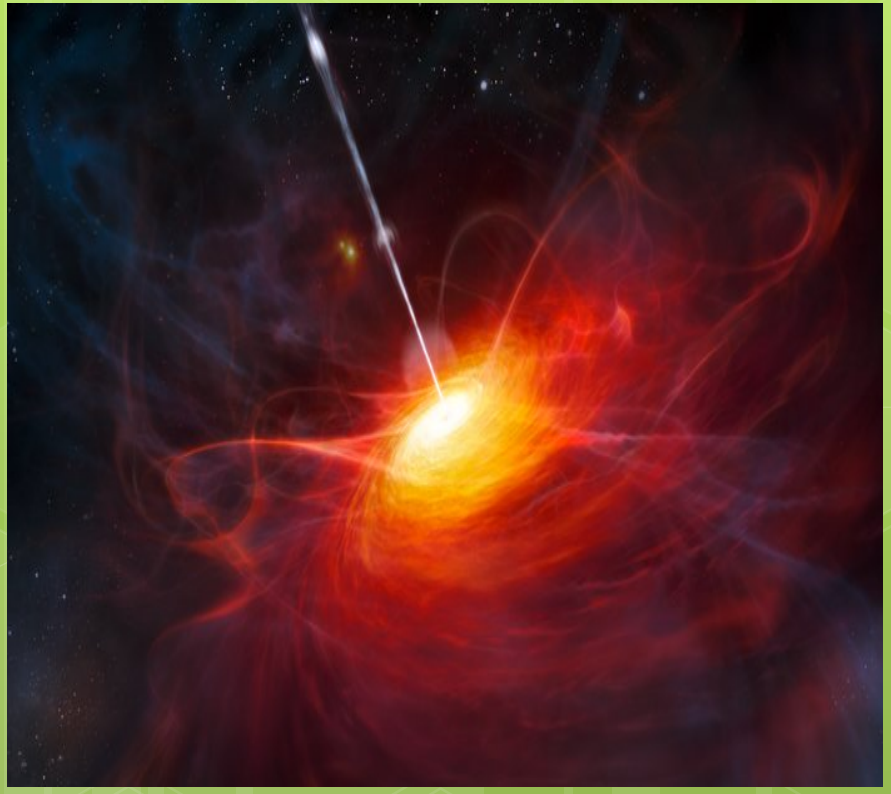


Image Courtesy: Quasar ULAS J1120+0641, ESO/M.Kornmesser

ISTRAC/ISRO Delta-DOR Correlator

ISTRAC/ISRO DDOR Working Group

14th Nov 2019

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

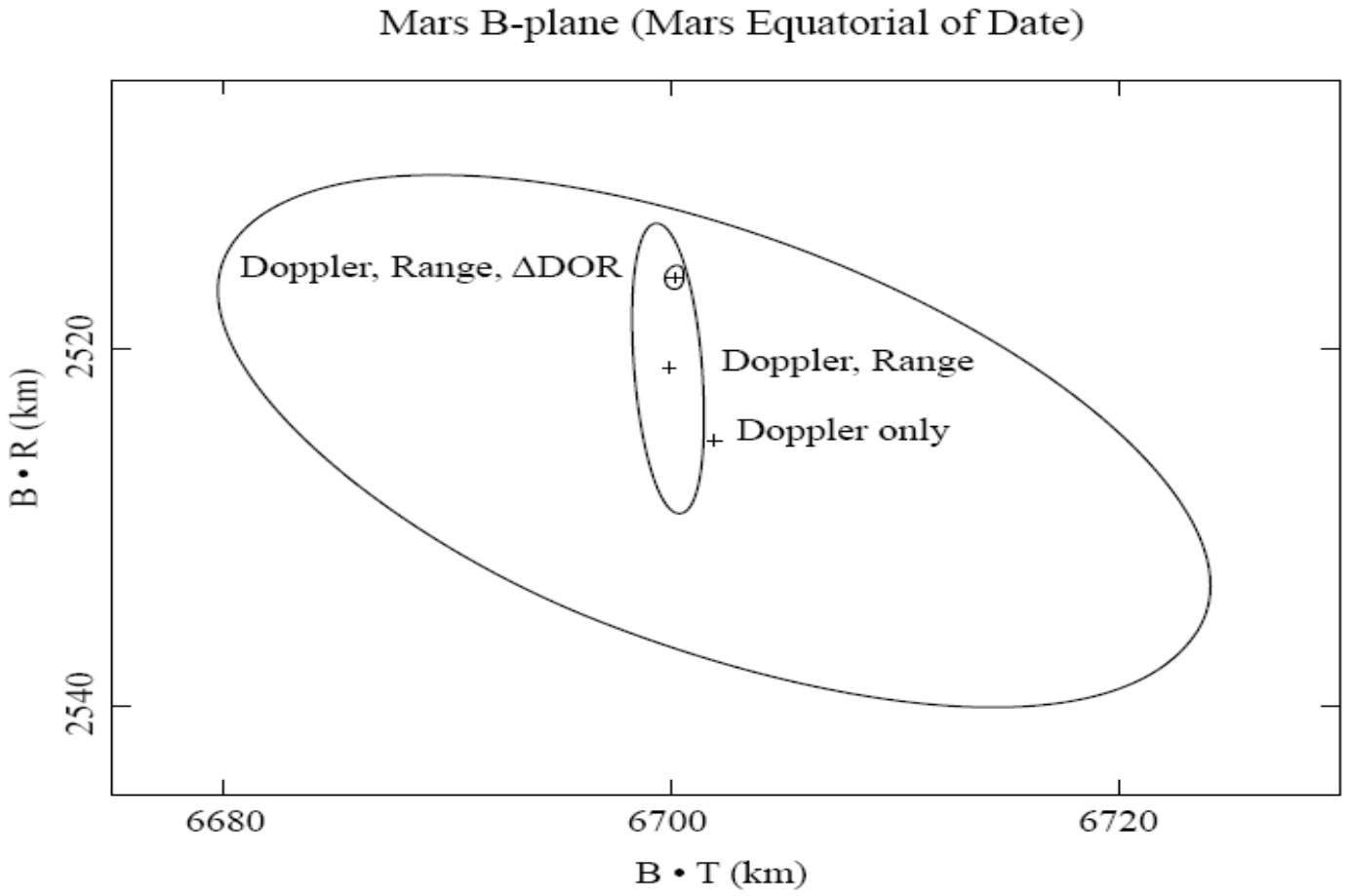


