Correlation Processing System for "Spectr-R" (Radioastron) Spacecraft Beacon Signal

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The paper describes the RadioAstron space radio telescope beacon signal processing technique and a brief review of the software package used for data processing. The beacon emits monochromatic signal at 8.4 GHz. Observations were carried out at "Quasar" VLBI network, data was processed using the software package designed in IAA RAS. The package consists of the ephemeris, correlation processing, postprocessing and GUI utilities implemented with C++ with Qt 4.8 and qwt 6.0 frameworks.

Keywords: RadioAstron, beacon, spacecraft, correlation processing, software.

1 Introduction

The paper describes the RadioAstron space radio telescope beacon signal processing technique and a brief review of the software package designed for data processing.

Observations were carried out at "Quasar" VLBI network, with a help of three stations (Svetloe, Zelenchukskaya and Badary). During a session of observations (ru0109) continuous 60 minute beacon signal recording was made. The beacon emits monochromatic signal at 8.4 GHz, it was recorded in a 16 MHz bandwidth with a data rate of 32 Mbps and 1 bit sampling. Receiver had a setup that placed beacon signal in the middle of recorded band.

The software package was designed for recorded data processing. It consists of ephemeris software, correlation and postprocessing software and a graphical user interface. The speed of spacecraft along the station-spacecraft axis and the distance variations between stations and spacecraft were determined during the scan.

The paper illustrates full cycle for the spacecraft scan (292–0000) processing for one of three stations (Svetloe) participated in observations. Processing results for all stations are given.

2 Ephemeris software for spacecraft observations

In order to provide RadioAstron spacecraft observations at "Quasar" VLBI network spacecraft ephemeris software was developed. The software is based on universal processor for ephemeris calculations (ERA) designed in IAA RAS, it was used for the following operations:

— spacecraft declination angle and right ascention calculations for tracking;

— calibration source selection in X/S bands for ionospheric data used for processing;

— delays pre-calculations for IAA RAS correlators;

— radioAstron orbit data calculated in Keldish Institute of Applied Mathematics RAS (ftp://ftp.kiam1.rssi.ru/pub/gps/spectr-r/nu/) were used as initial data.

3 Primary data processing of the RadioAstron spacecraft observations

Due to movement of a spacecraft relative to Earth and Earth's diurnal motion beacon signal has a Doppler frequency shift that can be detected in both VLBI and single station modes. The value of a Doppler shift determination during scan is the goal of primary data processing of the RadioAstron spacecraft observations.

Primary processing was carried out with a help of software package designed for monochromatic signals data processing. It consists of correlation, postprocessing software and graphical user interface (GUI). Correlation software extracts spacecraft signal and determine it's parameters (amplitude and phase) on the short (1 ms) periods of time. Postprocessing software analyzes extracted signal and makes adjustments to the signal tracking on the following iterations. Graphical user interface provides visualization and control of the whole process. The software package was developed using C++, Qt and qwt based libraries were used for GUI. The software can run under the control of any operation system.

Each of the observations scan processing is done using iterative algorithm. Each iteration includes correlation and postprocessing.

4 Initial Iteration

At the beginning of each scan processing during first few seconds the power spectral density of recorded signal was calculated for each station. Doppler shift of a beacon signal for the beginning of a scan was determined based on the spectral data.

