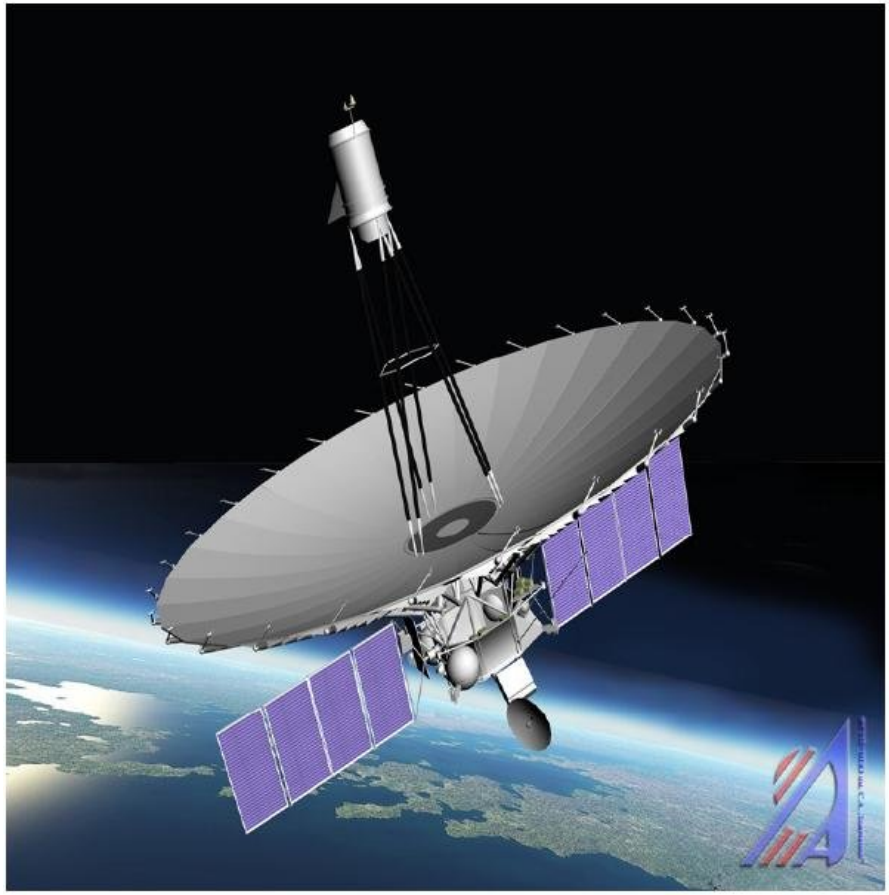
DiFX Spacecraft Antenna Correlation



James M Anderson
anderson@mpifr-bonn.mpg.de

On behalf of MPIfR and the RadioAstron team

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Collaborators/Contacts

- MPIfR
  - Walter Alef — MPIfR correlator group head
  - Andrei Lobanov — MPIfR RadioAstron project leader/Russian document translator
  - Helge Rottmann — DiFX coding help/instructions on how to correlate at the MPIfR
  - Anton Zensus — director
  - The MPIfR correlator and geodesey crew — help on many small issues
- ASC/RadioAstron
  - Vladimir Kostenko — ASC correlator
  - Yuri Kovalev — primary RadioAstron contact, “mission scientist” for AGN science
  - Mikhail Lisakov — spacecraft orientation
  - Kirill Sokolovsky — general assistance/data transfer
  - Petr Voitsik — own correlator/fringe detector
  - Numerous other people involved in RadioAstron — help in understanding many issues about how RadioAstron works

Further Information

- RadioAstron webpage
  - http://www.asc.rssi.ru/radioastron/
- Newsletter (sign up for automatic delivery)
  - http://www.asc.rssi.ru/radioastron/news/news.html
- Astro Space Center (Lebedev Physical Institute of Russian Academy of Sciences)
  - http://asc-lebedev.ru/index2.php

- Announcement of Opportunity
  - http://www.asc.rssi.ru/radioastron/ao-1/ao1.html

