ISTRAC/ISRO Delta-DOR Correlator Updates & Future Plans

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Image Courtesy: Quasar ULAS J1120+0641, ESO/ M.Kornmesser

AGENDA

- Overview
  - Correlator
  - Recent Updates
  - Future Plans

Delta Differential One-Way Ranging (DDOR)

- VLBI-based Spacecraft Navigation Technique
  - Pioneered by NASA/JPL in the 1970s and 80s.
- Evolved for interplanetary missions
- Gets accurate angular position of a Spacecraft in the nano-radian range

- Supplements the Ranging and Doppler Navigation Techniques

- Crucial especially after Orbit Insertion Maneuvers as with ISRO's Mars Orbiter Mission (MOM)

  – Typically - brings accuracy of orbit-determination in the 1-2 kms range at Mars distance.

Typical Mars Orbital B-Plane Error Ellipses

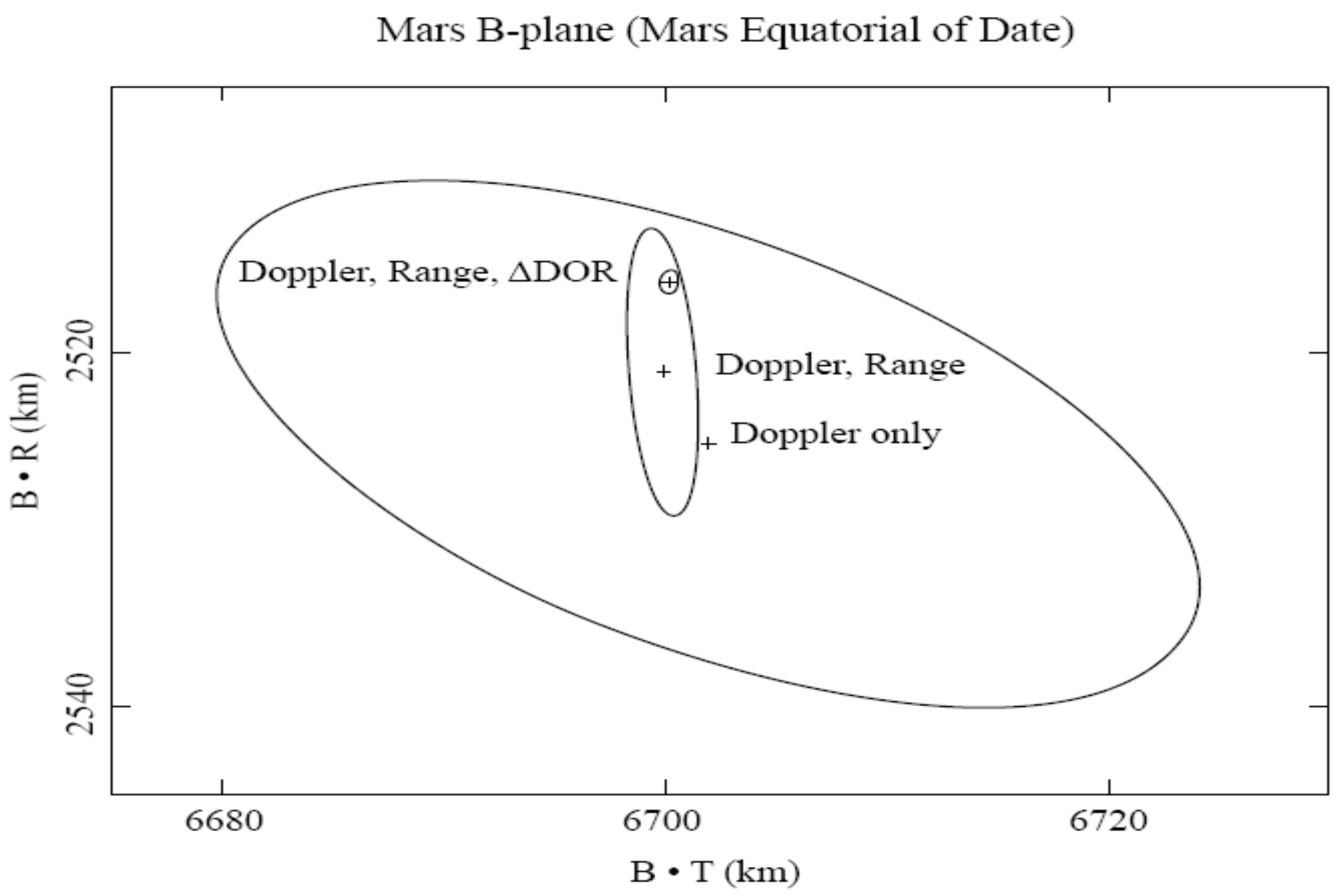


Figure 2-2: Error Ellipses in the Mars Targeting Plane[1]

