.881	1 874.481
Water vapour (H_2O)	1 867.819	1 865.951	1 869.687			
Formylium (HCO^+)	1 869.893	1 868.023	1 871.763			
Carbon monoxide (^{13}CO)	1 870.141	1 868.271	1 872.011			
Heavy water (HDO)	1 872.609	1 870.736	1 874.481			
Heavy water (HDO)	1 877.487	1 875.609	1 879.364		1 875.609	1 883.172
Water vapour (H_2O)	1 880.753	1 878.872	1 882.634			
Heavy water (HDO)	1 881.291	1 879.410	1 883.172			
Heavy water (HDO)	1 890.757	1 888.866	1 892.647		1 888.866	1 896.218
Water vapour (H_2O)	1 893.687	1 891.793	1 895.580			
Water vapour ($H_2{}^{18}O$)	1 894.324	1 892.429	1 896.218			
Water vapour ($H_2{}^{18}O$)	1 899.604	1 897.705	1 901.504		1 897.705	1 902.438
Carbon ion (C II)	1 900.537	1 898.637	1 902.438			
Heavy water (HDO)	1 909.602	1 907.693	1 911.512		1 907.693	1 911.512
Water vapour (H_2O)	1 918.475	1 916.557	1 920.394		1 916.557	1 922.353
Water vapour (H_2O)	1 918.485	1 916.567	1 920.404			
Water vapour (H_2O)	1 919.360	1 917.440	1 921.279			
Water vapour (H_2O)	1 919.360	1 917.440	1 921.279			
Heavy water (HDO)	1 920.433	1 918.513	1 922.353			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	1 929.255	1 927.326	1 931.184		1 927.326	1 932.259
Heavy water (HDO)	1 930.329	1 928.398	1 932.259			
Heavy water (HDO)	1 941.797	1 939.855	1 943.739		1 939.855	1 943.739
Hydrogen cyanide (HCN)	1 946.235	1 944.288	1 948.181		1 944.288	1 948.181
Heavy water (HDO)	1 950.155	1 948.204	1 952.105		1 948.204	1 952.159
Heavy water (HDO)	1 950.209	1 948.259	1 952.159			
Azanylidene (NH)	1 955.027	1 953.072	1 956.982		1 953.072	1 960.579
Carbon monoxide (CO)	1 956.018	1 954.062	1 957.974			
Azanylidene (NH)	1 958.198	1 956.240	1 960.156			
Formylium (HCO^+)	1 958.621	1 956.662	1 960.579			
Heavy water (HDO)	1 965.554	1 963.588	1 967.519		1 963.588	1 967.519
Carbon monoxide ($C^{18}O$)	1 972.211	1 970.239	1 974.183		1 970.239	1 987.905
Water vapour ($H_2{}^{18}O$)	1 974.636	1 972.661	1 976.611	G		
Azanylidene (NH)	1 978.464	1 976.485	1 980.442	G		
Carbon monoxide (^{13}CO)	1 979.727	1 977.747	1 981.707	G		
Heavy water (HDO)	1 982.064	1 980.082	1 984.046	G		
Water vapour ($H_2{}^{18}O$)	1 985.919	1 983.933	1 987.905	G		
Heavy water (HDO)	1 994.285	1 992.291	1 996.280	G	1 992.291	1 996.280
Heavy water (HDO)	2 003.495	2 001.491	2 005.498		2 001.491	2 008.785
Heavy water (HDO)	2 005.180	2 003.175	2 007.186			
Methylidyne (CH)	2 006.779	2 004.772	2 008.785			
Methylidyne (CH)	2 010.799	2 008.788	2 012.810		2 008.788	2 016.880
Heavy water (HDO)	2 014.370	2 012.355	2 016.384			
Water vapour (H_2O)	2 014.865	2 012.850	2 016.880			
Heavy water (HDO)	2 019.134	2 017.115	2 021.154		2 017.115	2 021.154
Heavy water (HDO)	2 031.743	2 029.711	2 033.774		2 029.711	2 033.774
Water vapour (H_2O)	2 040.477	2 038.436	2 042.517		2 038.436	2 042.517
Oxygen (O I)	2 060.070	2 058.010	2 062.130		2 058.010	2 062.130
Heavy water (HDO)	2 064.690	2 062.625	2 066.755		2 062.625	2 066.755

