Observations at Bochum of HAKUTO-R Moon Landing Attempt
2023 Apr 25

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Preliminary Remarks

1. Hakuto entry orbit was 100 km circular above the Moon's surface. Circular speed = 1634 m/s and orbital period = 7071s.

2. The Bochum antenna 20m G/T at 8.4 GHz is 40 dB [K].

3. Bochum has two software defined spectrum analysers, 'Airspy' and 'Aaronia' taking an IF of 1342.5 MHz (for HAKUTO). Their displays are streamed via YouTube - Peter G.

https://www.youtube.com/watch?v=lfg23f9yyMo	Airspy
https://www.youtube.com/watch?v=Uqk3qVlBzaE	Aaronia

4. Another system at Bochum includes a PLL to lock onto a spacecraft carrier (also at 1342.5 MHz). Lock is achieved when the carrier-noise-density ratio exceeds approx 25 dB [Hz]. (SNR in 1Hz).

The PLL is managed by software which augments the loop by computing the expected doppler shift of the target. Thus the PLL only has to track unmodelled variations of target frequency, which are generally small (of order Hz). But if a spacecraft trajectory is not fully defined, then
the estimated spacecraft TX frequency appears to be far from constant in consequence.

In the case of HAKUTO-R, Bochum was set up to target the Atlas crater on the Moon. Lon 43.38, Lat 46.74. If the spacecraft was stationary on the Moon, its estimated TX frequency would appear constant as described above.

IMPORTANT:

But as the TX is moving relative to the target (Atlas crater) then the reported apparent spacecraft TX frequency is not constant, and includes the doppler shift due the TX motion relative to Atlas crater resolved along the vector (Atlas_crater - Earth_observer).

Observations of this unmodelled frequency shift can be useful, provided the PLL system stays locked. If it loses lock, a human operator can retune, though with a high unmodelled dynamic this can be stressful.

For a fuller understanding of the Bochum PLL system see Appendix A.
For frequency observations see Appendix B.

5. What I was looking for was the apparent spacecraft TX frequency to stabilise at a steady value as this would normally imply the s/c had landed.

6. The wavelength used in calculations is 0.035301 m.

7. Bochum as seen from the Moon at 1600 utc was at AZ 226, EL 26.2 deg. See Appendic C.

Observations

16:18:19 Aaronia spectrum display shows first hint of signal

16:19:04 Airspy spectrum display shows first hint of signal at RX frequency 8492.530400 MHz (+/- 5 kHz)

16:28:00 Aaronia shows sub-carrier data (PSK?) sidebands at +/-125 kHz

16:32:10 PLL LOCKED after manual intervention.

Estimated TX frequency is 8492.530404 MHz. 37 dB [Hz]. Rate of change -49.5 Hz/s, +1.75 m/s^2 resolved along Atlas-Earth range vector.

16:37:55 The Airspy spectrum shows a SMALL SIGNAL about -20 dB below the main signal carrier and ~1 kHz higher in frequency. Signal is a 2-3 kHz wide. Also just visible on the Aaronia display. Daniel E. suggest this could be an echo off the Moon's surface.

	MHz	Hz/s	
16:38:40	8492.511953 MHz	-47.5 Hz/s	1.67 m/s^2
16:38:50	8492.511478 MHz	-47.5 Hz/s	
16:39:00	8492.511159 MHz	-31.9 Hz/s	
16:39:10	8492.511148 MHz	-1.1 Hz/s	) Mean +1.2 Hz/s
16:39:20	8492.511171 MHz	2.3 Hz/s	) -0.042 m/s^2

16:39:20 Acceleration drops to approx -0.042 m/s^2. Engines stopped?

Up to this moment the spacecraft acceleration (resolved along our Range vector) was steady at +1.68 m/s^2. Assuming that the spacecraft was more or less on its side, slowing down, we can 'unresolve' that by 1/cos(26.2) to be 1.86 m/s^2 retardation. (26.2 deg is the Earth's elevation above Atlas crater's horizon).

We don't know what speed it was doing at that 16:39:10/20 moment, or the altitude, and have to guess what it ought to have been. Quite slow we assume and quite low we hope.