[1] Courtesy: JPL/CalTech

ΔDOR Concept

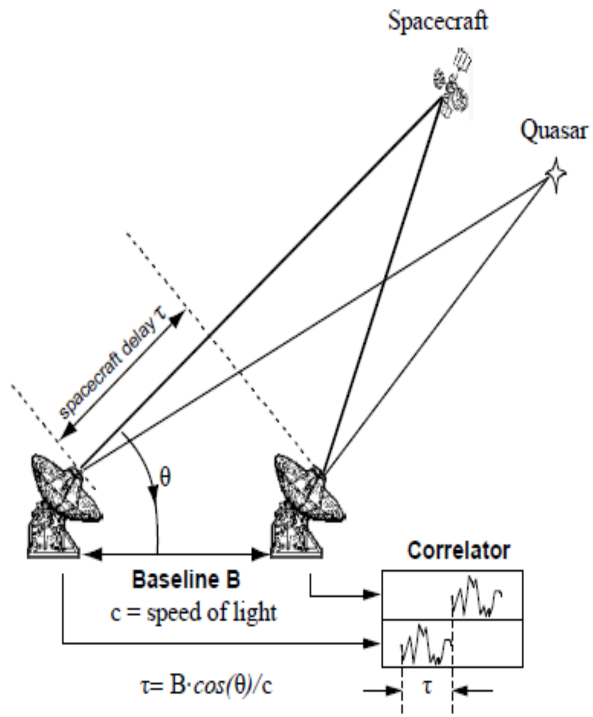


Figure 2-1: Delta-DOR Observation Geometry

Figure Courtesy: CCSDS RDEF Blue-Book

- τ_{sc} Differential One-way Ranging (DOR) Measurement
  - Itself tells the Spacecraft-Baseline angle θ
  - But has errors due to Station Clock Errors and other Instrumental and Atmospheric media effects
- τ_{qsr} DOR Measurement of well-known catalogued radio-sources : Quasars, are used to derive and eliminate these common errors and improve accuracy of θ
- QSR: Essentially, a Calibration Source for the Measurement

Diff. One-Way Delay: Qsr vs S/C

- **Quasar data** is wide-band Gaussian noise, and is well below the station system noise-floor
- Correlation and integration of the data for large number of samples are required to extract out the Quasar data

- **S/C signal** is well above the station system-noise floor and is visible during recording
- It is also a well-defined sinusoid
- Need is to establish a PLL type of mechanism to extract the phases at both the stations and get the differential phase

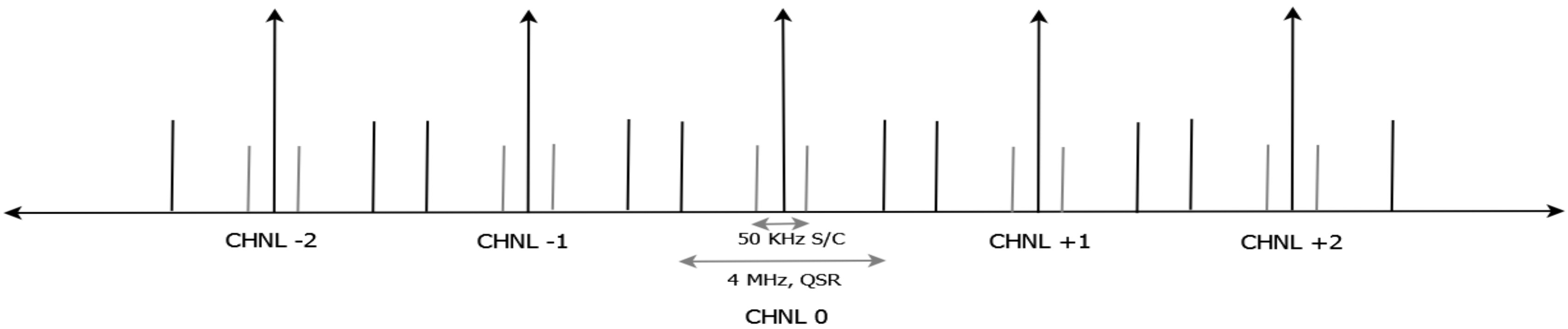
- Hence the optimal algorithms to derive the Differential One-Way delay for S/C and QSR are different.

Typical DDOR Session

- DDOR Sessions are planned in a sequence as follows:

  S – Q1 – S – Q2 – S – Q1 – S – Q2 – S
- A session lasts about an hour, and each scan S/C or QSR around 5 to 10 mins
- This sequence allows interpolation of measurements to the required time of S/C or QSR scan
- Q1, Q2 are generally chosen to within 10 degrees of the Spacecraft.

DDOR Channel Recording



- Central channel set to 2296.3 MHz + Predicted Doppler at both Stations
- Harmonics are 3.9 MHz apart [There actually is slight overlap between quasar channels: not shown in picture for clarity]

- 50 KHz Bandwidth, 8-bit complex I&Q sampling for S/C
- 4 MHz Bandwidth, 2-bit complex I&Q sampling for QSR

- Data recorded as per the CCSDS Raw Data Exchange Format (RDEF)
- Open specification – standard format for multi-agency DDOR data.

ISRO's Mars Orbiter Mission (MOM)..

- MOM carries a DDOR transmitter module
- DDOR sessions of MOM NASA/DSN stations at
  - Canberra (CNB)
  - Madrid (MAD) and
  - Goldstone, California (GDS) where scheduled
- DDOR-results were crucial in ensuring successful Mars Orbit Insertion on 24th Sept 2014
- Later, DDOR recording capability added to the Indian Deep-Space Network Station (32m) dish at Byalalu, near Bangalore
- BLR-MAD and BLR-CNB sessions have been successful thereafter..

