Near-Field Correlation with the DiFX Correlator

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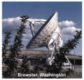

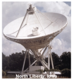

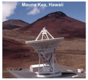

Trajectory representations (ephemeris types)

- Fixed position, e.g., (α, δ)
- Table of state vectors
  - Table of positions (and possibly velocities) by time
  - Used by DiFX in the `.calc` file
  - Supported by Binary SPice kernel (BSP) files
- Polynomials
  - One polynomial for each coordinate: x, y, z
  - Often time series of polynomials: improves accuracy
  - Supported by BSP files
- Osculating (from Latin for "kissing") orbital parameters
  - Essentially Keplerian orbit elements
  - Form the basis of TLE files
  - More on these below...

Osculating orbital parameters

Essentially 6 Keplarian parameters

* Can be considered a coordinate change from object's instantaneous position and velocity
* These values change very slowly with time, thus more stable to integrate
* B* also possibly included
  * Non-Keplerian drag/mass term, usually emperically determined
* Mostly used for Earth-orbiting objects
* Example: Two Line Elements (TLEs):

```
LEASAT 5
1 20410U 90002B   15120.74245392 -.00000079  00000-0  00000+0 0  9999
2 20410  11.2039  18.5110 0002211 200.9682 338.1622  1.00272989 77922
```

(From Celestrak: `https://www.celestrak.com/NORAD/elements/`)

Osculating orbital parameters (cont.)

Method of evaluation

1. Propagate orbital parameters. These change slowly (timescale of many orbits)
    - Evolution due to non-Keplarian effects: Earth mass distribution, moon, drag, solar radiation/shadows, spin-radiation coupling, ...
2. Evaluate propagated orbit at desired time

* Propagation requires several physical parameters
* Even with perfect physics, cannot describe manoeuvres
* Team producing the elements better use the same physics and parameters as those evaluating them!

BSP files

- Objects each have an ingegral body number, e.g., 3 represents Earth center
  - Note: Earth center (3) differs from Earth barycenter (399), which includes the moon (301)
  - Convention: negative numbers for man made objects, e.g., -31 represents Voyager I
- Contains ephemerides as polynomials or state vector tables for one or more objects
- Each object ephemeris is relative to the position of another object
- Relative positions handled by linkage, e.g.:
  - Phobos (401) $\leftarrow$ Mars barycenter (4) $\leftarrow$ solar system barycenter (0) $\leftarrow$ Earth barycenter (3) $\leftarrow$ Earth center (399)
- Arbitrary motions can be represented
- No physics or choice of physical parameters needed to evaluate

JPL Spice Toolkit

* JPL spice toolkit needed
  `https://naif.jpl.nasa.gov/naif/toolkit.html`
    - This toolkit includes useful utilities for manipulating and probing ephemeris files
    - Interfaces are a bit clunky, but are well documented
* "difxio" library needs to be compiled with spice support
* Supports `.bsp` files (e.g., as available at `http://naif.jpl.nasa.gov/naif/data.html`)
* `.bsp` files can be made from state vector data using `mkspk` from spice toolkit
* `.bsp` files must include linkage to solar system barycenter (0) and Earth center (399)

Overview of DiFX

* FX-architecture VLBI correlator implemented in software
* Designed to harness parallel processing at instruction, core, and cluster levels
* Supports wide range of processing capabilities
    - Time and frequency resolutions
    - Pulsar binning and gating modes
    - Massive-multiple phase centers
    - Geodetic (Mark 4) and astronomical (FITS) output
* Originally coded by Adam Deller at Swinburne
* Maintained by global community
* Tenth annual users/developers meeting Oct 29-Nov 3 in Shanghai

