WP 3.1.1 RFI Mitigation
Date: 06.02.2012

Achievements in reporting period: 1st July 2010 until 31st of December 2011.

1st July 2010 to 30 June 2011:

No final deliverables were delivered during that period, but
significant development work was carried out.
See previous periodic reports.

1st July 2011 to 31 December 2011:

> A summary of progress towards objectives and details for each task;

RFI Mitigation in Focal Plane Arrays

Final software, documentation, and report on RFI mitigation in focal plane arrays was
delivered in DiFX and C++ libraries, and is available here:

http://www.radionet-eu.org/fp7wiki/lib/exe/fetch.php?media=jra:albius:beamformer-0.1.0-ug.pdf

http://www.radionet-eu.org/fp7wiki/lib/exe/fetch.php?media=jra:albius:beamformer-0.1.0-refman.pdf

http://www.radionet-eu.org/fp7wiki/lib/exe/fetch.php?media=jra:albius:beamformer-0.1.0.tar.gz
https://svn.atnf.csiro.au/difx/libraries/beamformer/

Good performance was demonstrated in mitigating RFI in simulated data
especially with reference antennas.

An algorithm improvement over those previously published yielded much
improved mitigation at low interference-to-noise ratio.

Beamformer design for Effelsberg APERTIF tile has been modified to
provide the full covariance matrix needed to apply these algorithms.

Figures illustrating the mitigation performance are available in the
User Guide (beamformer-0.1.0-ug.pdf), linked above.

RFI mitigation in VLBI

The multi-rate filter for RFI mitigation was implemented in DiFX
and used for correlation of an EVN observation of OH in Cyg A, and
NGC 1068 (E10C014) for RFI mitigation test.
This progress was reported in previous reports.

We have now compared spectra made with and without RFI mitigation to
validate the mitigation effectiveness. This revealed that RFI from
GPS is present in some baseline spectra as expected by the design of
the test observation. Surprisingly however, RFI mitigation was not
effective and sometimes even made the RFI stronger.

We investigated the cause as follows.

We generated synthetic recordings for two of the EVN stations
(Effelsberg and Westerbork), consisting of, selectably, uncorrelated
noise, correlated noise, GPS carrier, and GPS carrier modulated with C/A code.

We correlated the synthetic data (noise plus modulated GPS carrier) in DiFX and in Matlab and obtained the same results, which verified the correctness of the DiFX implementation of the multi-rate filter for RFI mitigation.

We then focussed on the filter characteristics in detail.

The filter infrastructure implemented in DiFX passed the validation test shown in Figure 1, in which the GPS tone near 22 Hz fringe rate was mitigated by 70 dB. This is an excellent result.

Figure 1: figure1_right.png
Captions: See below.

However, the final baseline visibility spectrum unexpectedly still contains the GPS tone, mitigated by only 3 dB, shown in Figure 2 This is inconsistent with the result in Figure 1, and the reason is not yet entirely understood.

Figure 2: figure2.png

We tested whether the modulation of the RFI was causing poor mitigation by switching off the modulation and repeating the first two tests with noise plus pure tone. The result (good mitigation in the fringe-rate spectrum but poor mitigation in the final baseline spectrum) was repeatable, seen in Figure 3 and Figure 4.

Figure 3: figure3_right.png

Figure 4: figure6.png

We tested whether the poor mitigation might be coming from an unexpectedly long filter settling time, in which case the settling could be accelerated by initializing the filter at the start of the accumulation period. The test result showed that the filter was settling rapidly and that initialization was not necessary, seen in Figure 5. This same test explained how the RFI could be stronger after mitigation; when the sinc ring-down function of the standard integrator chances to pass through a null then the RFI is mitigated below the level of the IIR filter.

Figure 5: figure5_left.png and figure5_right.png

> Highlight clearly significant results;

See description above.
- RFI mitigation in focal plane arrays works well and is delivered.
- RFI mitigation in DiFX is implemented, performance tests are mixed, showing fringe-rate spectra with an excellent 70 dB of mitigation, but RFI remains in the final baseline spectra.

> Deliverables and Milestones

- RFI mitigation in focal plane software, documentation and user guide are delivered.

Figure Captions:

Figure 1: Fringe frequency spectra zoomed to 0-45 Hz for channels 48 to 50. Spectra are Hanning windowed Fourier transforms of the cross-correlation time series of a channel. The 1 MHz BPSK modulation by the GPS CA chip sequence was enabled. Modulation spreads the GPS carrier in channel 49 across neighboring channels. Spectra of raw cross-correlation data (solid blue) show GPS at a 22 Hz fringe frequency. Mean filtering reduces GPS levels in the time series by ~20 dB (solid green). A 10 Hz low-pass filter alone suppresses GPS by ~50 dB but if followed by a mean filter, GPS is suppressed ~70 dB over the original (dashed red).

Figure 2: Cross-correlations in all 128 channels after T=2.094 seconds, the final baseline visibility. Although Figure 1 demonstrates low-pass mean filtering with 50 dB improved GPS suppression compared to mean filtering alone, the final visibility still contains significant amounts of GPS (dashed red, top). There is almost no reduction in level compared to mean filtering (solid green, top). The absolute difference |int(xc) - flt(xc)| is sometimes larger because low-pass mean and mean results have different phase (middle). The final low-pass mean filtered visibility fails to demonstrate the expected 50 dB decrease in GPS level. The reason is not yet entirely understood.

Figure 3: Fringe frequency spectra zoomed to 0-45 Hz for channel 49 data with a clean GPS carrier and no modulation. The spectrum of the raw data time series (solid blue) is overlaid with spectra from mean filtered data (solid green), and using 16 Hz low-pass mean filtering increases the GPS suppression from ~30 dB to ~60 dB (dashed red).

Figure 4: Cross-correlations in all 128 channels after T=2.094 seconds, the final baseline visibility. No GPS carrier modulation. As in Figure 1 with CA chip modulation, even now the final visibility has more GPS signal than anticipated. For the low-pass mean filtered data the final visibility (dashed red, top) happens to be reduced by factor 2 (3 dB << 40 dB) compared to the mean filtered (solid green, top). This is depends however on the choice of time T. Further, the integrated and filtered complex visibilities have different phase, resulting in a possibly larger absolute difference |int(xc) ? flt(xc)| (middle). The normalized absolute difference (bottom) shows certain channels such as channel 104 with noise seemingly enhanced by the filter.

Figure 5: Absolute value of filtered time series when using uninitialized filters (left panel) and initialized filters (right panel). Channel 49 contains a clean GPS carrier and no modulation. The DiFX mean filtered output exhibits a large sinc(x) ripple pattern due to the poorly attenuated GPS tone (green curve). You may compare this ripple to the 22 Hz fringe frequency in Figure 3. The filter output from a two stage filter that consists of a 16 Hz low-pass followed by a mean filter reduces the ripple by ~60 dB (red). For an uninitialized low-pass the output starts from zero (left panel, red). Before filtering actual data the low-pass section may also be initialized first by Gaussian noise equal to the expected later level. In this case the output starts from the estimated noise mean (right panel, red). In both cases the filter output after 100 ms is essentially identical and converges equally fast.