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Carbon monoxide (CO)	2 070.616	2 068.545	2 072.687		2 068.545	2 076.519
Water vapour (H_2O)	2 074.432	2 072.358	2 076.507			
Water vapour (H_2O)	2 074.444	2 072.370	2 076.519			
Carbon monoxide ($C^{18}O$)	2 081.311	2 079.229	2 083.392		2 079.229	2 085.118
Heavy water (HDO)	2 082.718	2 080.635	2 084.801			
Heavy water (HDO)	2 083.035	2 080.952	2 085.118			
Heavy water (HDO)	2 087.226	2 085.139	2 089.313		2 085.139	2 091.330
Carbon monoxide (^{13}CO)	2 089.241	2 087.151	2 091.330			
Water vapour ($H_2{}^{18}O$)	2 099.963	2 097.863	2 102.063		2 097.863	2 102.063
Heavy water (HDO)	2 110.993	2 108.882	2 113.104		2 108.882	2 113.104
Heavy water (HDO)	2 121.216	2 119.095	2 123.338		2 119.095	2 123.338
Water vapour ($H_2{}^{18}O$)	2 143.752	2 141.608	2 145.895		2 141.608	2 154.357
Water vapour ($H_2{}^{18}O$)	2 147.733	2 145.585	2 149.880			
Heavy water (HDO)	2 149.224	2 147.075	2 151.373			
Heavy water (HDO)	2 152.205	2 150.052	2 154.357			
Water vapour (H_2O)	2 164.132	2 161.968	2 166.296		2 161.968	2 166.296
Carbon monoxide (CO)	2 185.135	2 182.950	2 187.320		2 182.950	2 187.320
Water vapour (H_2O)	2 196.346	2 194.149	2 198.542		2 194.149	2 201.998
Heavy water (HDO)	2 199.798	2 197.599	2 201.998			
Heavy water (HDO)	2 204.707	2 202.503	2 206.912		2 202.503	2 206.912
Heavy water (HDO)	2 213.707	2 211.493	2 215.921		2 211.493	2 215.921
Water vapour (H_2O)	2 221.751	2 219.529	2 223.972		2 219.529	2 223.972
Water vapour ($H_2{}^{18}O$)	2 227.872	2 225.644	2 230.100		2 225.644	2 230.100
Water vapour ($H_2{}^{18}O$)	2 242.198	2 239.956	2 244.440		2 239.956	2 244.440
Water vapour (H_2O)	2 264.150	2 261.886	2 266.414		2 261.886	2 266.414
Heavy water (HDO)	2 269.686	2 267.416	2 271.956		2 267.416	2 271.956
Heavy water (HDO)	2 278.017	2 275.739	2 280.295		2 275.739	2 280.295
Heavy water (HDO)	2 283.942	2 281.658	2 286.226		2 281.658	2 288.499
Heavy water (HDO)	2 286.213	2 283.926	2 288.499			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	2 291.309	2 289.018	2 293.601		2 289.018	2 293.601
Heavy water (HDO)	2 296.248	2 293.952	2 298.544		2 293.952	2 302.002
Heavy water (HDO)	2 297.652	2 295.355	2 299.950			
Carbon monoxide (CO)	2 299.569	2 297.269	2 301.868			
Heavy water (HDO)	2 299.702	2 297.402	2 302.002			
Carbon monoxide (^{13}CO)	2 308.031	2 305.723	2 310.339		2 305.723	2 310.339
Water vapour ($H_2{}^{18}O$)	2 318.554	2 316.236	2 320.873		2 316.236	2 320.873
Heavy water (HDO)	2 327.429	2 325.101	2 329.756		2 325.101	2 329.756
Heavy water (HDO)	2 335.788	2 333.452	2 338.123		2 333.452	2 338.556
Heavy water (HDO)	2 336.220	2 333.883	2 338.556			
Heavy water (HDO)	2 343.735	2 341.392	2 346.079		2 341.392	2 368.266
Water vapour (H_2O)	2 344.290	2 341.945	2 346.634			
Methylene (CH_2)	2 344.726	2 342.381	2 347.071			
Methylene (CH_2)	2 348.622	2 346.274	2 350.971			
Heavy water (HDO)	2 351.731	2 349.380	2 354.083			
Heavy water (HDO)	2 355.192	2 352.837	2 357.548			
Ammonia (NH_3)	2 357.210	2 354.853	2 359.568			
Ammonia (NH_3)	2 357.727	2 355.369	2 360.084			
Ammonia (NH_3)	2 358.563	2 356.205	2 360.922			
Heavy water (HDO)	2 360.340	2 357.980	2 362.700			
Trihydrogen (H_2D^+)	2 363.306	2 360.943	2 365.669			
Amino (NH_2)	2 364.268	2 361.903	2 366.632			
Water vapour (H_2O)	2 365.900	2 363.534	2 368.266			
Heavy water (HDO)	2 382.166	2 379.784	2 384.548		2 379.784	2 384.548