RadioAstron

- RadioAstron is a radio telescope instrument on the Spektr-R spacecraft
- 4 receivers: 0.327, 1.665, 4.828, and 18–25 GHz
- Dual polarization
- Orbital period 7–10 days
- Apogee height 300 000 to 400 000 km (~ distance to the Moon)
- Software correlator at ASC for processing RadioAstron data

MPIfR Interest in Correlating RadioAstron VLBI Data With DiFX

- Contribution to RadioAstron project
- Offers a test of the output provided by the ASC software correlator
  - Cross checking results is a good thing to validate sensible operation
  - DiFX is assumed to provide reasonably correct correlation — it is used by the geodetic community
  - Spacecraft antenna correlation is not exactly easy — there are many things that one can get wrong
- Opens up ability to correlate RadioAstron observations to users around the world
  - DiFX is an open project and is well established in the VLBI community
  - Many major VLBI correlators are already DiFX-based and upgrading to a spacecraft-enabled DiFX should be easy

Changes to DiFX

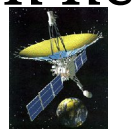
- Branched off from DiFX 2.0.1 in 2012 February
  - I expected the development period to take many months, and wanted to work with my own “stable” version
  - Changes will be folded back into trunk in the very near future
- No changes at all made to the actual “correlator” code in mpifxcorr
  - Modifications only made to the input file reading section, to handle new input keys
- Significant changes to difx_input areas of code to support spacecraft antennas
- Significant changes to the DiFX CALC software to support spacecraft antennas
- Data format converter from RadioAstron RDF format to Mark5B format
  - Will eventually enable DiFX to read RDF natively

Teaching DiFX About Spacecraft Antennas: 1

- Started with DiFX code for spacecraft targets, but had to make major changes for spacecraft antennas
- Spacecraft antennas move
  - Keep track of position, velocity, acceleration as a function of time, with switches for ground antenna motion (geological timescale) versus spacecraft antenna (orbital velocity timescale)
  - Standard orbital elements (e, a, Ω, ω, ...) cannot be used for RadioAstron, as the RadioAstron orbit is significantly perturbed by the Moon
  - RadioAstron mission does not use SPICE, so new routines for position information handling were written
  - Better interpolation functions written for DiFX (need at least position, velocity, and acceleration) with sub-millimeter accuracy in position interpolation
    - Copy over to spacecraft target code?

Teaching DiFX About Spacecraft Antennas: 2

- Time
  - Because of a hardware bug in recording the spacecraft telemetry data in the RadioAstron datastream at the Pushchino ground station, timestamp information from the on-board clock is lost
  - Timestamps are generated by the ground station recording the time at which each recording scan is started
    - There are occasional errors in this process…
  - Time after that is determined by the on-board sampler clock
  - Must calculate spacecraft to ground station delay for the start of each scan
  - There are possible ways around this in the future using some of the remaining partial timestamp information
- General relativity
  - Ground antennas are tied to the TT reference frame
  - The spacecraft clock must be corrected for redshift (velocity, gravitation), integrated over the length of the experiment
  - The (significant) gravitational potential of the Moon needs to be added in



Teaching DiFX About Spacecraft Antennas: 3

- Polarization
  - Spacecraft orientation information required to reconstruct rotation angle of feed with respect to the sky (equivalent of parallactic angle for Alt-Az mounts)
  - Decided to feed this information into CALC for angle calculation — this also allows the telescope pointing direction to be separated from the target source direction for multi-phase center correlations
  - Spacecraft orientation eventually important for astrometry
    - Orbit modeling done with center of mass, not the phase center of the antenna
    - Satellite tracking (for example, PRIDE) sees the position of the communications antenna, not the astronomy antenna