Typical DiFX data flow

1. `.vex`, `.v2d` $\longrightarrow$ `vex2difx` $\longrightarrow$ `.input`, `.calc`, `.flag`
2. Calculate delay model
   (a) `.calc` $\longrightarrow$ `calcif2` $\longrightarrow$ `.im`
   (b) `.calc` $\longrightarrow$ `difxcalc` $\longrightarrow$ `.im`
3. `.input`, `.im`, {data} $\longrightarrow$ `mpifxcorr` $\longrightarrow$ `.difx/`
4. Convert output to standard format
   (a) `.input`, `.calc`, `.im`, `.flag`, `.difx/` $\longrightarrow$ `difx2fits` $\longrightarrow$ `.FITS`
   (b) `.input`, `.calc`, `.im`, `.flag`, `.vex`, `.difx/` $\longrightarrow$ `difx2mark4` $\longrightarrow$ mark4

vex2difx

* Program that reads `.vex` file and produces DiFX fileset
  - `.input` : control parameters, data sources/formats
  - `.calc` : scan definitions and geometric parameters
  - `.flag` : used to mask unphysical mpifxcorr output
* `.v2d` file can augment or modify `.vex` contents
  - Data formats
  - Source of data (e.g., files, network, Mark5, Mark6)
  - Change coordinates of sources or antennas
  - Clock and Earth orientation parameters
  - Special features: pulsars, multiple phase centers, ...
  - Tuning paramters

`vex2difx` and moving objects

* Each source that is to be driven by an ephemeris needs some special extra information
* With upcoming VEX 2 standard, this won't be necessary
* With upcoming DiFX 2.5, the `naifFile` entry will not be needed

```
SOURCE Phobos
{
calCode=Z # this is an NRAO convention
ephemFile=de405.bsp # here just use a standard SS ephem.
naifFile=naif0011.tls # this file contains leap seconds
ephemObject=401 # the object number
}
```

* `guardNS` might need setting: warning messages will tell you!

Contents of `.calc` file

* Contains "everything" needed to generate delay model
* Coordinates
  - Stations (x, y, z) and mount geometry
  - Sources (α, δ)
* Scan definitions
  - Start and stop times
  - Phase center(s)
* Earth orientation parameters
* State vector table for moving antennas or sources

`.calc` file state vector table

* Entry could apply to station or target; linked by name
* Each row has 7 values: $t, x, y, z, \dot{x}, \dot{y}, \dot{z}$
    - Units: MJD, meters, meters per second
* `vex2difx` can generate state vectors from `.bsp` or `.tle` files
* Your own calculated state vectors could be used instead
    - Would require manual insertion of data into `.calc` file
    - It is recommended that these be tabulated at the same interval as the model calculation (24 seconds by default for 120 second polynomials)

Sample `.calc` state vector table

```
NUM SPACECRAFT:     1
SPACECRAFT 0 NAME:  UFO
SPACECRAFT 0 ROWS:  240
SPACECRAFT 0 ROW 0:  57627.812777777777 -9.51458797618570e+11
3.66054497085946e+10 3.53675144474771e+10 -1.22838595949839e+04
-4.95720058376211e+04 -3.12581995714533e+04
SPACECRAFT 0 ROW 1:  57627.813055555554 -9.51459092429529e+11
3.66042600180937e+10 3.53667643644866e+10 -1.22837281468915e+04
-4.95689114974430e+04 -3.12487475692030e+04
SPACECRAFT 0 ROW 2:  57627.813333333332 -9.51459387237801e+11
3.66030703999428e+10 3.53660145069503e+10 -1.22835966388336e+04
-4.95658191463195e+04 -3.12393123764453e+04
SPACECRAFT 0 ROW 3:  57627.813611111109 -9.51459682042354e+11
3.66018808582524e+10 3.53652648770869e+10 -1.22834650715663e+04
-4.95627287965551e+04 -3.12298939767468e+04
.
.
.
```

Evaluating the delay model

* Two options for delay models
* Both are based on Goddard's CALC program, conveniently encapsulated for DiFX use
* `calcif2 *.calc` $\longrightarrow$ `*.im`
  - Calc 9.1 w/ near-field perturbations; OK beyond the moon
  - Needs `calcserver` running
* `difxcalc *.calc` $\longrightarrow$ `*.im`
  - Calc 11 w/ proper near-field support
  - Native DiFX code; runs stand-alone; will be available w/ upcoming DiFX 2.5
* Each `.calc` file yields one `.im` (interferometer model) file
* Your own delay model could be used instead
* Both DiFX delay programs produce delays measured on a virtual baseline connecting to Earth center
* Vacuum propagation and Earth gravity effects are disabled for Earth center
* Earth center becomes the refrence position and time for output data