Water vapour ($H_2{}^{18}O$)	2 388.325	2 385.936	2 390.713		2 385.936	2 393.964
Water vapour (H_2O)	2 391.573	2 389.181	2 393.964			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	2 399.218	2 396.819	2 401.618		2 396.819	2 407.526
Ammonia (NH_3)	2 400.018	2 397.618	2 402.418			
Ammonia (NH_3)	2 400.578	2 398.178	2 402.979			
Ammonia (NH_3)	2 402.265	2 399.863	2 404.667			
Ammonia (NH_3)	2 405.121	2 402.716	2 407.526			
Heavy water (HDO)	2 411.827	2 409.415	2 414.239		2 409.415	2 420.888
Carbon monoxide (CO)	2 413.924	2 411.510	2 416.338			
Water vapour ($H_2{}^{18}O$)	2 418.469	2 416.051	2 420.888			
Nitrogen ion (N II)	2 459.379	2 456.920	2 461.839		2 456.920	2 468.338
Water vapour (H_2O)	2 462.933	2 460.470	2 465.396			
Heavy water (HDO)	2 463.054	2 460.591	2 465.517			
Hydrogen fluoride (HF)	2463.427	2 460.964	2 465.891			
Heavy water (HDO)	2 465.872	2 463.406	2 468.338			
Heavy water (HDO)	2 477.453	2 474.976	2 479.931		2 474.976	2 486.788
Heavy water (HDO)	2 480.807	2 478.326	2 483.287			
Heavy water (HDO)	2 484.303	2 481.819	2 486.788			
Hydroxyl (^{18}OH)	2 494.674	2 492.179	2 497.169		2 492.179	2 516.847
Hydroxyl (^{18}OH)	2 498.970	2 496.471	2 501.469			
Hydroxyl (^{17}OH)	2 501.856	2 499.355	2 504.358			
Heavy water (HDO)	2 502.167	2 499.665	2 504.669			
Hydroxyl (^{17}OH)	2 506.186	2 503.680	2 508.692			
Hydroxyl (OH)	2 509.965	2 507.455	2 512.475			
Hydroxyl (OH)	2 514.333	2 511.819	2 516.847			
Water vapour ($H_2{}^{18}O$)	2 526.741	2 524.214	2 529.268		2 524.214	2 531.838
Carbon monoxide (CO)	2 528.166	2 525.638	2 530.694			
Heavy water (HDO)	2 529.308	2 526.779	2 531.838			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	2 541.065	2 538.524	2 543.606		2 538.524	2 547.650
Amino (NH_2)	2 545.105	2 542.560	2 547.650			
Amino (NH_2)	2 553.966	2 551.412	2 556.520		2 551.412	2 563.471
Heavy water (HDO)	2 558.905	2 556.346	2 561.464			
Amino (NH_2)	2 560.910	2 558.349	2 563.471			
Heavy water (HDO)	2 577.667	2 575.089	2 580.244		2 575.089	2 582.211
Heavy water (HDO)	2 579.631	2 577.052	2 582.211			
Water vapour ($H_2{}^{18}O$)	2 591.047	2 588.456	2 593.638		2 588.456	2 595.117
Heavy water (HDO)	2 592.524	2 589.932	2 595.117			
Heavy water (HDO)	2 598.288	2 595.690	2 600.886		2 595.690	2 606.031
Hydroxyl (OH)	2 603.427	2 600.824	2 606.031			
Heavy water (HDO)	2 616.165	2 613.549	2 618.781		2 613.549	2 618.781
Water vapour ($H_2{}^{18}O$)	2 622.939	2 620.316	2 625.562		2 620.316	2 625.562
Water vapour (H_2O)	2 630.960	2 628.329	2 633.590		2 628.329	2 633.682
Water vapour (H_2O)	2 631.051	2 628.420	2 633.682			
Water vapour (H_2O)	2 640.474	2 637.833	2 643.114		2 637.833	2 644.963
Carbon monoxide (CO)	2 642.321	2 639.679	2 644.963			
Water vapour (H_2O)	2 657.666	2 655.008	2 660.323		2 655.008	2 660.323
Water vapour (H_2O)	2 664.561	2 661.897	2 667.226		2 661.897	2 677.662
Water vapour ($H_2{}^{18}O$)	2 666.732	2 664.065	2 669.398			
Heavy water (HDO)	2 669.415	2 666.745	2 672.084			
Heavy water (HDO)	2 674.283	2 671.609	2 676.957			
Deuterated hydrogen (HD)	2 674.987	2 672.312	2 677.662			
Water vapour (H_2O)	2 685.639	2 682.953	2 688.325		2 682.953	2 688.325
Heavy water (HDO)	2 735.277	2 732.541	2 738.012		2 732.541	2 738.012
Water vapour ($H_2{}^{18}O$)	2 741.675	2 738.933	2 744.416		2 738.933	2 744.416
Heavy water (HDO)	2 748.312	2 745.564	2 751.060		2 745.564	2 751.060
Carbon monoxide (CO)	2 756.383	2 753.626	2 759.139		2 753.626	2 759.139