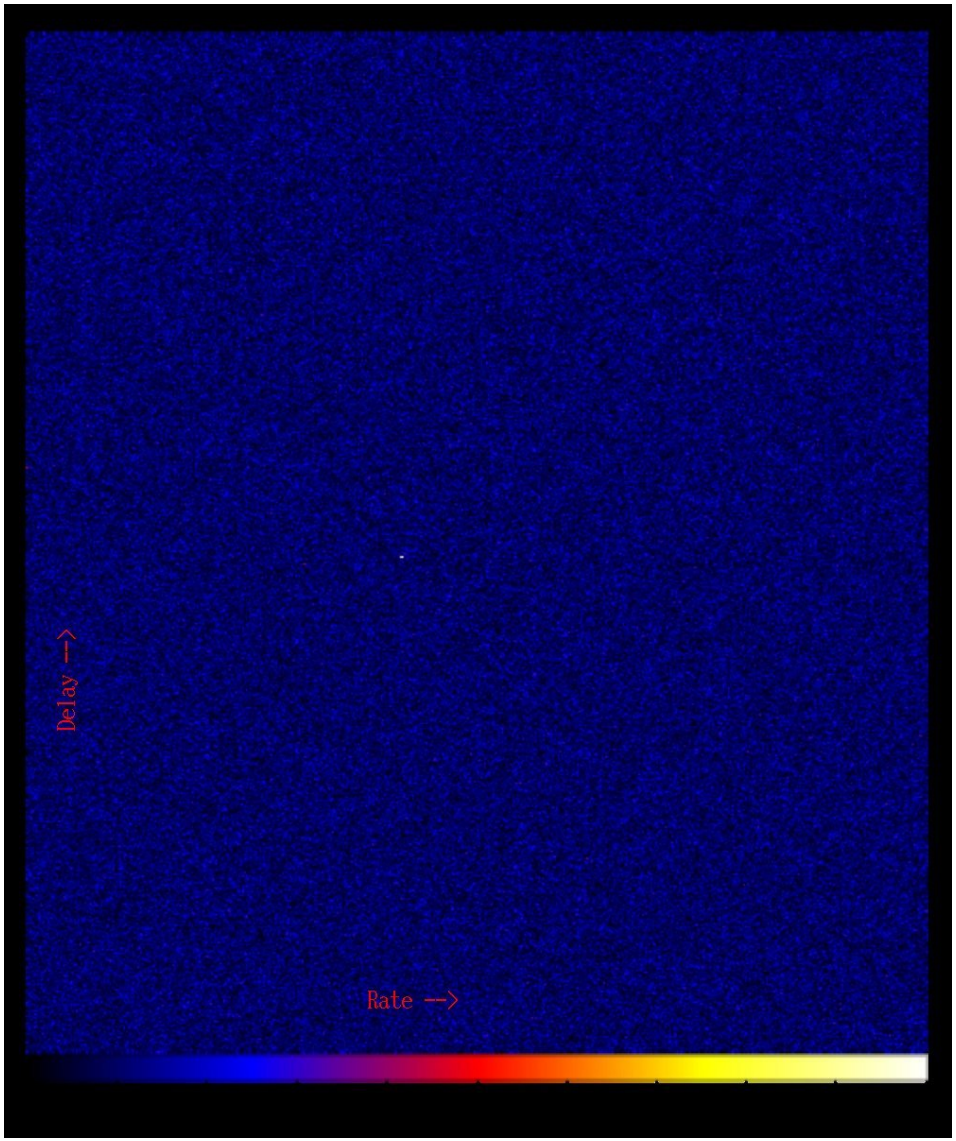
Teaching DiFX About Spacecraft Antennas: 4

