Memo: merits and perils of long integration time at X-band

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1 Problem statement

Baseline sensitivity is proportional to the square root of integration time, *provided the noise is uncorrelated*. Therefore, it is beneficial to increase the integration time if one wants to detect a weak source without resorting to phase calibration. However, atmosphere path delay fluctuations and instability of frequency generator make samples of the cross-correlation function correlated, and therefore, they set the limit of coherent averaging. At frequencies above 5–6 GHz, fluctuations in neutral atmosphere usually dominate. What is the optimal integration time at 8.4 GHz? Since the neutral atmosphere path delay fluctuations are a non-stationary process, they cannot be reliable predicted. At the same time, analyzing past experiments, we can evaluate the magnitude of decorrelation at long integration time. This allows us to work out a guideline for scheduling absolute astrometry programs.

2 Analysis of VLBA data with long integration times

I used two VLBA X-band campaigns which were completely re-analyzed in April 2010: the Northern Polar Cup Survey NPCS — three winter 24^h sessions which ran on 2006.02.14, 2006.02.16, and 2006.02.23; and the RDV — three summer 24^h sessions which ran on 2007.06.26, 2007.07.10, and 2007.08.01.

2.1 NPCS campaign

During 72 hour long NPCS campaign each target source was observed at X-band for 450–460 s. The scheduling goal of the experiment was absolute astrometry of sources with declinations in range [+75°, +90°]. Experiment was re-analyzed with restricting effective duration of each scan: when the effective duration exceeded 300 s, weights of any further accumulation periods were set to zero. The effective duration was defined as $\sum_i w_i t_{ap}$ where w_i is the data weight equal to the share of used samples in the accumulation period, and t_{ap} is duration of the accumulation period. Fringe fitting procedure for each full (long) scan of 450–460 s and short, truncated scan of the same data, 300 s long, ran independently.

If the noise were uncorrelated, then the SNR over a 455 s length long scan would be higher than the SNR over a 300 s long scan by $\sqrt{455/300} = 1.23$. If the noise is correlated, than $\mathrm{SNR}_l/\mathrm{SNR}_s$ will be less than 1.23, and may be even be less than 1, i.e. additional data may degrade result. Here SNR_l stands for the signal to noise ratio of a long scan of 450–460 s, and SNR_s stands for signal to noise ratio of the same scan with only 300 s data used. If due to decorrelation $\mathrm{SNR}_l/\mathrm{SNR}_s < 1.0$, then the source detected at long scan may not be detected at

Table 1: Statistics of the comparison of fringe fitting results of the winter NPCS campaign using full (long) scan lengths of 450–460 s and restricted (short) scans of 300 s long. D_s is the number of observations detected at short integration time, and not detected at long integration time. D_l is the number of observations detected at long integration time, and not detected at short integration time. N_s and N_l are the total number of observations detected at short and long integration time respectively. L is the geometric mean of decorrelation over scans detected at both long and short integration time.

Exp	D_s	D_l	N_s	N_l	L
NPCS-A	16	104	775	879	0.980
NPCS-B	13	89	747	836	0.976
NPCS-C	17	106	1127	1216	0.970
all	46	299	2649	2931	0.975

short integration time, and vice versus of $\mathrm{SNR}_l/\mathrm{SNR}_s > 1.0$. Detection limit from this campaign defined as the probability of false detection 0.001 was SNR > 5.6. Refer to (Petrov et al., 2007) for more details. This estimate of the detection limit was produced by fitting the histogram of the SNR distribution. The for computing the SNR, the ratio of fringe amplitude to the noise level, the noise level was calculated as the average amplitude of randomly selected 32768 samples of the Fourier transform of the cross-correlation spectrum, with outliers exceeding 3.5σ removed by an iterative procedure. Estimates of the noise level in processing long and short scans are at great extent independent.

One of the measures of merits of using long scans is the count of observations undetected at short scans, but detected at long scans. The measure of perils of long scans is the count of observations undetected at long scans, but detected at short scans. Actually, we always can reduce amount of used data, so the only penalty of using long scans is a waste of precious array time. We also can count detections with short and long scans.