Contents of `.im` file

* Polynomials in time
  * Typically 5^{th} order (6 terms)
  * Typically every 2 minutes
* Values included
  * DELAY (μs): total delay; positive in most cases
  * DRY (μs): dry atmosphere component
  * WET (μs): wet atmosphere component
  * AZ, EL (rad)
  * U, V, W (m): baseline vector, to Earth center
* Exactly the same format for fixed objects and moving ones

Example .im file

```
NUM SCANS:          55
SCAN 0 POINTING SRC:1133-032
SCAN 0 NUM PHS CTRS:1
SCAN 0 PHS CTR 0 SRC:1133-032
SCAN 0 NUM POLY:    1
SCAN 0 POLY 0 MJD:  57538
SCAN 0 POLY 0 SEC:  0
SRC 0 ANT 0 DELAY (us):  1.3753455730428352e+04 6.7819442594455692e-01 -3.8632442266967256e-05
-6.0107639578948250e-10 1.7397834430748901e-14 -7.7098821291350927e-19
SRC 0 ANT 0 DRY (us):  9.4345353103572390e-03 -4.6271638075802339e-07 4.8987224832213467e-11
-3.2715326425443683e-15 2.6361024754165288e-19 -1.8089498214257483e-23
SRC 0 ANT 0 WET (us):  2.7104102433600405e-04 -1.3333826830828904e-08 1.4146097077032810e-12
-9.4950881015107343e-17 7.6866932813668647e-21 -5.3148340043177368e-25
SRC 0 ANT 0 AZ: 1.3522940390388294e+02 4.4751623559656810e-03 1.6464979250789493e-07
4.0628931117948455e-12 -2.6473450776232725e-16 -4.1315687671995350e-20
SRC 0 ANT 0 EL GEOM: 4.0186056919298785e+01 2.3872944222947082e-03 -9.3980619026188016e-08
-4.7325893846819364e-12 -1.2778326493846462e-16 -8.5516631551342412e-22
SRC 0 ANT 0 U (m):  2.7941848824031376e+06 -3.1831621499764731e+02 -7.4281672580211837e-03
2.8721200421529445e-07 -4.4412371356793019e-11 1.5783795547714915e-13
SRC 0 ANT 0 V (m):  -3.9757198230946325e+06 -1.2818884075996014e+01 7.2723600401837355e-04
1.2978917474366126e-08 -1.6328622953049862e-11 5.4428645708683644e-14
SRC 0 ANT 0 W (m):  -4.1231852090778868e+06 -2.0331743123935692e+02 1.1581699704442549e-02
1.8019941897496882e-07 -5.2180153199729340e-12 2.3830959962863830e-16
SRC 0 ANT 1 DELAY (us):  1.9571827338641200e+04 -2.3176531909501438e-01 -5.3112891036048665e-05
2.0540576646985665e-10 2.3417938827056088e-14 3.3123938045181445e-19
SRC 0 ANT 1 DRY (us):  8.3995729968806502e-03 9.9181652305145647e-08 2.3898512509474895e-11
4.6183363509031717e-16 5.8938940196523491e-20 1.4796207393215864e-24
SRC 0 ANT 1 WET (us):  4.2045374742592806e-04 4.9728350816649673e-09 1.1983832164231852e-12
2.3225591781303439e-17 2.9652756982650306e-21 7.4548376192931681e-26
SRC 0 ANT 1 AZ: 2.0351485474542463e+02 9.8103751905450742e-03 -6.4521638932697381e-07
-4.0295954501836502e-11 1.4419060795596890e-14 -8.9978369590889767e-19
SRC 0 ANT 1 EL GEOM: 6.6856753773144078e+01 -1.5875841729501221e-03 -3.1236279443569437e-07
2.1453258451259683e-11 6.3741985797804925e-16 -3.2212256314605370e-19
SRC 0 ANT 1 U (m):  -9.5484190684528474e+05 -4.3761478946405276e+02 2.5395651084215423e-03
3.7776611402815343e-07 9.6662438455835329e-11 -3.2656224927354656e-13
```

`mpifxcorr`: the core of DiFX

What it needs

* Uniformly sampled, timestamped signals, $v_i(t)$
* Delay (signal alignment) information, $\tau_i(t)$
* Bounds for averaging output
* Various control parameters

What it does

* Calculates auto- and cross-correlation functions of input signals

$$V_{ij} = \left\langle v_i \left(t + \tau_i(t)\right) v_j^* \left(t + \tau_j(t)\right)\right\rangle$$

* Extracts pulse cal tone phases and amplitudes

`mpifxcorr`: the core of DiFX (cont.)