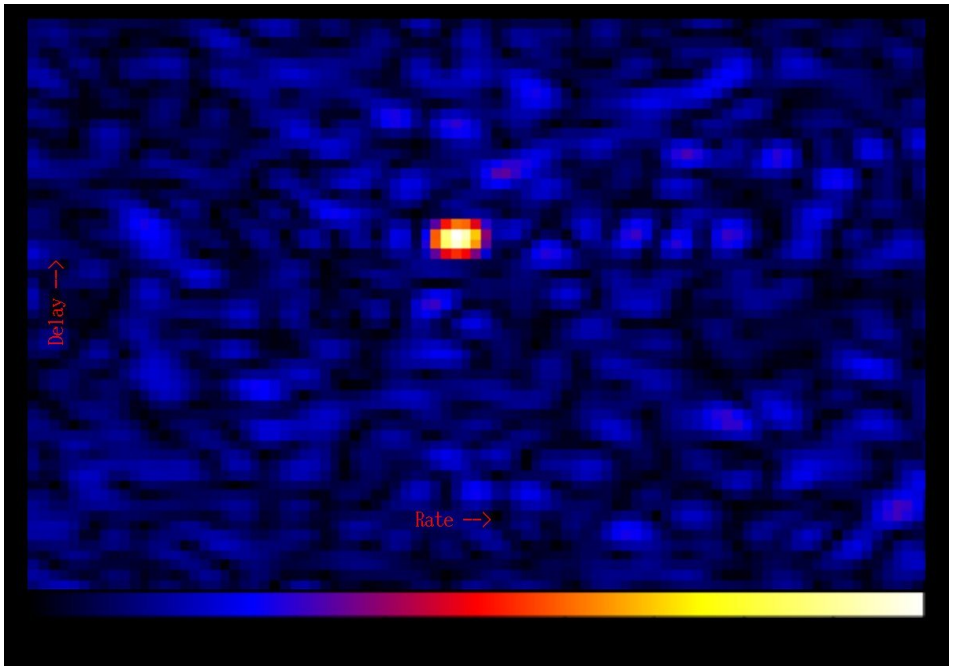
- Spacecraft state vector corrections
  - The standard RadioAstron final orbit model (2–3 weeks after the observation) has uncertainties of
    - 600 m in position
    - 0.02 m/s in velocity
    - Uncertainties huge compared to K-band 0.013 m wavelength
  - Minimizing delay and rate residuals for all ground–spacecraft baselines requires making corrections to the spacecraft state vectors
  - Implemented polynomial offset mechanism to specify trial offset in v2d file
- Names
  - Keep track of ground station name for CALC
  - Separate v2d antenna key for name to pass to CALC
    - Also useful when faking antennas in DiFX, such as when trying to correlate separate recording systems from the same antenna for testing — the same name can be fed to CALC to get the same ocean loading parameters

Teaching CALC About Spacecraft

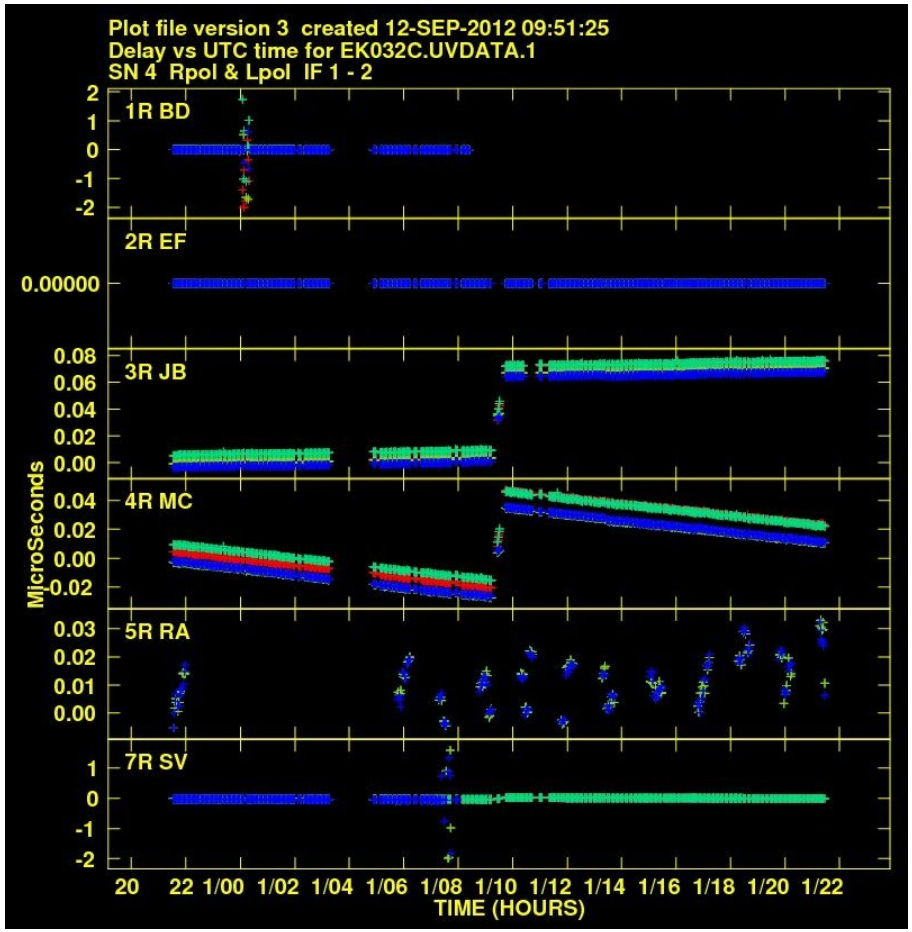
- Implemented new mount type to specify that antenna is a spacecraft
- New information fields passed through RPC communications from/to calcif2
  - Antenna position/velocity/acceleration vectors
  - Antenna orientation information
  - Source direction and information to support non-barycentric source frames
    - RadioAstron spacecraft state vectors are in J2000 frame fixed to the center of the Earth frame
    - Needed to support getting spacecraft to ground station delay
  - Backwards compatible with old DiFX RPC struct for standard calls
- Lots of code changed to handle spacecraft
  - Many calculations can be dropped (ocean loading…)
  - Many areas where attachment to ground assumed in code
- Testing so far shows that ground–ground delays are unaffected