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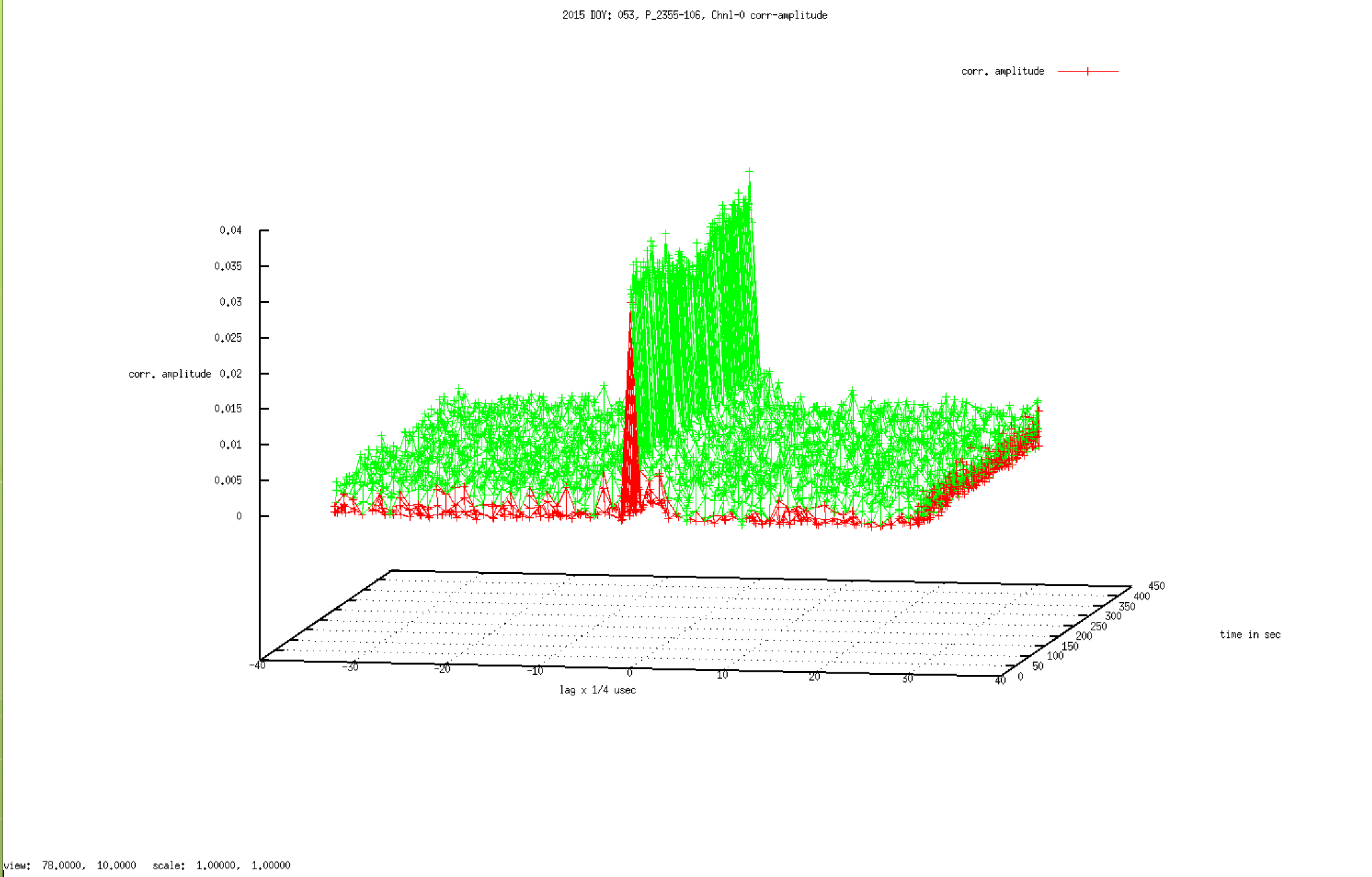
Delta-DOR Correlator

- Effort to indigenously develop our own DDOR Software Correlator.
- Entailed Three Major Aspects:
  - Quasar Correlator
  - Spacecraft Correlator
  - Model-Delay Generator

Quasar Correlator

- XF-model
- First-level cross-correlator
- Implements Fringe-Fitting via Bandwidth Synthesis – using all the 5 channels
  - via both
    - MIT HOPS Fourfit and
    - JPL PhaseTracking Approaches

