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Bill Petrachenko

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Introduction

One of the options being considered for VLBI2010 involves starting with a broadband 2-15 GHz (S-Ku) system and then migrating to a traditional 10% bandwidth X/Ka system. The reason for starting with the "broadband" S-Ku system is that it allows inter-operability with existing S/X antennas during the transition to full VLBI2010 operations. However, because of its broad continuous frequency coverage, the S-Ku system has a second advantage. It potentially enables the use of the phase observable even at low SNR, making a high precision VLBI system feasible at reasonable cost. The delay determined in this way is being referred to as the "broadband" delay.

The reason for wanting to eventually migrate to an X/Ka system is that those bands are comparatively free of problems with RFI and source structure. Unfortunately, using the phase observable at X/Ka is more difficult, e.g.: within the foreseeable future, there are no plans to develop a broadband 8-36 GHz feed; the middle of the 8-36 GHz band is not useable due to the water vapour line; and, due to the higher frequencies involved, it is more difficult to resolve phase at X-Ka band than at S-Ku band.

The purpose of this memo is to investigate the relative performance of S/X and X/Ka group delay systems and S-Ku "broadband" systems to see, in each case, if the use of 12m dishes meets the VLBI2010 requirements for 4 ps delay precision and the minimum detectable flux of 0.1 to 0.2 mJ needed to detect all (or most) sources in the ICRF. In addition, the systems will also be evaluated with respect to the number of sources that can be observed per day.

System Description

All of the systems considered will have the following parameters in common:

- Antenna diameters = 12m
- Antenna efficiencies = 0.5
- Receiver Temperatures = 40K
- Max data record or transmission rate = 8 Gbps

A total of 10 different systems will be considered, each differing with respect to frequency allocations, bandwidths and bit-rates. Two of the systems are S/X systems, two are X/Ka systems, and six are "broadband" systems. Of the broadband systems, four use four bands each, and two use six bands. Each of the systems will be described in detail below [Note that all quoted band frequencies are at the lower edge of the band]:

1. This is an S/X system using a total bit rate of 1 Gbps. It is representative of the highest performance systems in use operationally today.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.25	0.125	0.5	0.288
8.2	0.720	0.5	0.4

2. This is an S/X system using a total bit-rate of 6.76 Gbps. To achieve this bit-rate requires 2-bit Nyquist sampling of the full continuous bands and the use of both polarizations. Its performance represents the greatest sensitivity that can be efficiently achieved using the current S/X feed design.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.25	0.125	1.0	0.288
8.2	0.720	5.76	0.288

3. This is an X/Ka system using traditional 10% bandwidth feeds and having a total bit-rate of 2 Gbps. A prototype version of a system like this could easily be assembled today given a new X/Ka front end and current geodetic VLBI technology.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
8.2	0.82	0.4	0.4
31.0	3.1	1.6	0.4

4. This is an X/Ka system using traditional 10% bandwidth feeds and having a maximum total bit-rate of 31.36 Gbps. To achieve this bit-rate requires 2-bits Nyquist sampling for the full continuous bands and the use of both polarizations. The total bit rate is higher than the max specified record rate of 8 Gbps, so, it is assumed that the full bit-rate will be acquired in a burst manner into RAM and then written more slowly (i.e. 8 Gbps) to the record or transmission system.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
8.2	0.82	6.56	0.288
31.0	3.1	24.8	0.288

5. This is a 4-band S-Ku “broadband” system having a total bit rate of 2 Gbps (BB4a). It is intended to represent a system that could be put together with digital back ends, feeds and record systems that are in existence (or nearly in existence) today. In other words, a system like this could be used for proof of concept studies/experiments of the S-Ku “broadband” concept. The frequencies were determined by searching through the 2-15 GHz range in 0.25 GHz steps for the combination of bands that resulted in reliable phase resolution at the lowest possible signal level.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.0	0.5	0.5	0.4

4.0	0.5	0.5	0.4
5.5	0.5	0.5	0.4
9.0	0.5	0.5	0.4

6. This is a 4-band S-Ku "broadband" system having a total bit rate of 2 Gbps (BB4b). It is very similar to system 5 above. The only difference is that the frequency ranges were restricted to regions where (according to the Observing Strategies Sub-group report) there is expected to be no commercial broadcast downlink signals. The frequency ranges from the report are 2.69-3.4, 4.8-6.7, 7.75-10.7 and 12.75-17.3 GHz. The frequency search was done in 0.1 GHz steps and for convenience the frequency ranges were adjusted somewhat to 2.7-3.4, 4.7-6.7, 7.7-10.7 and 12.7-15 GHz.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.7	0.5	0.5	0.4
4.8	0.5	0.5	0.4
6.2	0.5	0.5	0.4
10.2	0.5	0.5	0.4