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Water vapour (H_2O)	2 773.977	2 771.203	2 776.751		2 771.203	2 776.751
Methylene (CH_2)	2 783.064	2 780.281	2 785.847		2 780.281	2 785.847
Heavy water (HDO)	2 794.002	2 791.208	2 796.796		2 791.208	2 796.829
Heavy water (HDO)	2 794.035	2 791.241	2 796.829			
Water vapour ($H_2{}^{18}O$)	2 805.384	2 802.579	2 808.190		2 802.579	2 816.325
Heavy water (HDO)	2 807.498	2 804.691	2 810.306			
Heavy water (HDO)	2 809.406	2 806.597	2 812.216			
Heavy water (HDO)	2 810.880	2 808.069	2 813.691			
Heavy water (HDO)	2 813.511	2 810.698	2 816.325			
Heavy water (HDO)	2 834.411	2 831.577	2 837.245		2 831.577	2 837.245
Water vapour ($H_2{}^{18}O$)	2 845.980	2 843.134	2 848.826		2 843.134	2 848.826
Heavy water (HDO)	2 855.631	2 852.776	2 858.487		2 852.776	2 861.891
Heavy water (HDO)	2 859.032	2 856.173	2 861.891			
Carbon monoxide (CO)	2 870.338	2 867.468	2 873.208		2 867.468	2 875.782
Heavy water (HDO)	2 872.909	2 870.036	2 875.782			
Water vapour (H_2O)	2 880.025	2 877.145	2 882.905		2 877.145	2 890.914
Water vapour (H_2O)	2 884.279	2 881.395	2 887.163			
Water vapour (H_2O)	2 884.312	2 881.427	2 887.196			
Water vapour (H_2O)	2 884.941	2 882.056	2 887.826			
Water vapour (H_2O)	2 884.950	2 882.065	2 887.835			
Water vapour ($H_2{}^{18}O$)	2 888.026	2 885.138	2 890.914			
Heavy water (HDO)	2 900.172	2 897.272	2 903.072		2 897.272	2 906.294
Heavy water (HDO)	2 903.391	2 900.487	2 906.294			
Heavy water (HDO)	2 916.109	2 913.193	2 919.025		2 913.193	2 923.819
Heavy water (HDO)	2 920.898	2 917.977	2 923.819			
Water vapour ($H_2{}^{18}O$)	2 938.998	2 936.059	2 941.937		2 936.059	2 944.831
Water vapour ($H_2{}^{18}O$)	2 939.000	2 936.061	2 941.939			
Heavy water (HDO)	2 941.889	2 938.947	2 944.831			