Over the 7m 10s, change in frequency is -19233 Hz, +679 m/s total velocity change resolved along Atlas-Earth range vector.

During the 7m 10s the Airspy signal shows rapid carrier amplitude flutter approx. +/- 2 dB. The analyser has display smoothing, so the true flutter would be larger.

16:39:30 PLL lock LOST   Damn.   Why?

At this moment, the SMALL SIGNAL also disappears.

2.5 minutes hiatus while I intervened to recover PLL lock. This time mainly due to the Youtube stream latency. Takes time to see things respond to your control. Airspy display shows my hacking.

16:42:05 PLL LOCK re-acquired; frequency 8492.511957 MHz

From 16:42:10 to 16:43:40 the spacecraft acceleration (resolved along our Range vector) was very steady at -0.0424 m/s^2 (as before the loss of lock.)

That's a very small value. 90s hovering? (Or velocity perpendicular to the Range vector for a long time? Unlikely.)

16:43:40 Airspy now shows LARGE SIGNAL STRENGTH variations. +/- 5 dB Amplitude flutter distinct on data sidebands with period ~1.7s

16:43:40 to 16:45:00 the mean acceleration (resolved along our Range vector) CHANGES ABRUPTLY to +0.55 m/s^2 . Assuming that's free fall or at least generally downwards, we can unresolve that by cos(90-26.2) to get a vertical downward acceleration value of 1.24 m/s^2.

Slightly less than Moon gravity 1.62 m/s^2. Why? Not vertical?

16:44:06 SMALL SIGNAL appears again about 4 dB in amplitude, 15 dB below the carrier. Visible in Airspy waterfall too.

16:44:31 SMALL SIGNAL distinct, about +2 kHz from carrier. See attached screenshot.

16:45:09 Spectrum display carrier signal stops abruptly.

During the final 89s the spacecraft will have acquired additional speed of 111 m/s, travelling 4929 m plus 89*any_initial_speed.

Appendix A. Frequency Management - Description

There is a system at Bochum to track spacecraft carriers. Its primary purpose is to track the Stereo-A spacrcraft, but in general can follow any carrier.

It is a Frequency Locked Loop comprising 4 elements. (See diagram)

1. AOR AR5000 radio receiver plus
2. external 10.7 MHz to 38.4 kHz downconverter
3. Standalone hardware PLL coupled to
4. computer with controlling software "BoCR".

In normal operation, the computer knows a-priori the nominal spacecraft carrier frequency and the spacecraft trajectory in space. Software computes the EXPECTED receive frequency and tunes the radio to that frequency.

The radio receiver signal output at 10.7 MHz IF (bandwidth 30 kHz) is downconverted to 38.4 kHz and an ADC in the computer samples this. An FFT looks for the strongest signal within a +/-15 kHz window and retunes the radio receiver to centre the carrier in the hardware PLL.

If PLL LOCK is detected by the hardware, the computer accepts frequency HI or LO status bits from the PLL to fine tune the radio receiver when the spacecraft carrier appears to be drifting. The tuning steps are 1 Hz/s or 3 Hz/s and the PLL bandwidth 20 or 80 Hz.

The software displays the tracking performnce on the LOCAL display, which includes both the corrected and therefore ESTIMATED spacecraft TX frequency, the radio receiver frequency and the LOCK/HI/LO status. This information is also reported at 10s intervals to a REMOTE user.