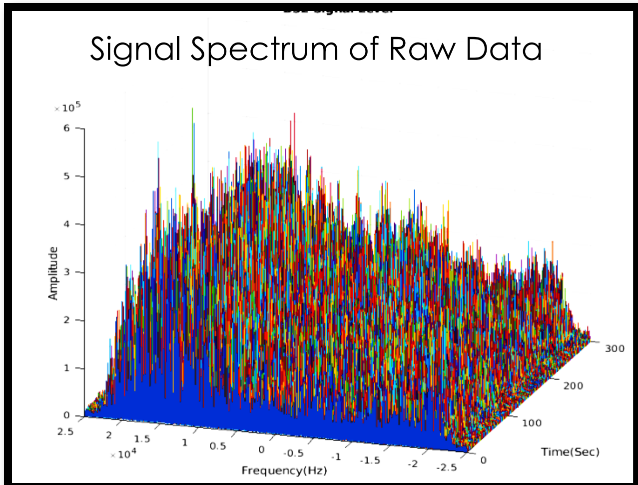
Sample First-level Correlation Results



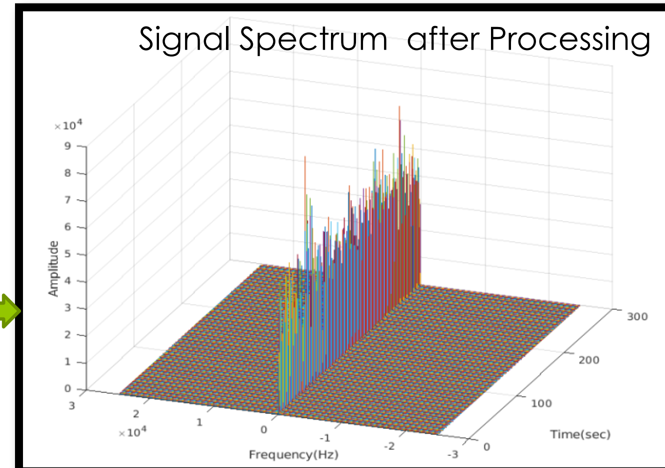
S/C Correlation

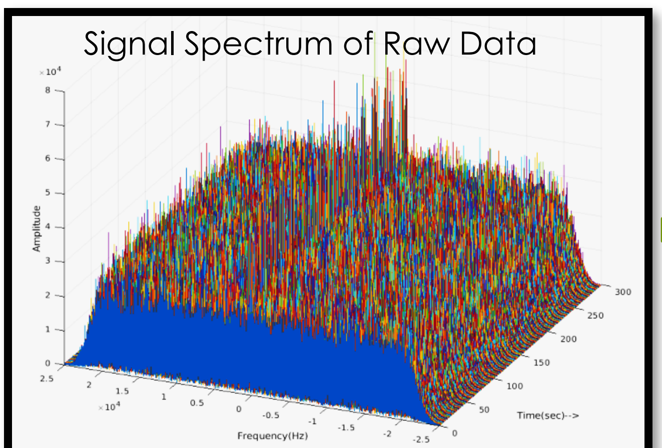
- General PLL based approaches such as Analog / Digital PLL, AGC-based PLL approach, Complex-Filtering, Windowing-based Digital Filtering method etc., alone were not sufficient to handle the OUTER channels (+2, -2 harmonics) noisy-data processing.
- Evolved our own approach to doing accurate phase measurement in this environment

Outermost S/C Channel Processing

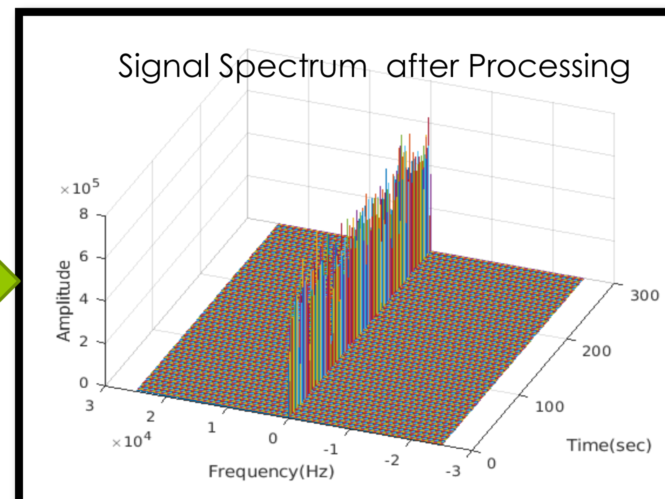


Exact Signal Extraction From D32 +2 Channel Extraction





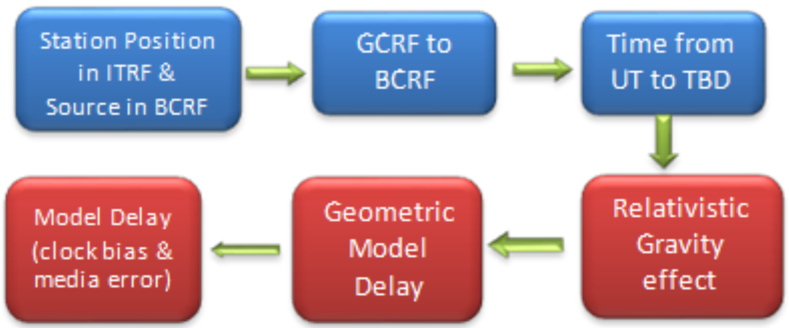
Exact Signal Extraction From D32 -2 Channel Extraction