TABLE 1 (*continued*)

Species	Rest frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)	Remarks	Consolidated minimum frequency (GHz)	Consolidated maximum frequency (GHz)
Heavy water (HDO)	2 948.042	2 945.094	2 950.990		2 945.094	2 955.592
Ammonia (NH_3)	2 948.411	2 945.462	2 951.359			
Ammonia (NH_3)	2 948.669	2 945.721	2 951.618			
Ammonia (NH_3)	2 949.480	2 946.531	2 952.430			
Ammonia (NH_3)	2 950.815	2 947.864	2 953.765			
Ammonia (NH_3)	2 952.640	2 949.687	2 955.592			
Water vapour (H_2O)	2 962.111	2 959.149	2 965.073		2 959.149	2 975.081
Heavy water (HDO)	2 966.081	2 963.115	2 969.047			
Water vapour (H_2O)	2 968.749	2 965.780	2 971.717			
Water vapour ($H_2{}^{18}O$)	2 969.868	2 966.899	2 972.838			
Water vapour (H_2O)	2 970.800	2 967.829	2 973.771			
Water vapour (H_2O)	2 970.801	2 967.830	2 973.772			
Oxonium (H_3O^+)	2 972.109	2 969.137	2 975.081			
Oxonium (H_3O^+)	2 980.735	2 977.754	2 983.715		2 977.754	3 002.430
Carbon monoxide (CO)	2 984.168	2 981.183	2 987.152			
Heavy water (HDO)	2 984.559	2 981.575	2 987.544			
Ammonia (NH_3)	2 989.643	2 986.653	2 992.632			
Water vapour ($H_2{}^{18}O$)	2 990.139	2 987.149	2 993.129			
Ammonia (NH_3)	2 991.555	2 988.564	2 994.547			
Ammonia (NH_3)	2 994.786	2 991.792	2 997.781			
Heavy water (HDO)	2 997.115	2 994.118	3 000.112	H		
Ammonia (NH_3)	2 999.430	2 996.431	3 002.430	H	2 977.754	3 002.430

NOTE 1 – G in the "Remarks" indicates that the line is observable from the ground under very good atmospheric condition.