Another measure of perils of long scans is the average decorrelation loss factor determined as

$$L = \left(\prod_i^n \frac{\mathrm{SNR}_l/\mathrm{SNR}_s}{\sqrt{t_l}/\sqrt{t_s}} \right)^{1/n}$$

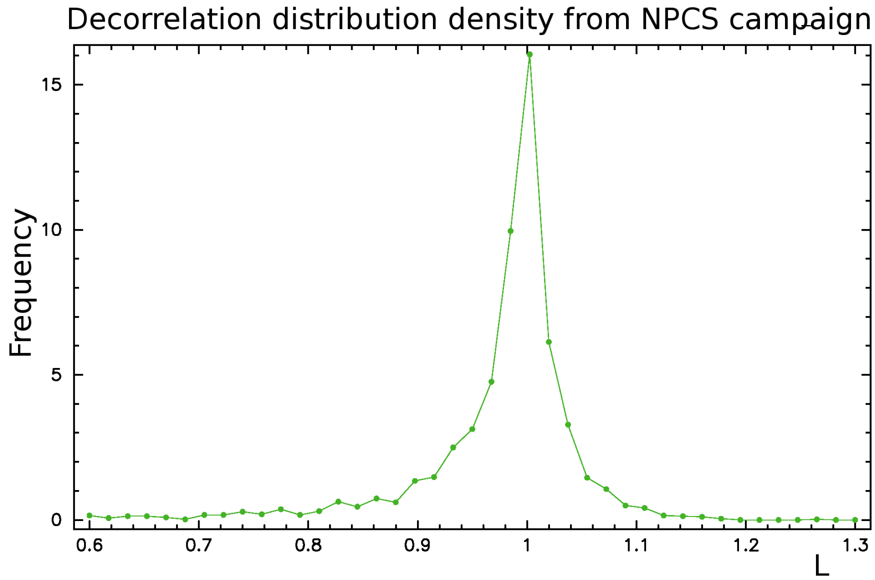
where t_l and t_s is duration of the long and short scans respectively. This factor accounts for deviation of the growth of SNR from the $\sqrt{t}$ rule. Decorrelation is computed over scans which were detected during both short (300 s) and long (455 s) integration time.

The estimate of the decorrelation factor is a stochastic quantity. Even if the atmosphere were frozen, it would have had a scatter due to the thermal noise. Figure 1 shows its distribution density. The asymmetry at the low part of the distribution is due to propagation effects. Integrating the distribution, we can get estimates of the share of observations with decorrelation factors exceeding certain thresholds (NB: smaller decorrelation factor means greater losses due to decorrelation). Decorrelation factor less than 0.81 means that the long scan has the SNR less than the short scan. Table 2 shows the distribution.

2.2 RDV campaign

VLBA experiments under RDV program were observed from 1994 through 2009 six times a year. They were scheduled by geodetic software SKED. Scheduling goal was geodesy. The schedules had sources at elevations as low as 5°. Maximum scan length through 2006 was 770 s — the length of one pass of Mark-3 tapes. The maximum length was reduced to 630 s at the end of

Figure 1: Normalized distribution of decorrelation from three NPCS observing sessions. The median value is 0.975



2006. All 10 VLBA stations and 5–10 non-VLBA globally distribution antennae participated. I took three summer experiments and re-ran fringe search routines for scans longer than 470 s. The scan length used for re-analysis varied from 470 to 630 s with the median value of 520 s. Detection limit from this campaign was SNR > 5.0.

Three RDV experiments were re-processed exactly the same way as NPCS observing sessions: each long scan was truncated to 300 s of effective duration by setting weights to zero at the end of the scan. Table 3 shows statistics of fringe fitting results, figure 2 shows normalized distribution of decorrelation loss factors, and table 4 shows the share of observations with decorrelation loss factors exceeding certain thresholds.