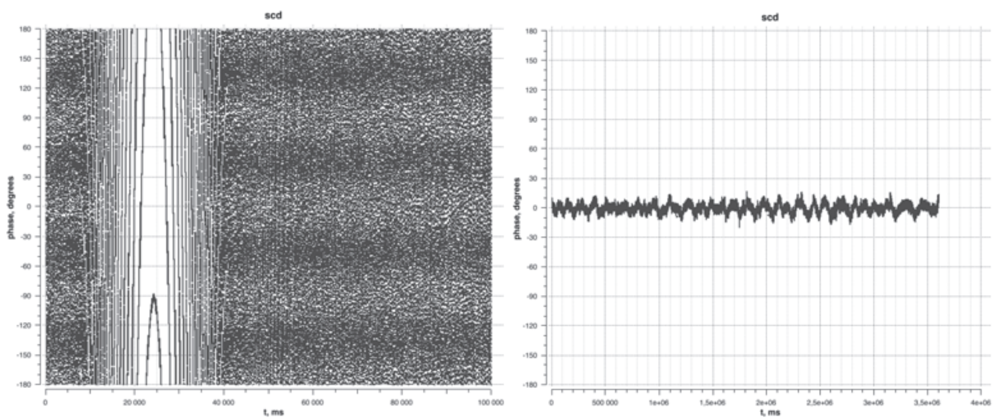
5 First iteration

The next step was correlation processing of the scan data. For each accumulation period of recorded signal T cosine and sine components of correlation function (CF) were calculated as:

$$
\begin{aligned}
C_{\cos,i} &= \int_{T_i} S(t)\, \cos 2\pi(f_0 - f_d(t))t\, dt, \\
C_{\sin,i} &= \int_{T_i} S(t)\, \sin 2\pi(f_0 - f_d(t))t\, dt,
\end{aligned} \tag{1}
$$

where $f_0 = 8$ MHz — bandwidth center (initial beacon signal frequency without Doppler shift), $f_d(t) = const$ — initial Doppler shift determined using a high resolution spectrum, T_i — 1 ms accumulation period was chosen.

Sine and cosine components of the CF for i-th accumulation period (AP) were treated as real and imaginary parts of a complex number. Phase and amplitude for each AP were calculated. Sample phase-AP relationship is shown at Fig. 1(a).



(a) (b)

Fig. 1. First (a) and fourth (b) iterations, X-axis — AP count ($AP = 1$ ms), Y-axis — phase degrees (from -180 to 180)

Amplitude is fading over time that is caused by scan's long duration and corresponding Doppler shift over time. At the beginning of a scan phase changes slowly then velocity of phase changes increases. That is due to using a constant Doppler shift during correlation processing determined for the first few seconds of a scan. However spacecraft and observing stations are moving with acceleration and Doppler shift is changing over time.

Residual frequency displacement (after removing Doppler shift) is calculated by the postprocessing software.

Frequency shifts for the first 128 AP (0.128 s) are determined on the first iteration. Then Fourier transformation is performed with a following search for the maximum amplitude in received spectrum and beacon signal frequency is determined within the accuracy of 8 Hz. After that there is a search nearby received frequency value for the exact frequency value that provides maximum amplitude in the spectrum.

When frequency value is calculated software is moving to the next 64 AP and repeats computations. In the end using the least squares method relationship between frequency and time $f_d(t)$ is being estimated and approximated with a polynomial. At this point second order polynomial is used.

6 Second iteration

Next there was made another correlation processing with amplitude and phase beacon signal extraction, this time polynomial Doppler shift model $f_d(t)$ was used for tracking.

The next stage of postprocessing is devoted to moving from frequency to phase tracking of spacecraft signal.

Phase and amplitude values are averaged over time with 0.1 s interval. Phase leaps over 360 degrees are removed. Phase-time relationship is approximated with 5-th order polynomial.

7 Third iteration

On the next iteration correlation processing was carried out with a help of phase polynomial, sine and cosine components of CF were calculated as follows:

$$\begin{aligned} C_{\cos,i} &= \int\limits_{T_i} S(t)\,\cos 2\pi(f_0 t - p_d(t))t\,dt, \\ C_{\sin,i} &= \int\limits_{T_i} S(t)\,\sin 2\pi(f_0 t - p_d(t))t\,dt, \end{aligned} \tag{2}$$

where $p_d(t)$ — Doppler phase set by a polynomial.

To make phase tracking more accurate at a larger interval of 60 minute scan on the next stage there was made a transfer to spacecraft signal phase-time approximation using piecewise-polynomial. Time interval was separated to smaller pieces of equal length with a 5-th order polynomial trend used on each. Polynomials were calculated the certain way to have there values and derivatives equal at the limiting points to prevent steps in their values.