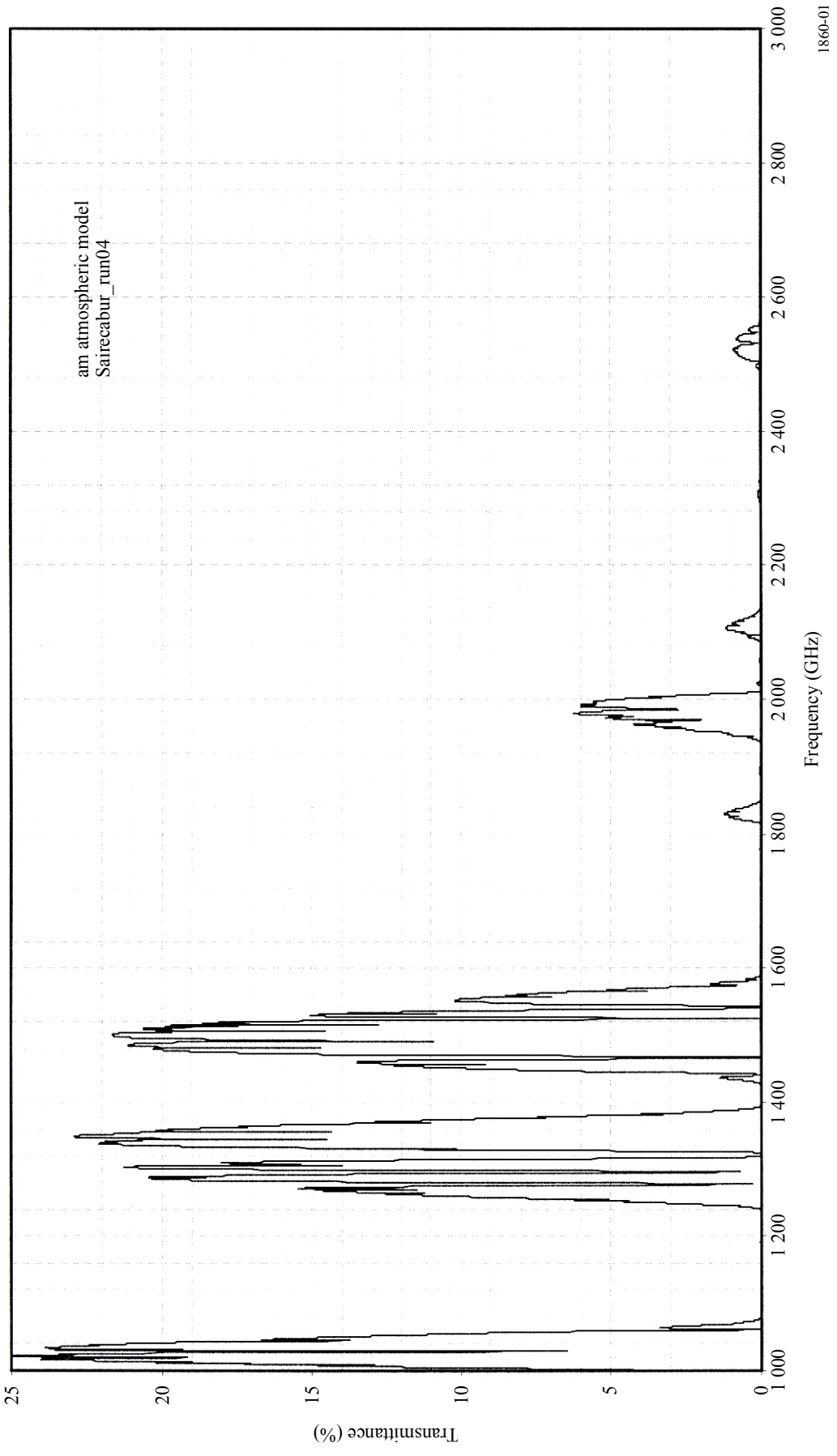
H in the "Remarks" indicates that maximum suggested frequencies are exceeding 3 000 GHz.

Suggested minimum and maximum frequencies correspond to Doppler-shifted frequencies for +300 km/s and –300 km/s, respectively.

References: IAU Resolution A.2 (1991, Buenos Aires; revised 2009, Rio de Janeiro)
JPL Molecular Spectroscopy Database (http://spec.jpl.nasa.gov/)
The Cologne Database for Molecular Spectroscopy (http://www.astro.uni-koeln.de/cdms/).

FIGURE 1

Calculated vertical transmittance through the atmosphere, using inputs in § 2 of Annex 1