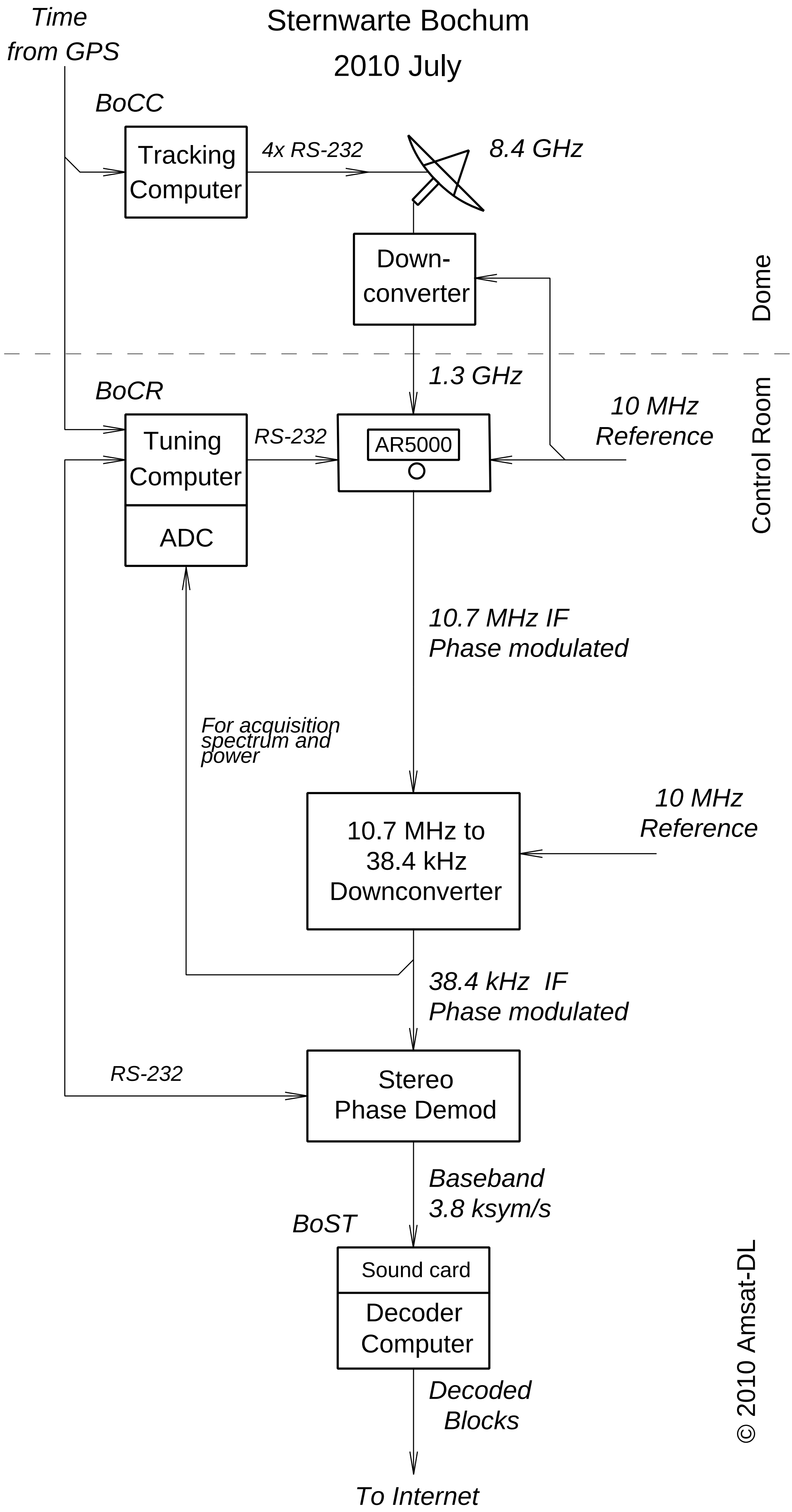
The remote user can take control of the tracking system, in particular open the loop and manually change the estimated spacecraft TX frequency.

This is important, as spacecraft frequencies are sometimes substantially different from nominal due to their various operational modes, or the spacecraft may be moving in a way not modelled by the receive system's tracking control software. Such is often the case when spacecraft orbiting a body such as a planet or Earth's moon and the exact orbit may be unknown to the precision needed for tracking.

The reported ESTIMATED spacecraft TX frequency of a spacecraft in an unmodelled orbit about a fully modelled moving primary body such as a planet or Moon will show large variations from the quite well known and probably constant true spacecraft TX frequency.

The variations can however be used to infer information about the motion of the spacecraft relative to the primary body. In the case of a lander, for example, whether it has landed. Or not.

Stereo A/B Reception
Sternwarte Bochum
2010 July



Appendix B. Doppler record

There were two periods when the PLL requency tracking system was in lock, as below.

Frequency below is the measured spacecraft frequency + the un-modeled trajectory doppler.

The frequency the RX is tuned to can be seen at the top of the Airspy spectrum display.

ddF is the rate of change of frequency over the preceding interval.