What it doesn't need

* Geometry / reference frames / coordinates
  * Antenna mounts
  * Earth orientation, ICRF, ITRF
* Physics
  * Propagation
  * Gravity

Why not?

* This information is encoded in the delay model
* A globally ticking clock is the only link to reality
* Provides a clean separation between the “brains” and the “brawn”

mpifxcorr output

* Raw DiFX output is not in a form usable by standard packages
* Two primary conversion paths exist
* `difx2fits`
  - The FITS-IDI format recognized by AIPS can handle data with moving sources or antennas
  - `difx2fits` will create usual data structure and will add Orbit (OB) tables
* `difx2mark4`
  - Produces data to be fed into HOPS
  - This should work with no problem
  - Probably will experience issues if the sky coordinates of the object are needed: only a single RA/Dec is conveyed, I believe

Baseline vectors: (u, v, w)

* In imaging inferferometry, each interferometric visibility has (u, v)
* A collection of visibililites is gridded onto U-V plane and FFTed
* w is third component of a vector in 3-D space
* What is (u, v, w)?
* In vacuum, non-relativistic, far-field interferometry, (u, v, w) is vector separating the two interferometer elements
* Relativity brings in aberration, akin to “beaming” of jets
* Atmosphere brings in refraction, akin to a giant lens in front of array
* Near-field brings in parallax; the same array at different distances will see the object scaled differently
  - Translation invariance is broken

Generalized (u, v, w) vectors

* Don't think of (u, v, w) in terms of array geometry
* Instead, use an analytic prescription (motivated by the imaging use case)
  1. Choose coordinate system in which image is to be made (e.g., J2000)
  2. Define local coordinate axes in that frame: $l =$ angle of α, m $=$ angle of δ, relative to a reference position
  3. Taylor expand delay function in these coordinates:

$$\tau(l, m) = \tau + l\frac{\partial \tau}{\partial l} + m\frac{\partial \tau}{\partial m} \dots$$

  4. Then identify $u = c\frac{\partial \tau}{\partial l}, v = c\frac{\partial \tau}{\partial m}$, and $w = \tau$
* This procedure is used by DiFX delay model programs.

Some remarks about time

* Time enters the interferometry process in several ways:
    * Individual voltage samples are timetagged to local time
    * Each station may have an intrinsic delay between local time and timetag (cable delays, digital propagation delays, ...)
    * The delay model is an intentional offset into the voltage streams
    * The correlator averages the correlation coefficient over some duration
    * A final time tag is assigned to the resultant visibility
* In an FX correlator (like DiFX and SFXC, but not like Mark4) all baselines are processed synchronously
* Specifically, in DiFX the time tag applied to the visibility is determined by the delay model
    * For calcif2 and difxcalc the virtual baseline to Earth center dictates that the time-tag corresponds to arrival of signal at Earth center

Some final words of caution

- Man-made signals are, in general, non-noiselike
- Signals may be very strong
  - Will not follow assumptions of samplers (state counts)
  - May put amplifiers into compression (amplitude and phase distortion)
  - Strong tones within bands can inter-modulate and appear in spectrum w/ wrong fringe rate
  - Standard interferometric radiometer equation for noise fails
- Signals often have repeating waveforms (e.g., data frame headers) and thus show strong temporal coherence.
  - Leads to delay solution ambiguity
- Correlation requires higher accuracy ephemerides than observing
  - TLEs are low precision! 1 km at epoch, 1-3 km worse per day
- Low fringe rates from geostationary objects lead to some unexpected issues

Conclusions

- `mpifxcorr` has always had the capability to correlate near-field
  - It doesn't know the difference!
- Calc 11 brings with it better modeling of near-field objects
- Once the delay model has been calculated, things mostly work as usual...
- Bigger issues likely reside outside the DiFX environment (post-processing and analysis)