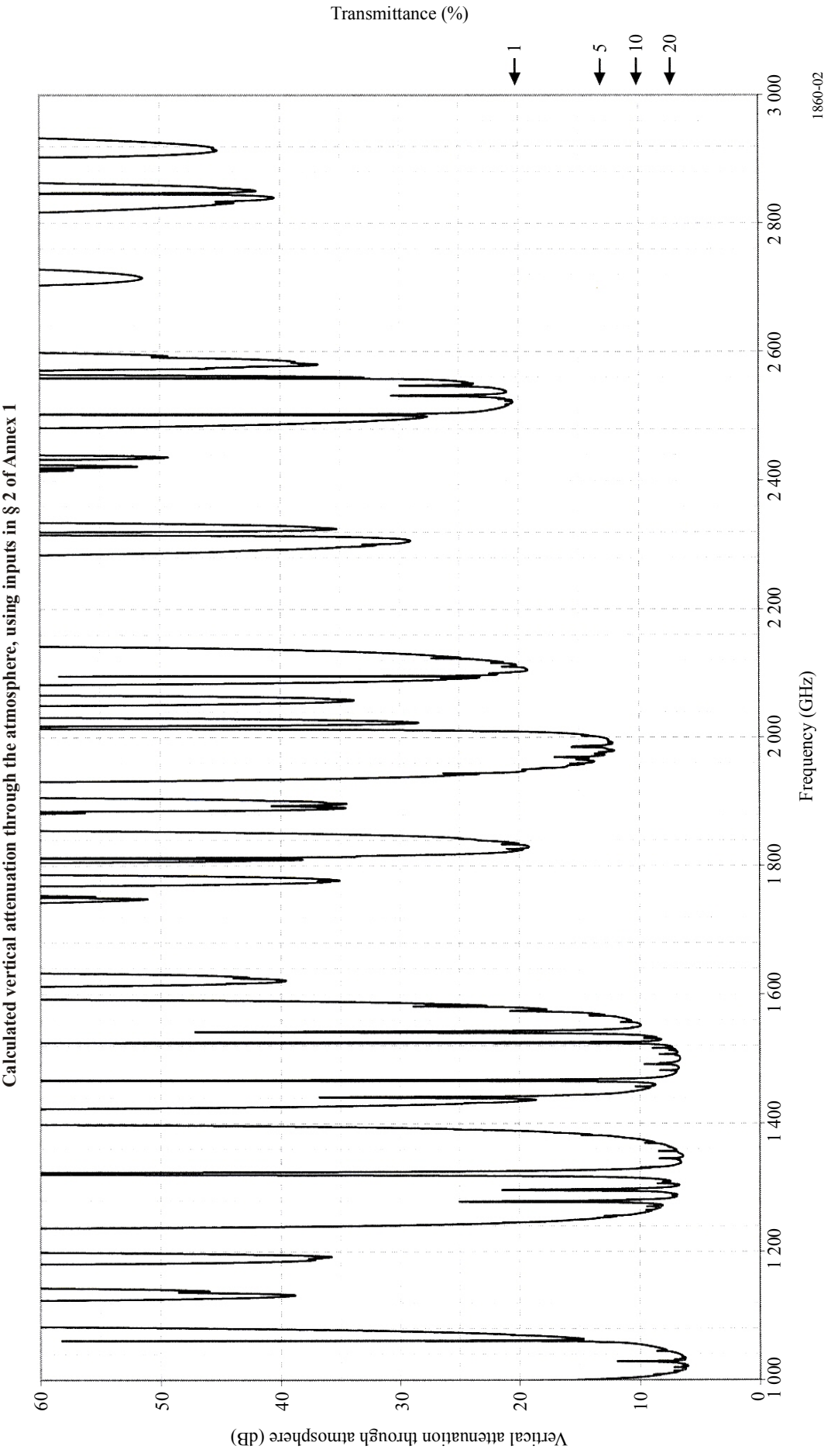


FIGURE 2

Calculated vertical attenuation through the atmosphere, using inputs in § 2 of Annex 1