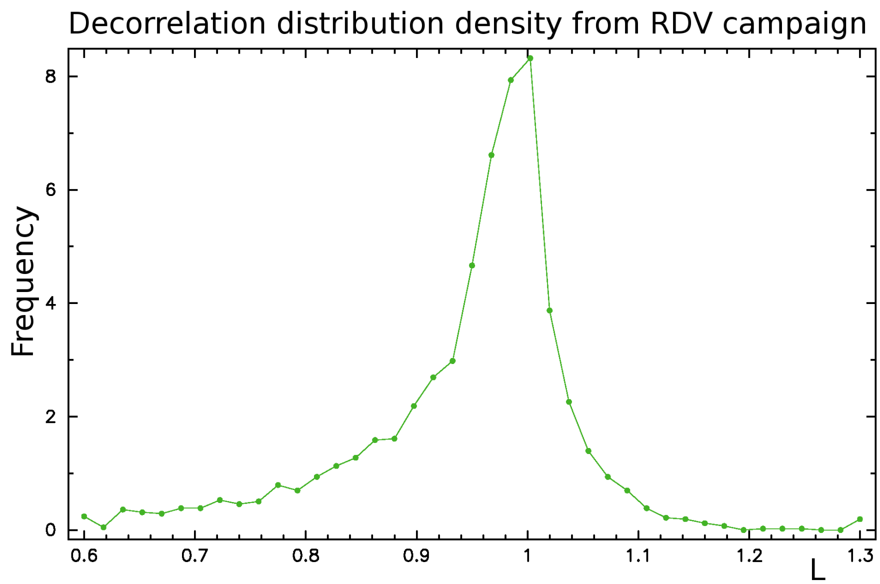
3 Discussion

Decorrelation losses depend on weather conditions, on elevation angle, and on baseline length (f.e. atmosphere fluctuations at 236 km long baseline LA-VLBA/PIETOWN are partially coherent). In the present study I did not try to account each factor separately, but tried to get an overall picture, because for planning absolute astrometry experiments we are not much interested to know what will be the outcome of each specific observation, but we are rather interested to learn the general statistics of an experiment for making a judgment of how much will we gain or lose

Table 2: The share of observations with decorrelation factors L less than certain thresholds in winter NPCS campaign.

L	share
0.80	3%
0.90	9%
0.95	18%
1.00	60%

Figure 2: Normalized distribution of decorrelation loss factors from three RDV observing sessions. The median value is 0.944



on average.

As it was expected, decorrelation in summer sessions is greater than in winter sessions. However, not much worse. Increasing the scan length significantly increases the number of detections. The number of sources which were detected using long scans is greater than the number of sources detected during short integration time (300 s), but not detected during long scans (450–630 s) by the factor of 5–10. It is worth mentioning that for 82% of winter observations and 65% of summer observations decorrelation is less than 5%, i.e. insignificant.

The issue of optimal scan length was studied in the past in relationship to a recommendation for maximum switching cycle for phase referencing (Beasley and Conway, 1995). If the integration time is too long, then after switching from the calibrator to the target and back, the fringe phase may drift far away and may not be connected. Ulvestad (1999) computed the table of recommended switching angles derived from average parameters of the atmosphere turbulence derived by Treuhaft and Lanyi (1987). Wrobel et al. (1999) recommend switching time of 160–440 s at 8.4 GHz at elevations above 20° and they note that experience shows that 300 s switching time does indeed work for observations at this frequency. The recommended switching time is shorter than the optimal integration time for absolute astrometry which was found in this study. These two recommendations should not be confused. According to Wrobel

Table 3: Statistics of the comparison of fringe fitting results of three summer RDV experiments campaign using full (long) scan lengths of 470–630 s and short scans restricted to 300 s long. The meaning of columns is the same as in table 1.

Exp	D_s	D_l	N_s	N_l	L
RDV-63	7	39	708	741	0.951
RDV-64	9	45	516	516	0.938
RDV-65	11	130	1701	1701	0.943
all	27	214	2649	2931	0.944

Table 4: The share of observations with decorrelation factors L less than certain thresholds in summer RDV campaign

L	share
0.80	8%
0.90	21%
0.95	35%
1.00	74%

et al. (1999), switching time should be short enough that the root mean square path variations between successive calibrator observations (including slewing time, antenna settling and tape/disk spin-up) be less than $\pi/2$ radian 95% of the time. This criterion is **different** than the decorrelation loss, and it is **more stringent**. If the phase was connected through a gap of length $\mathcal{S}$ and was not connected through the gap $\mathcal{L}$, such that $\mathcal{L} > \mathcal{S}$, it does not necessarily follow that the $\mathrm{SNR}_{\mathcal{L}} \leq \mathrm{SNR}_{\mathcal{S}}$! As it was already mentioned, the only penalty for exceeding the correlation limit for absolute astrometry observations is a waste of a portion of observing time, while the penalty or exceeding the correlation limit for phase referencing is a ruined experiment. Therefore, the recommendation for maximum switching time is more conservative.

4 Conclusions

Although decorrelation at 8.4 GHz may happen even after 240 seconds at specific conditions, extending integration time from 300 seconds to 480 or 600 is still on average beneficial and helps to improve the SNR and detect more sources. Extending integration time beyond 300 s to 480 s and further caused the degradation of results (easily corrected) due to decorrelation of 3% of observations in winter and 8% in summer. Considering these experiments representative, **raising the maximum scan** length from 300 s to 480 s **improves sensitivity** depending on weather conditions for **92–97% observations**. The average improvement is 20–23%. For remaining 3–8% observations no improvement takes place.

References

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