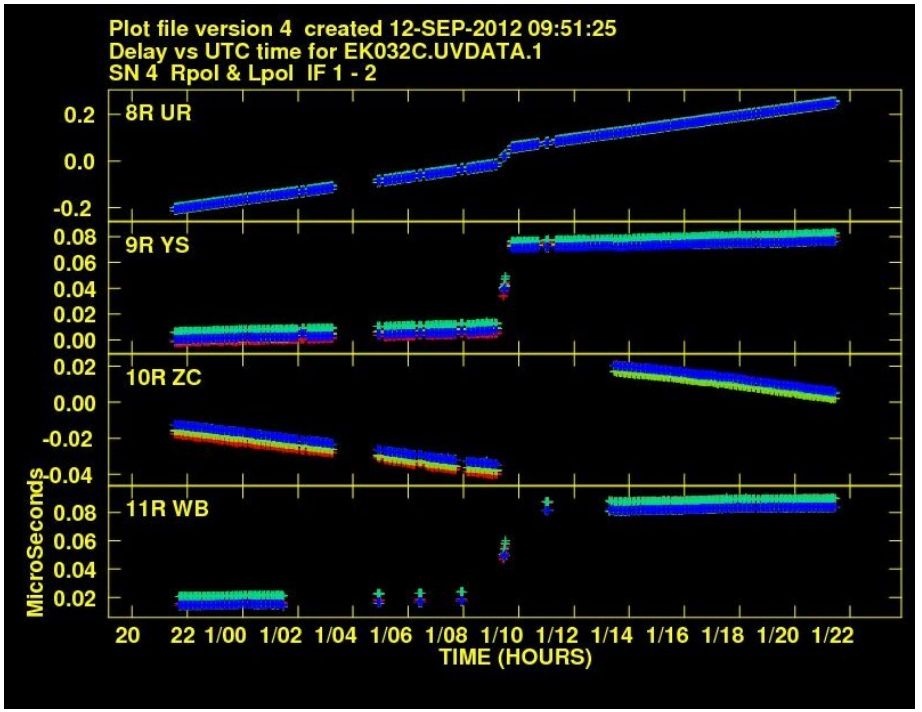
First DiFX Fringes: 2012 Jun 14





Imaging Experiment EK032C





Images to be shown at EVN Symposium in October!