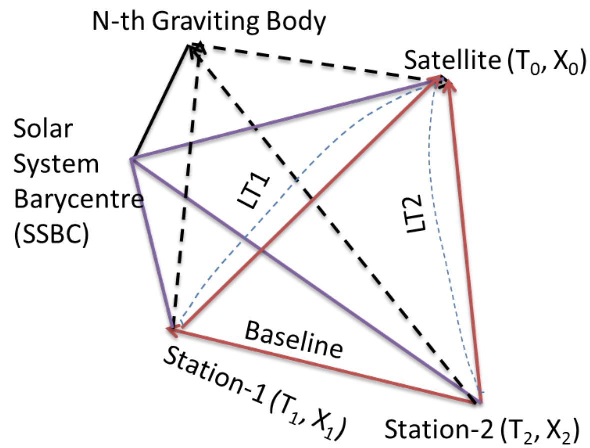


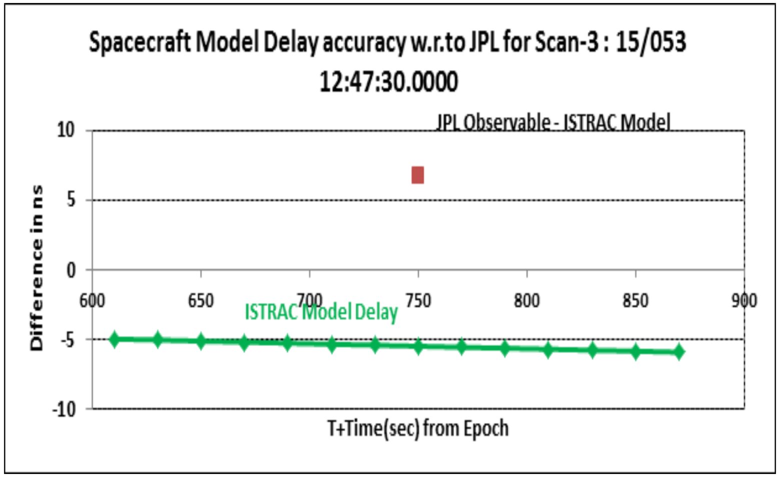
Delay Model Generation

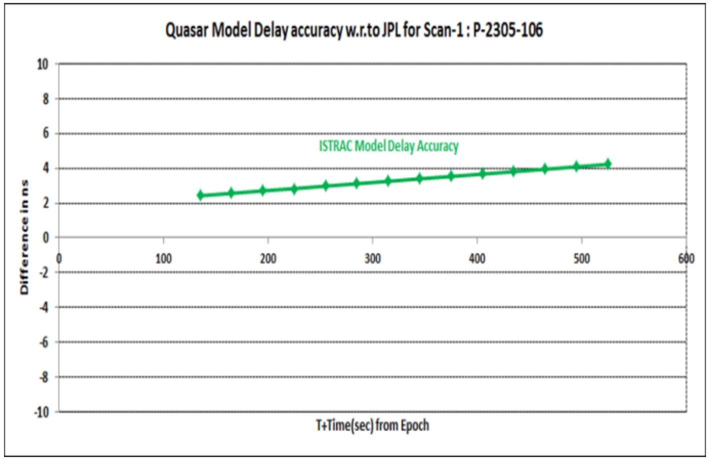
- Accurate Delay Model Generation – on the order of 10-20 nsec is mandatory for accurate Quasar Correlation
- Initially adapted DifxCALC-11 for QSR purpose
- S/C Correlation also requires good modeling of S/C expected delay.
- CLOCK-BIAS estimation based on Quasar Correlation is an essential step in this process - also getting completed.
- Independent ISTRAC delay-model is developed for both QSR and S/C and yielding good results.

Delay Model Generation









Correlator Status (Nov 2019)

- Getting good observables
  - Matching at sub nano-sec level with those produced by NASA/JPL Correlator for both Quasar and S/C DOR.
  - Delay-Modeling is good and meeting requirements.

  - Correlator overall is satisfactory for Operations.

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Clock-Bias (cbias) Estimation

- Good Frequency Standards: H-MASER, Caesium
  - But **micro-sec** order clock-offset with UTC (therefore, also with each-other) is typical
- Critical to estimate this for successful correlation

Idea

- Quasars are stationary for all practical purposes;
- Locations very well known (sub milli-arc-sec level)
- Use the strength of Quasar Delay-Modeling (accurate in **10-nsec** order) to estimate cbias

- Clock-Bias search is the initial step to correlation
- Delay models (QSR & S/C) are updated with Clock-Bias before correlation