7. This is a 4-band S-Ku "broadband" system having a total bit rate of 32 Gbps (BB4c). Like systems 2 and 4, achieving this bit-rate requires the use of 2-bit Nyquist sampling of the full continuous bands and the use of both polarizations. Like system 5, the frequencies were determined by searching through the 2-15 GHz range in 0.25 GHz steps for the combination of bands that resulted in reliable phase resolution at the lowest possible signal level.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.0	1.0	8.0	0.288
4.75	1.0	8.0	0.288
6.5	1.0	8.0	0.288
10.75	1.0	8.0	0.288

8. This is a 4-band S-Ku "broadband" system having a total bit rate of 29.6 Gbps (BB4d). It is very similar to system 7 above, except that, like system 5, the frequency ranges were restricted to regions where (according to the Observing Strategies Sub-group report, Memo?) there is expected to be no commercial broadcast downlink signals. The frequency ranges from the report are 2.69-3.4, 4.8-6.7, 7.75-10.7 and 12.75-17.3 GHz. The frequency search was done in 0.1 GHz steps and for convenience the frequency ranges were adjusted somewhat to 2.7-3.4, 4.7-6.7, 7.7-10.7 and 12.7-15 GHz.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.7	0.7	5.6	0.288
4.7	1.0	8.0	0.288
5.7	1.0	8.0	0.288
9.6	1.0	8.0	0.288

9. This is a 6-band S-Ku "broadband" system having a total bit rate of 48 Gbps (BB6a). Achieving this bit-rate requires the use of 2-bit Nyquist sampling of the full continuous bands and the use of both polarizations. The frequencies were determined by searching through the 2-15 GHz range in 0.25 GHz steps for the combination of bands that resulted in reliable phase resolution at the lowest possible signal level.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.0	1.0	8.0	0.288
3.5	1.0	8.0	0.288
5.0	1.0	8.0	0.288
6.5	1.0	8.0	0.288
9.25	1.0	8.0	0.288
14.00	1.0	8.0	0.288

10. This is a 6-band S-Ku "broadband" system having a total bit rate of 45.6 Gbps (BB6b). Achieving this bit-rate requires the use of 2-bit Nyquist sampling of the full continuous bands and the use of both polarizations. It is very similar to system 9 above, except that, the frequency ranges were restricted to regions where (according to the Observing Strategies Sub-group report, Memo?) there is expected to be no commercial broadcast downlink signals. The frequency ranges from the report are 2.69-3.4, 4.8-6.7, 7.75-10.7 and 12.75-17.3 GHz. The frequency search was done in 0.1 GHz steps and for convenience the frequency ranges were adjusted somewhat to 2.7-3.4, 4.7-6.7, 7.7-10.7 and 12.7-15 GHz.

Freq(GHz)	BW(GHz)	Bit-rate (Gbps)	Rms factor
2.7	0.7	5.6	0.288
4.8	1.0	8.0	0.288
7.7	1.0	8.0	0.288
8.7	1.0	8.0	0.288
9.7	1.0	8.0	0.288
13.9	1.0	8.0	0.288

Analysis

The two channel systems (S/X and X/Ka) were analyzed differently than the "broadband" (BB) systems. For the two channel systems, group delay solutions were used, while for the "broadband" systems, phase delay solutions were used. The phase delay solutions were done in three steps: first, a simple group delay solution was done; then, the group delay information was used to resolve phase differences between adjacent channels, moving in a bootstrap fashion from the easiest to the hardest to resolve pair; and, finally, all the group delay and phase difference data were used to resolve the rf phase.

Each of the parameters was calculated assuming two different antenna pointing angles. In all cases, antenna 1 was assumed to point at an elevation angle of 45 deg, but antenna 2 was assumed to point at either 30 or 7 deg elevation. In this way, results for both a moderate and a thick atmosphere could be examined. For this purpose, atmospheric opacities were picked off of a plot on page 418 of Thompson, Moran and Swenson. Note that the precision of the picks was considerably worse than the precision quoted below. The values used (in nepers) were:

- 0.008 at S-band (~2.5 GHz),
- 0.012 at X-band (~10 GHz),
- 0.021 at Ku-band (~15 GHz),
- 0.068 at Ka-band (~32 GHz).

Apparent Tatm (Tatm=Tsys-Tr) for varying elevation angles and bands are displayed in the table below. Clearly, the contribution of the atmosphere to apparent system temperature is significant for Ka-band. If low elevation sources continue to be required for atmosphere estimation, Ka-band observations will have somewhat of a disadvantage.