Comparison Against ASC Correlator

- Report from Michael Bietenholz
- (u,v,w) differences of about 0.3% for ground–spacecraft and ground–ground baselines
- EF–JB baseline shows 180 degree phase offset
- RR visibility delays and amplitudes agree
- LL has lower amplitudes in DiFX correlation and noisier phases

1–2 bit Correlation

- RadioAstron data are 1 bit sampled
- Ground station recording is frequently done in 2 bit sampling mode, either intentionally or unintentionally
  - DRUDG bug for Mark5B systems has lead to Mark5B stations that were supposed to record in 1 bit mode recording some or all channels in 2 bit mode
- Correlation seems to work fine in DiFX, in that sensible results are produced
- However, in trying to track down the 180 degree phase offset with the ASC correlator, it seems that the Mark5B documentation suggests that 1 bit data should have the opposite sign from the way the mar5access library treats the data
  - Issue to be sorted out later

RadioAstron Fringe Finding

- RadioAstron currently has large fringe search window because of timestamp uncertainty and spacecraft state vector uncertainty
  - Typical initial delay offset up to 50 μs, sometimes many ms
  - Initial rate offset up to about 2 Hz
- Need high frequency and time resolution for initial fringe search
- HOPS strongly dislikes RadioAstron data
  - 1–2 bit correlation, spacecraft antenna, channel ordering wrong, unused channels in ground station datastream, HOPS is nowhere near 64 bit clean and makes errors allocating memory for processing RadioAstron data
  - Gave up trying to fix code…
- Need 64 bit version to process data in AIPS
  - But AIPS is not terribly informative about what is going on, whether or not there are secondary peaks, sidelobe structure, and so on
- Wrote own quick and dirty fringe finder for RadioAstron processing

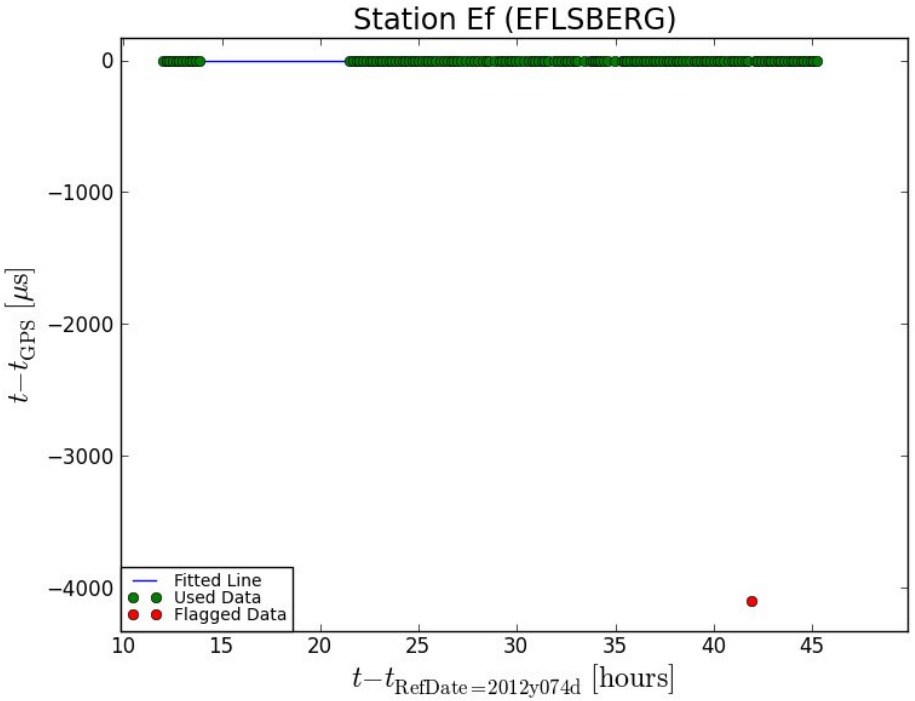
Suggestions for Future Space Missions

- Documentation!
- Use an existing data format
- Have your system compatible with standard VLBI observing modes
  - The DRUDG bug cost me several weeks sorting out what happened at each station
- Timestamps for the datastream are crucial
- Simultaneously observe with as many ground stations as possible, in the hope that at least one of them is working well
  - The major datasets I have been working on have EF losing phase lock in some LO component in RCP every couple of minutes, JB has so many phase jumps that it is practically worthless, WB is very weak and noisy for some reason…