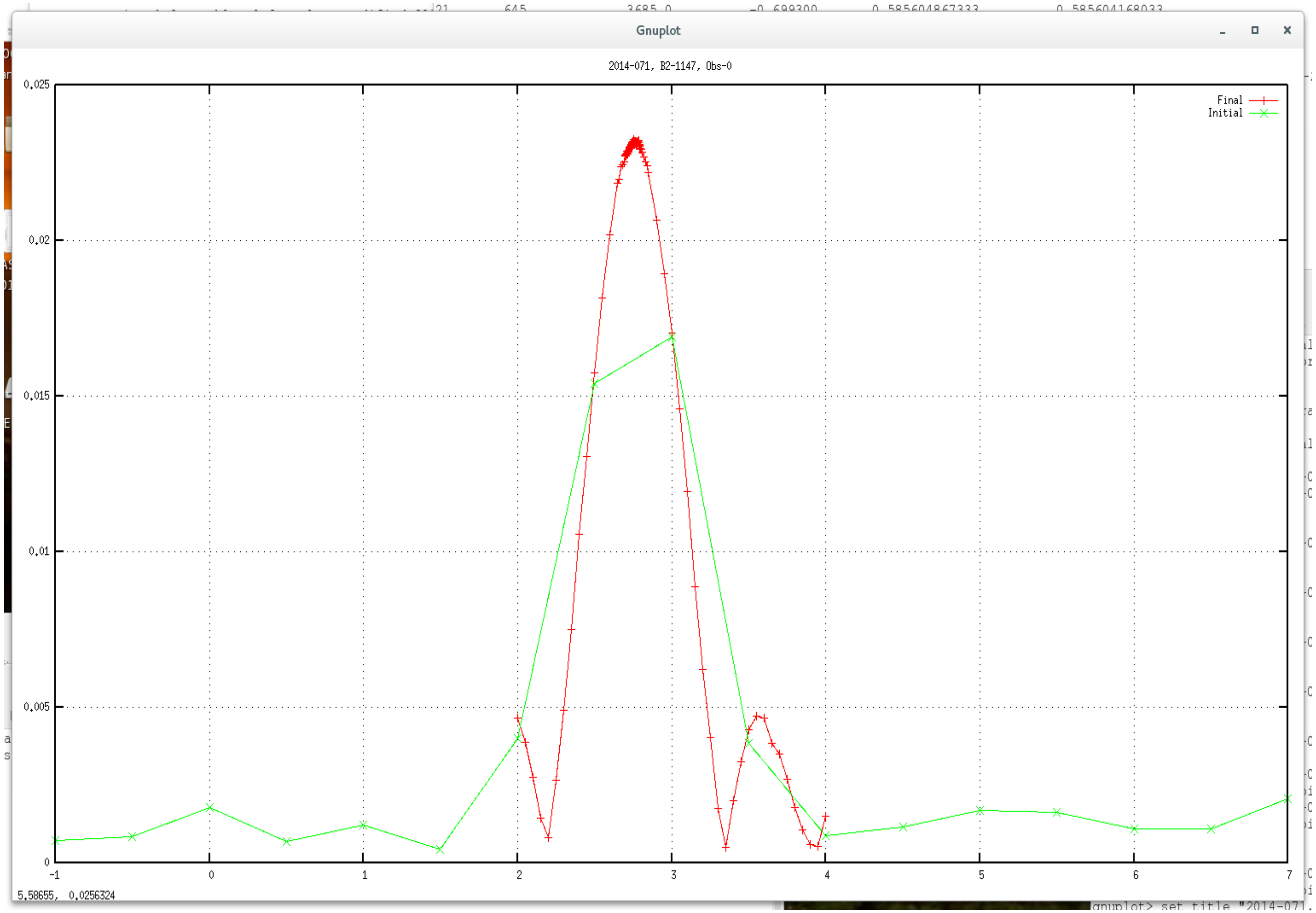
CBIAS Estimation

- Quasar Sampling is done at 4 MHz: this is 0.25 usec or 250 nsec interval
- We need an estimate accurate in 10 nsec order
- Initial Quasar Correlation:
  - Choose lag-window large enough to cover max. CBIAS expected – may be ±5 usec
  - A shorter period – 30 sec – of data, should suffice
  - Perform Correlation and locate the lag value where correlation peak-amplitude is seen. This is the initial guess for the iterative procedure.

CBIAS Estimation (contd.)

- Iterative Procedure:
  - Try trial cbias values – say ± 5 x 100 nsec intervals around the initial-guess value for the lag. Locate the peak in this iteration.
  - Try trial cbias values – say ± 5 x 10 nsec intervals around this peak. Locate the peak in this iteration
  - Try trial cbias values – say ± 5 x 1 nsec intervals around this peak. Locate the peak in this iteration
  - Fit all the correlation amplitudes vs lag trial-values with abs(sinc()) function, and estimate peak.
  - Average the peak values obtained for all channels to give final estimate
- This is our best-estimate of cbias and is typically accurate to 10 ns order

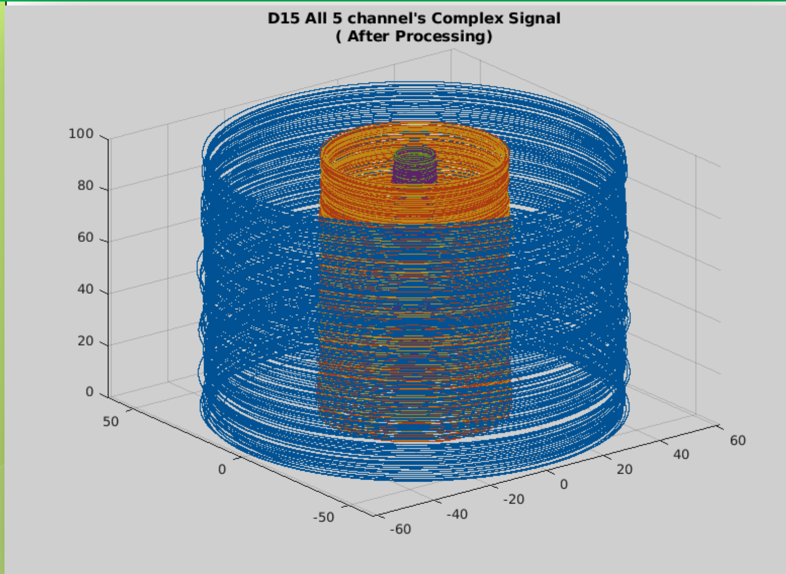
CBIAS Results (Sample)