Elevation(deg)	*S-band*	*X-band*	*Ku-band*	*Ka-band*
90	2.7	4.0	7.0	23.2
80	2.7	4.0	7.1	23.6
70	2.8	4.2	7.5	24.8
60	3.1	4.6	8.1	26.9
50	3.5	5.2	9.2	30.6
40	4.1	6.2	10.9	36.8
30	5.3	8.0	14.1	47.9
20	7.7	11.7	20.7	81.9
10	15.0	22.7	40.8	161.5

Table 1. Tatm vs elevation angle for four different observing bands

In addition to the above analysis, the number of sources that could be observed per day was calculated for the ten different systems. Two cases were considered, one assuming that all slews are 65 s in duration (i.e. 6 deg/s max azimuth slew rate like an upgraded Patriot antenna), and the other assuming all slews are 25 s in duration (i.e. 9 deg/s for the both azimuth and elevation max slew rates, and an elevation drive capable of ~180 deg motion from horizon to horizon). For the systems that have bit-rates less than the max record rate of 8 Gbps (i.e. systems 1, 2, 3, 5, and 6) an "on source" integration time of 60 s was assumed. In the remaining cases, where bit rate is greater than the max record rate, it was assumed that data would be acquired in a burst fashion into RAM and written more slowly (8 Gbps) to media or transmission systems. It was assumed that data would be written to media during the entire time of the max slew as well as during the time of data acquisition. For these systems, the integration times were selected such that all data would just finish being written to media at the instant that the slew ended. This resulted in integration times shorter than 60 s. In these cases, this choice would simultaneously lead to high SNR and a large number of scans per day.

Results

The results are presented in two tables. Table 2 assumes a slew time of 65 s, and Table 3 assumes a slew time of 25 s. The columns labeled dtau1J represent the 1-sigma delay precision (after ionosphere correction) for a source with flux 1 J. The columns labeled mnflx represent the minimum useable flux. In the two-band cases, i.e. systems 1-4, this is set by the minimum detectable flux. In the “broad-band” cases, i.e. systems 5-10, this is set by the minimum flux required to reliably resolve phase. The columns labeled flux4ps represent fluxes required to achieve the vlbi2010 delay precision target (after ionosphere correction) of 4 ps. This is determined by scaling dtau1J. If dtau4ps based on this calculation is less than mnflx, then mnflx is the value used in the table for dtau4ps. Because of their inherent high delay precision, this latter case need to be applied for all of the “broadband” systems (systems 5-10).

Sys_name	Bit-rate (Gbps)	Int time (s)	Dtau1J 30deg (ps)	dtau1J 7deg (ps)	mnflx 30deg (J)	Mnflx 7deg (J)	flux4ps 30deg (J)	Flux4ps 7deg (J)	nsrc/ day
1. S/X	1.0	60	18.0	21.7	0.201	0.233	4.50	5.43	691
2. S/X	6.76	60	8.9	10.6	0.062	0.076	2.23	2.66	691
3. X/Ka	2.0	60	3.6	6.0	0.191	0.332	0.907	1.50	691
4. X/Ka	31.36	22.3	2.1	3.6	0.084	0.117	0.527	0.898	990
5. BB4a	2.0	60	0.45	0.55	0.190	0.233	0.190	0.233	691
6. BB4b	2.0	60	0.42	0.52	0.231	0.282	0.231	0.282	691
7. BB4c	32.0	21.7	0.15	0.19	0.072	0.088	0.072	0.088	996
8. BB4d	29.6	24.1	0.19	0.23	0.103	0.126	0.103	0.126	969
9. BB6a	48.0	13.0	0.15	0.20	0.068	0.092	0.068	0.092	1107
10. BB6b	45.6	13.8	0.15	0.20	0.093	0.126	0.093	0.126	1096

Table 2. System performances assuming slew time = 65 s

Sys_name	Bit-rate (Gbps)	Int time (s)	Dtau1J 30deg (ps)	dtau1J 7deg (ps)	mnflx 30deg (J)	Mnflx 7deg (J)	flux4ps 30deg (J)	flux4ps 7deg (J)	nsrc/ day
1. S/X	1.0	60	18.0	21.7	0.201	0.233	4.50	5.43	1016
2. S/X	6.76	60	8.9	10.6	0.062	0.076	2.23	2.66	1016
3. X/Ka	2.0	60	3.6	6.0	0.191	0.332	0.907	1.50	1016
4. X/Ka	31.36	8.56	3.4	5.8	0.136	0.189	0.851	1.45	2574
5. BB4a	2.0	60	0.45	0.55	0.190	0.233	0.190	0.233	1016
6. BB4b	2.0	60	0.42	0.52	0.231	0.282	0.231	0.282	1016
7. BB4c	32.0	8.3	0.25	0.30	0.116	0.141	0.116	0.141	2592
8. BB4d	29.6	9.26	0.30	0.36	0.166	0.203	0.166	0.203	2521
9. BB6a	48.0	5.0	0.24	0.33	0.110	0.148	0.110	0.148	2880
10. BB6b	45.6	5.32	0.24	0.32	0.151	0.202	0.151	0.202	2849