CNR is Carrier/Noise_power_density ratio expressed in dB. Unit is Hz.

Spacecraft: HAKUTO-R
Station: Bochum 20m
Location: Lat 51.426990 Lon 7.192566 G_alt 205.16m
Target: Moon, Atlas Crater
Coords: Lat 46.74 Lon 43.38, Alt 0m
Date: 2023 Apr 25 [Tue]

UTC HH:MM:SS	AZ deg	EL deg	Range Mkm	Frequency MHz	ddF Hz/s	CNR dB [Hz]
16:32:05	193.944	65.758	0.393514	8492.530864		29.08
16:32:07	193.962	65.757	0.393514	8492.530562	-15.1	30.79
16:32:10	193.983	65.756	0.393514	8492.530404	-15.8	32.63
16:32:20	194.069	65.750	0.393515	8492.529909	-49.5	35.90
16:32:30	194.155	65.743	0.393515	8492.529414	-49.5	36.67
16:32:40	194.241	65.737	0.393516	8492.528899	-51.5	36.96
16:32:50	194.328	65.731	0.393517	8492.528404	-49.5	36.95
16:33:00	194.414	65.724	0.393517	8492.527889	-51.5	37.07
16:33:10	194.500	65.718	0.393518	8492.527394	-49.5	37.27
16:33:20	194.586	65.711	0.393519	8492.526899	-49.5	37.45
16:33:30	194.672	65.705	0.393519	8492.526384	-51.5	37.71
16:33:40	194.758	65.698	0.393520	8492.525889	-49.5	37.72
16:33:50	194.844	65.692	0.393521	8492.525394	-49.5	37.72
16:34:00	194.930	65.685	0.393521	8492.524899	-49.5	37.47
16:34:10	195.016	65.679	0.393522	8492.524404	-49.5	37.18
16:34:20	195.102	65.672	0.393523	8492.523909	-49.5	36.96
16:34:30	195.188	65.665	0.393523	8492.523414	-49.5	36.99
16:34:40	195.274	65.658	0.393524	8492.522919	-49.5	37.07
16:34:50	195.359	65.652	0.393525	8492.522444	-47.5	37.05
16:35:00	195.445	65.645	0.393525	8492.521949	-49.5	37.21
16:35:10	195.531	65.638	0.393526	8492.521474	-47.5	37.32
16:35:20	195.616	65.631	0.393527	8492.520979	-49.5	37.39
16:35:30	195.702	65.624	0.393527	8492.520504	-47.5	37.27
16:35:40	195.787	65.617	0.393528	8492.520029	-47.5	37.31
16:35:50	195.873	65.610	0.393529	8492.519554	-47.5	37.41
16:36:00	195.958	65.603	0.393530	8492.519099	-45.5	37.40
16:36:10	196.044	65.596	0.393530	8492.518664	-43.5	37.02

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16:36:20  196.129   65.589   0.393531   8492.518308  -35.6  36.64
16:36:30  196.215   65.582   0.393532   8492.517792  -51.6  36.54
16:36:40  196.300   65.575   0.393532   8492.517377  -41.5  36.57
16:36:50  196.385   65.567   0.393533   8492.516962  -41.5  36.87
16:37:00  196.471   65.560   0.393534   8492.516626  -33.6  36.85
16:37:10  196.556   65.553   0.393534   8492.516110  -51.6  37.07
16:37:20  196.641   65.545   0.393535   8492.515693  -41.7  37.02
16:37:30  196.726   65.538   0.393536   8492.515238  -45.5  37.41
16:37:40  196.811   65.531   0.393537   8492.514763  -47.5  37.07
16:37:50  196.896   65.523   0.393537   8492.514308  -45.5  36.86
16:38:00  196.981   65.516   0.393538   8492.513853  -45.5  36.77
16:38:10  197.066   65.508   0.393539   8492.513378  -47.5  36.54
16:38:20  197.151   65.501   0.393539   8492.512903  -47.5  36.66
16:38:30  197.236   65.493   0.393540   8492.512428  -47.5  36.77
16:38:40  197.320   65.485   0.393541   8492.511953  -47.5  36.86
16:38:50  197.405   65.478   0.393542   8492.511478  -47.5  36.88
16:39:00  197.490   65.470   0.393542   8492.511159  -31.9  36.71
16:39:10  197.574   65.462   0.393543   8492.511148   -1.1  37.82
16:39:20  197.659   65.455   0.393544   8492.511171    2.3  37.75