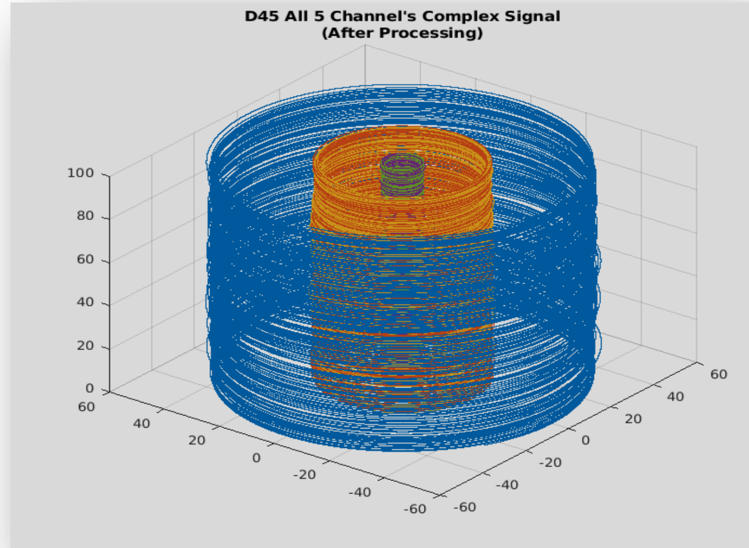


S/C Correlation

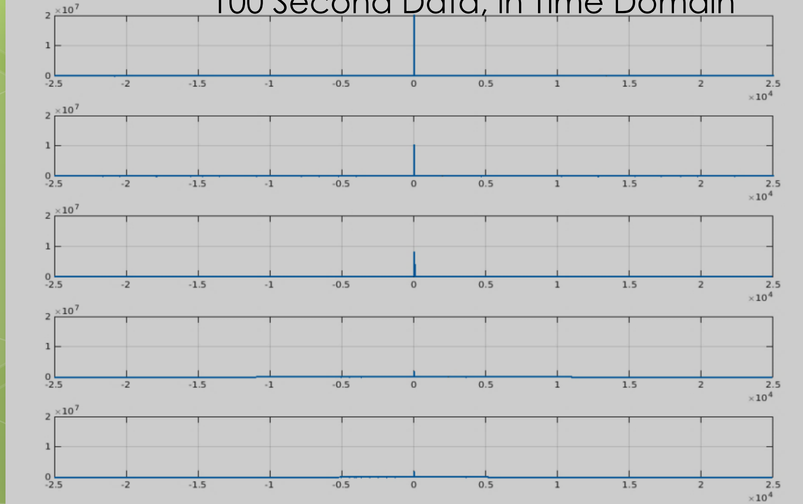
- Initial validation done for DDOR Sessions in orbital-phase
- Now, validated our Correlation for DDOR Data for the more critical cruise, pre-Orbit-Insertion phase
- Here, continuous tuning of local-oscillator wrt predicted-Doppler frequency was done for higher accuracy
- Spacecraft correlator software was modified for this.
  - It is able to produce consistent results in this scenario as well.