Table 3. System performances assuming slew time = 25 s

Discussion and Comments

1. The “broadband” phase delay systems (e.g. systems 5-10) performed much better with respect to delay precision than the 2-band group delay systems (e.g. systems 1-4). The improvement is approximately an order of magnitude.
2. The higher bit-rate systems (e.g. systems 2, 4, 7-10) performed better with respect to minimum useable flux than the low bit-rate systems (e.g. systems 1, 3, 5, and 6). For the slower slew rate case (Table 2), the difference was a bit more than a

factor of 2, and for the faster slew rate case (Table 3), the difference was a bit less than a factor of 2. [Note that the difference would have been even greater if all systems used the same integration time. Recall that the high bit-rate systems used shorter integrations so that the data could be fully written to disk during the slew time of 65 s or 25 s.]

3. The candidate proof-of-concept systems (e.g. systems 5 and 6) for the "broadband" concept performed about a factor of ~2 worse than the full bandwidth "broadband" systems (e.g. systems 7-10) with respect to both delay precision and minimum useable flux, as would be expected by the factor of ~4 difference in total number of bits (i.e. BT) written to media for each observation.
4. The high bit-rate systems (e.g. systems 4, 7-10) that used burst mode acquisition performed better with respect to number of scan per day than the low bit-rate systems (e.g. system 1, 3, 5, and 6). The improvement for the lower slew rate case (Table 2) was about a factor or 1.5 and, for the higher slew rate case (Table 3) it was as much as a factor of 2.5.
5. Three of the "broadband" systems (e.g. systems 6, 8, and 10) were tailored to avoid some parts of the RF spectrum where commercial downlink broadcast allocations exist. When these systems are compared with systems 6, 8, and 10 respectively that have no frequency restrictions, delay precision was degraded by less than about 20%, and minimum useable flux was degraded by less than about 50%.
6. It should be pointed out that the minimum useable flux (mnflx) from Table 2 and 3 does not include any margin. As a result, it would be prudent for real scheduling software to include some contingency for cases where, for example, correlated flux is lower than expected or the atmosphere is worse than expected, or in the "broadband" cases there are complications with source structure or non-linearities in the electronics

Conclusions

1. The goal of achieving 4 ps delay precision with nearly all sources in the ICRF can be achieved with "broadband" S-Ku systems using 12 m antennas (provided of course that complications due to source structure and instrumental instability are not too great).
2. The goal of achieving 4 ps delay precision with nearly all sources in the ICRF cannot be met with X/Ka systems using 12 m antennas, unless, of course, the "broadband" approach can successfully be applied to the X/Ka systems as well. To achieve the VLBI2010 target delay precision (without significantly impacting the number of observations per day), X/Ka systems will require 30 m class antennas. It is important to note this conclusion because it means that 12 m antennas deployed today for S-Ku "broadband" operation will have unacceptable performance at X/Ka band if it should become necessary in the future to use that band to avoid RFI at the lower frequencies.
3. High bit-rate systems (i.e. >~30 Gbps) can produce a significant improvement in the number of observations per day, especially if burst mode is used and the antennas have short slew times.

4. Within reason, S-Ku "broadband" system performance degrades only slowly if frequency restrictions are applied to avoid RFI.
5. Lower bit-rate systems (e.g. systems 5 and 6) can be used effectively to do proof-of-concept tests of the "broadband" concept.

Risks of the "Broadband" Approach

It is clear from this study, that the "broadband" approach allows high precision delay measurements to be made at low snr – and, hence, makes it possible to achieve the VLBI2010 delay precision target even with comparatively small antennas. However, there are risks:

- The "broadband" approach has not been proven. Hence, it is important to continue moving forward with further theoretical studies and, as soon as possible, to initiate proof-of-concept tests with real hardware (to investigate the effects of RFI, electronics, source structure, etc).
- If, in the future, it is necessary to move from S-Ku to X/Ka band to avoid RFI at lower frequencies, 12 m class antennas will be inadequate with respect to delay sensitivity.