8 Fourth iteration

Correlation processing on this stage is equal to previous one, the only difference is a transition from one polynomial to another during phase tracking. This iteration repeats until the specified accuracy of signal tracking is reached, then processing is finished. Residual root-mean square (RMS) deviation of initially extracted signal phase and the one polynomial calculated serves as accuracy criteria. Reasonable value is about of 10 degrees. Fig. 1(b) shows phase-AP relation obtained during final iteration.

9 Results

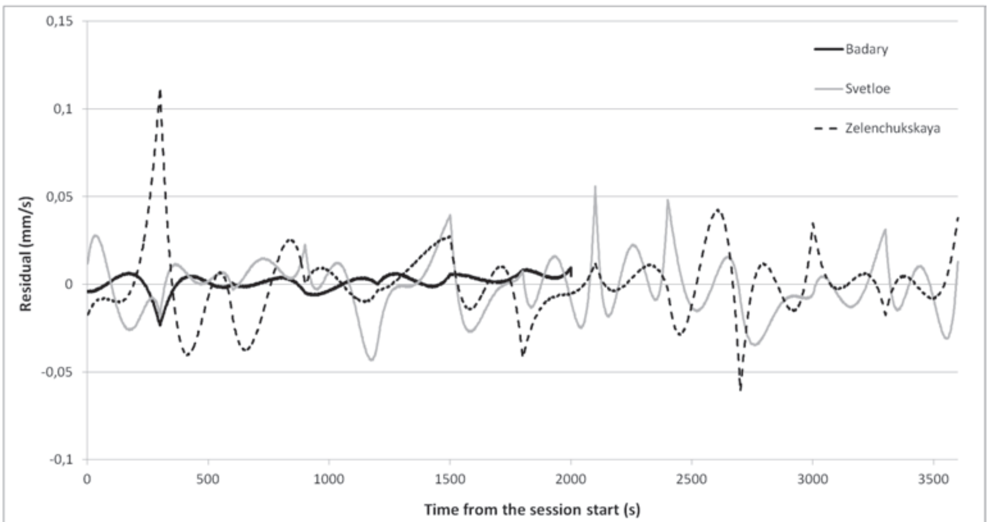


Fig. 2. Residuals for RadioAstron spacecraft Doppler observations 19.10.2014 at Svetloe, Badary and Zelenchukskaya

Output data are based on spacecraft's phase-time relation $\varphi(t)$ obtained during the last iteration. Integral phase $R(t)$ progression during the scan and Doppler frequency shift $V(t)$ derived from $R(t)$ are calculated as follows:

$$R(t) = \frac{\varphi(t)\, c}{2\pi\, f_0}, \quad V(t) = \frac{f(t)}{f_0} c = \frac{\partial\varphi(t)}{dt} \frac{c}{2\pi\, f_0}, \tag{3}$$

where f_0 — carrier frequency of spacecraft beacon signal.

Obtained data were transferred to the IAA spacecraft trajectory analysis center [1]. Calculated integral phase progression RMS $R(t)$ — 1 mm, Doppler frequency shift $V(t)$ — 0.02 mm/s. Residuals for spacecraft Doppler observations at Badary, Svetloe and Zelenchukskaya are shown at the Fig. 2.

10 Conclusion

Ephemeris software designed t at IAA RAS allow to perform accurate tracking by the observatories for RadioAstron spacecraft and calculate delays pre-calculations for IAA RAS correlators. Designed software package for monochromatic spacecraft signal processing allow to determine integral phase and Doppler frequency shift for RadioAstron spacecraft beacon with RMS of 1 mm and 0.02 mm/s.

References

1. *Vasilyev M. V., Zimovsky V. F. , Ilyin G. N., Marshalov D. A., Melnikov A. E., Mishina N. A., Mishin V. Yu., Mikhailov A. G., Surkis I. F., Shantyr V. A.* Space vehicles observations using "Quasar" VLBI network // Trudy IPA RAN, 2017. — Is. 41. — P. 131–134.