Results for Just Before MOM MOI Data Sets



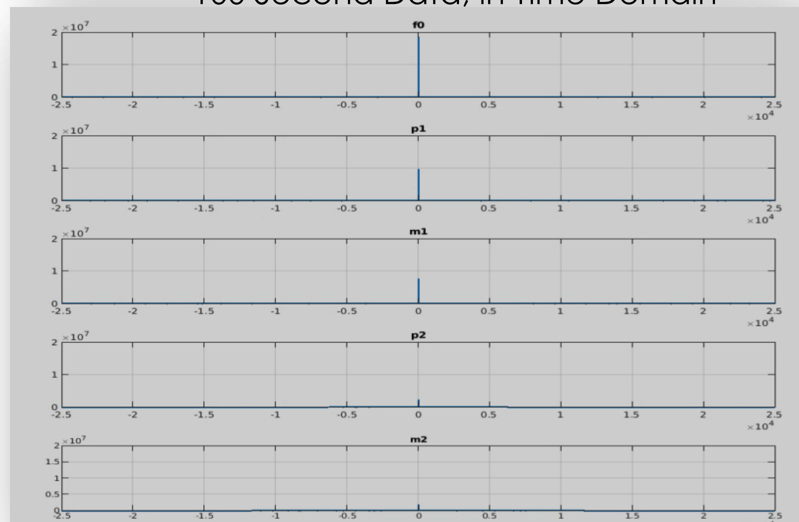


100 Second Data, in Time Domain



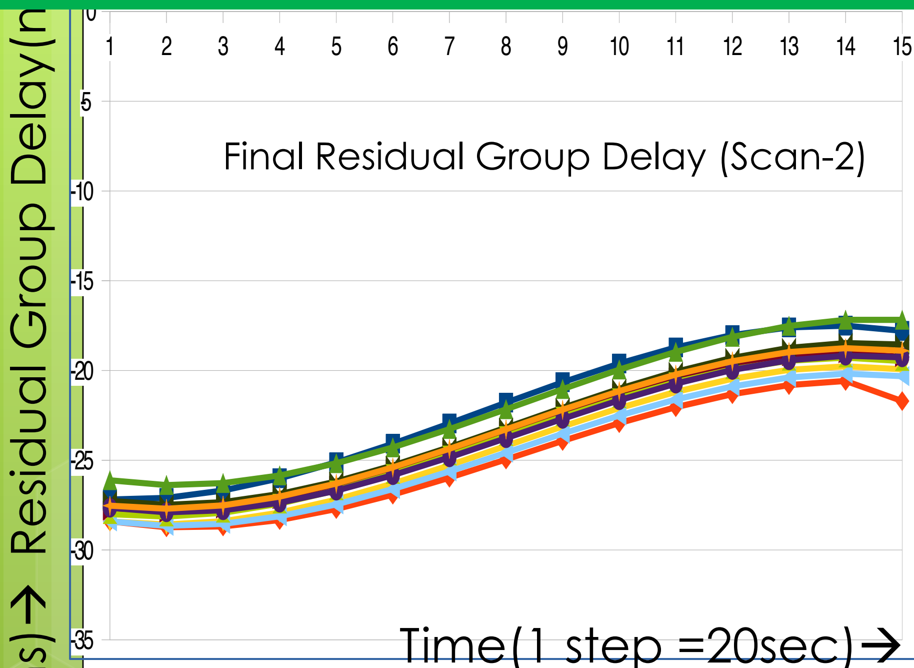
Spectrum of all five channels of D15

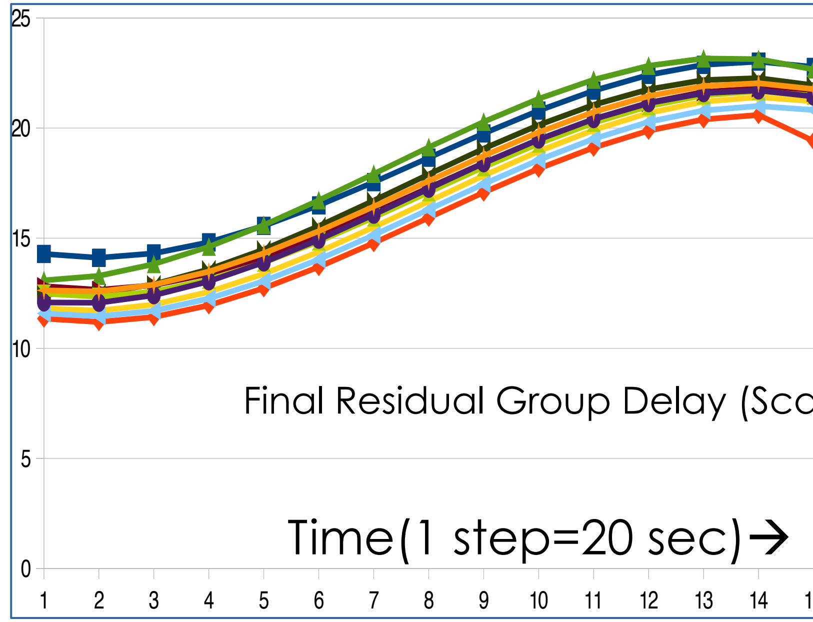
100 Second Data, in Time Domain

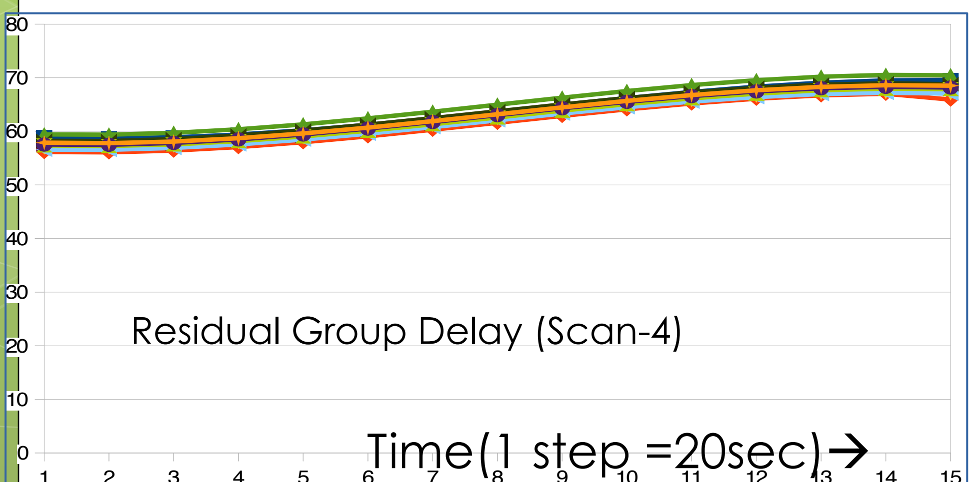


Spectrum of all five channels, D45

Results for Just Before MOM MOI Data Set







Remarks :
Residual Phase Delay Computation using all channel's data for all the three spacecraft scans shows good results.

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Performance Optimization

- Correlation is time-consuming!
  - Optimize for a multi-core / GPU operational environment: ***Need for Speed***
    - **3 to 3 ½ hours'** processing may be brought to **~ ½ hour**
- Basic parallelization: Correlate Each Channel independently as a thread
- Clock-Bias Search – each clock-bias trial value can be run independently as a thread
- Complex multiplication over a lag-window to be done as Single-Instruction-Multiple-Data (SIMD) Instruction
- Each second's correlation can be done independent of the next second's correlation – as much as CPU / Memory resources support..

Future Plans Contd..

- Using VLBI for other *solve-for* parameters such as Station Location estimation.
- Format conversion – CCSDS RDEF ←→ VLBI VDIF format and sharing of data from joint observations..
- IDSN-32m station – S/X Band participation in VLBI experiments – subject to the operational schedule and management clearances..
- Media Calibration – Best Practices / Approaches