Additional Software You May Be Interested In

- Or, stuff I wrote to make my own life easier while trying to correlate RadioAstron experiments

cmk4exp.py



- cmk4exp.pl is a perl script written by Dave Graham to extract clock offsets from station log files
- I wrote a python version to:
  - Accept multiple log files simultaneously to extend the time range
  - Accept log files from multiple stations simultaneously
  - Automatically flag outliers
  - VEX and v2d formatted output
  - Arbitrary polynomial order

Emacs Major Modes

```
File  Edit  Options  Buffers  Tools  Function  v2d  Development  Help
   SC_GS_clock_break=start@2012y075d20h05m00s/sync@2012y075d20h05m00s/clockfudge@
17.84
   SC_GS_clock_break=start@2012y075d21h15m00s/sync@2012y075d21h15m00s/clockfudge@
18.62
   SC_GS_clock_break=start@2012y075d21h25m00s/sync@2012y075d21h25m00s/clockfudge@
18.81
   SC_rec_delay=0.0
   GS_Name=Pu
   GS_difxName=Pu
   GS_calcName=Pu
   GS_X=2916948.887
   GS_Y=2248648.243
   GS_Z=5190099.798
   GS_dX=-0.01445
   GS_dY=0.01446
   GS_dZ=0.00994
   GS_pos_epoch=50449
   GS_axisType=AZEL
   GS_axisOffset0=0.0000
   GS_axisOffset1=0
   GS_axisOffset2=0
   GS_clockEpoch=2012y074d13h25m00s
 #  GS_clock0=-24.319  # \mu s
   GS_clock0=-11.220  # \mu s
   GS_clock1=-2.18654233327039l5E-07  # \mu s/s^1
   SC_pos_offsetEpoch=2012y074d13h55m00s
 #  SC_pos_offset0=0/0/0
 #  SC_pos_offset1=0/0/0
 }

 SETUP calibrator
 {
     tInt = 0.128
     nChan = 2048
     doPolar = True
     maxNSBetweenACAvg = 2000000
 }

--:**-  Emacs: ek032c.v2d          Bot (162,0)     (v2d FIC SScr)--------------------
```

```
File  Edit  Options  Buffers  Tools  Function  VEX  Development  Help
      site_name = URUMQI;
      site_ID = Ur;
*     elev= 2033.21 long=-087:10:41. lat= 43:28:17.4
      site_position =  228310.37260 m: 4631922.76970 m: 4367064.04250 m;
      site_velocity = -0.031470   m/yr: -0.001550   m/yr:  0.005510  m/yr;
*     First line below is VEX standard format.  Use only when readers are ready.
*     site_position_epoch = 2008y001d;
      site_position_epoch =   54466;
enddef;
*
def SHANGHAI;
      site_type = fixed;
      site_name = SHANGHAI;
      site_ID = Sh;
*     elev=   29.42 long=-121:11:58. lat= 31:05:57.0
      site_position =-2831687.24020 m: 4675733.54540 m: 3275327.56250 m;
      site_velocity = -0.029410   m/yr: -0.010920   m/yr: -0.011600  m/yr;
*     First line below is VEX standard format.  Use only when readers are ready.
*     site_position_epoch = 2008y001d;
      site_position_epoch =   54466;
enddef;
*
def SRT;
      site_type = earth_orbit;
      site_name = SRT;
      site_ID = Ra;
      site_position = 9999999.00000 m: 9999999.00000 m: 9999999.00000 m;
      site_velocity =  0.000000   m/yr:  0.000000   m/yr:  0.000000  m/yr;
      site_position_epoch =       0;
enddef;
*------------------------------------------------------------------------------
$ANTENNA;
*
def EFLSBERG;
      axis_type = az : el;
      antenna_motion = el :  15.0 deg/min :  9 sec;  *    0.020 deg/sec/sec
      antenna_motion = az :  25.0 deg/min :  9 sec;  *    0.020 deg/sec/sec
      axis_offset =    0.01300 m;
enddef;
*
--:---  Emacs: ek032c.vex          8% (330,0)     (VEX FIC SScr)--------------------
```

https://deki.mpifr-bonn.mpg.de/Cooperations/DiFX_Correlator/DiFX_Add-Ons/Emacs_Modes

The End