Loss of lock

16:42:00  199.007   65.326   0.393555   8492.511954          0.00
16:42:10  199.091   65.317   0.393556   8492.511969    1.5  34.63
16:42:20  199.175   65.309   0.393557   8492.511981    1.2  36.89
16:42:30  199.258   65.300   0.393558   8492.511993    1.2  37.42
16:42:40  199.342   65.292   0.393558   8492.512008    1.5  37.69
16:42:50  199.426   65.283   0.393559   8492.512020    1.2  37.70
16:43:00  199.509   65.275   0.393560   8492.512032    1.2  37.90
16:43:10  199.593   65.266   0.393561   8492.512044    1.2  37.92
16:43:20  199.676   65.258   0.393562   8492.512056    1.2  38.02
16:43:30  199.760   65.249   0.393562   8492.512068    1.2  37.80
16:43:40  199.843   65.240   0.393563   8492.512074    0.6  37.41
16:43:50  199.927   65.232   0.393564   8492.511964  -11.0  36.54
16:44:00  200.010   65.223   0.393565   8492.511771  -19.3  36.17
16:44:10  200.093   65.214   0.393565   8492.511639  -13.2  36.28
16:44:20  200.177   65.205   0.393566   8492.511405  -23.4  35.92
16:44:30  200.260   65.196   0.393567   8492.511292  -11.3  35.94
16:44:40  200.343   65.188   0.393568   8492.511039  -25.3  36.08
16:44:50  200.426   65.179   0.393569   8492.510926  -11.3  36.03
16:45:00  200.509   65.170   0.393569   8492.510673  -25.3  35.77
16:45:09  L.O.S.
------------------------------------------------------------------
  UTC       AZ        EL        Range      Frequency     ddF    CNR
HH:MM:SS    deg       deg        Mkm          MHz        Hz/s dB [Hz]
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APPENDIX C. Earth (Bochum) as seen from Moon Atlas Crater
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Via NASA/JPL Horizons.

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*************************************************************************
 Date__(UT)__HR:MN  Azi____(a-app)___Elev      Range km     R-Rate km/s
*************************************************************************
$$SOE
 2023-Apr-25 08:00  225.330741  27.101106  3.9738149797E+05  -0.1787478
 2023-Apr-25 09:00  225.268885  27.022089  3.9669382499E+05  -0.2008480
 2023-Apr-25 10:00  225.242107  26.924149  3.9595362755E+05  -0.2077611
 2023-Apr-25 11:00  225.253726  26.810985  3.9521680344E+05  -0.1989699
 2023-Apr-25 12:00  225.304617  26.687310  3.9453933007E+05  -0.1749519
 2023-Apr-25 13:00  225.393101  26.558548  3.9397367090E+05  -0.1371754
 2023-Apr-25 14:00  225.515022  26.430480  3.9356532103E+05  -0.0880255
 2023-Apr-25 15:00  225.664000  26.308857  3.9334974257E+05  -0.0306615
 2023-Apr-25 16:00  225.831859  26.199002  3.9334992942E+05   0.0311880
 2023-Apr-25 17:00  226.009184  26.105445  3.9357480339E+05   0.0934790
 2023-Apr-25 18:00  226.185983  26.031609  3.9401858039E+05   0.1521335
 2023-Apr-25 19:00  226.352375  25.979578  3.9466116316E+05   0.2033241
 2023-Apr-25 20:00  226.499267  25.949966  3.9546952616E+05   0.2437365
 2023-Apr-25 21:00  226.618951  25.941895  3.9639997308E+05   0.2707886
 2023-Apr-25 22:00  226.705590  25.953080  3.9740107872E+05   0.2827897
 2023-Apr-25 23:00  226.755565  25.980015  3.9841708266E+05   0.2790313
 2023-Apr-26 00:00  226.767657  26.018230  3.9939148503E+05   0.2598091
$$EOE
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