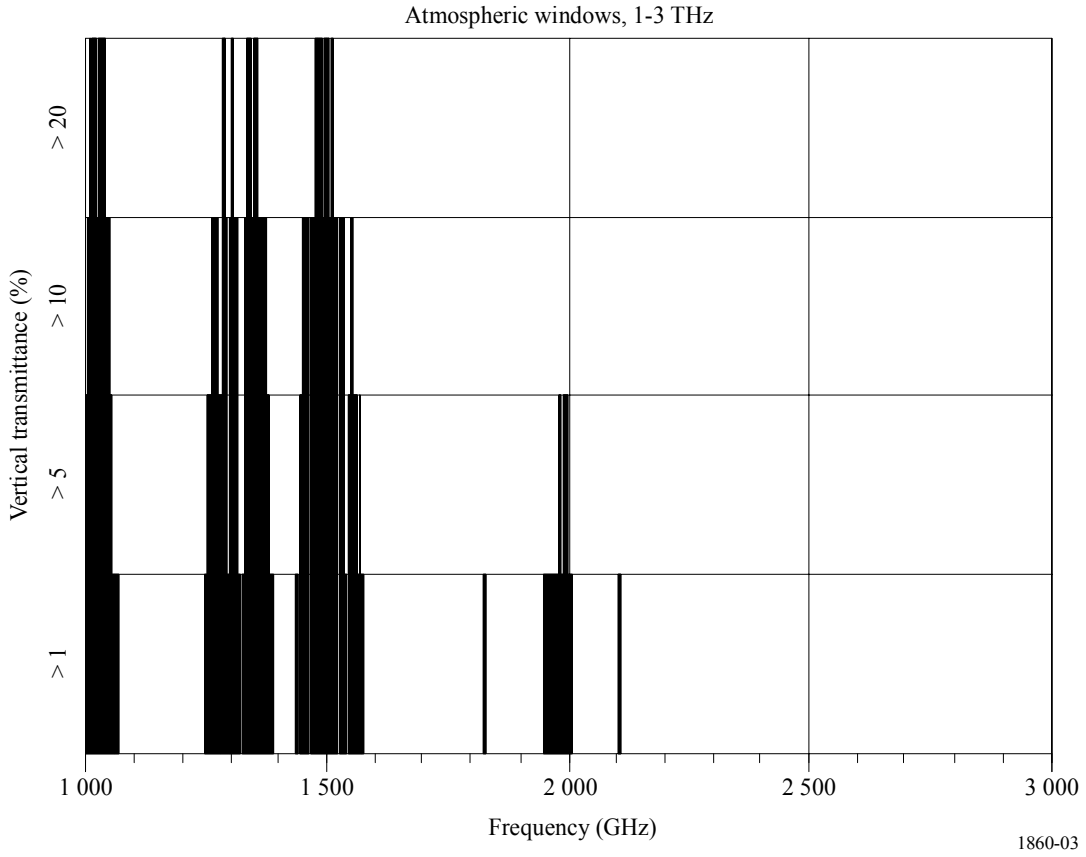
TABLE 2

Bands in Fig. 1 in which the atmospheric transmittance meets or exceeds the specified amount (GHz)

1%	5%	10%	20%
998.4-1 060.4	1 001.7-1 058.6	1 004.7-1 028.4 1 029.3-1 054.9	1 011.8-1 013.8 1 014.3-1 019.3 1 019.7-1 026.2 1 029.9-1 041.7
1 061.9-1 069.6	–	–	–
1 245.9-1 277.5	1 253.1-1 276.6	1 259.7-1 275.6	–
1 279.0-1 295.9	1 279.9-1 294.9	1 281.3-1 294.1	1 285.6-1 286.8 1 287.9-1 289.4
1 296.9-1 318.0	1 297.9-1 316.4	1 298.8-1 314.7	1 301.8-1 305.4
1 326.0-1 388.5	1 327.7-1 380.9	1 329.4-1 374.9	1 335.5-1 343.9 1 345.9-1 355.7 1 357.7-1 359.0
1 434.4-1 438.2	–	–	–
1 442.7-1 465.4	1 445.7-1 464.6	1 451.2-1 463.4	–
1 468.2-1 524.4	1 469.0-1 524.0	1 469.9-1 523.3	1 478.6-1 481.0 1 482.8-1 489.3 1 495.3-1 505.0 1 505.5-1 506.0 1 508.3-1 512.1
1 525.8-1 540.0	1 526.3-1 538.6	1 526.9-1 536.6	–
1 543.9-1 573.9	1 545.6-1 566.5 1 567.6-1 568.4	1 550.3-1 553.8	–
1 575.0-1 579.9	–	–	–
1 827.2-1 833.1	–	–	–
1 946.7-2 009.2	1 977.5-1 983.6 1 987.9-1 999.6	–	–
2 102.7-2 109.7	–	–	–

FIGURE 3

Graphical representation of Table 2



Based on consideration of the bands at which atmospheric transmittance at a good astronomical site exceeds 5%, enabling useful observations, the following bands are suggested minimum bands for protection of radio astronomy observations conducted from the surface of the Earth:

TABLE 3

Suggested minimum bands for ground-based radio astronomy

1 000-1 060 GHz
1 250-1 320 GHz
1 325-1 385 GHz
1 445-1 540 GHz
1 545-1 570 GHz
1 975-2 000 GHz

Due to excessive atmospheric attenuation even at high and dry ground-based astronomical observing sites, the use of bands above 2 000 GHz for radio astronomy is limited to airborne- and space-based applications.