Figure 2-2: Error Ellipses in the Mars Targeting Plane[1]

[1] Courtesy: JPL/CalTech

ΔDOR Concept

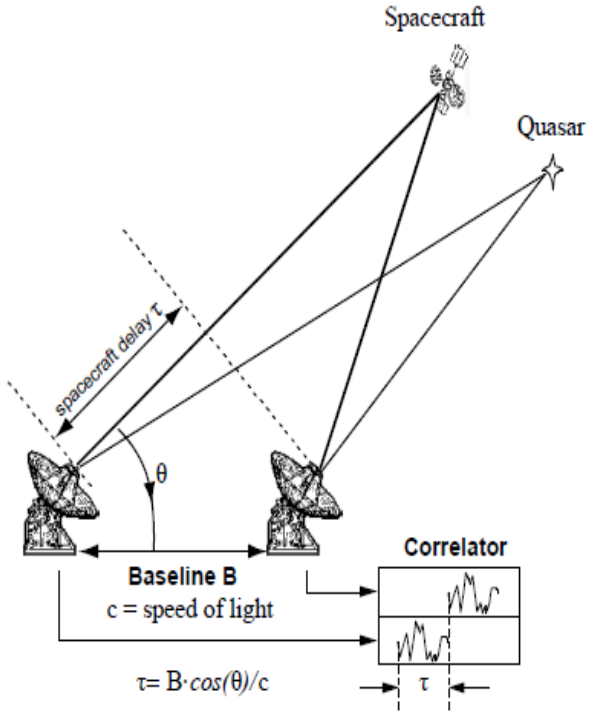


Figure 2-1: Delta-DOR Observation Geometry

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

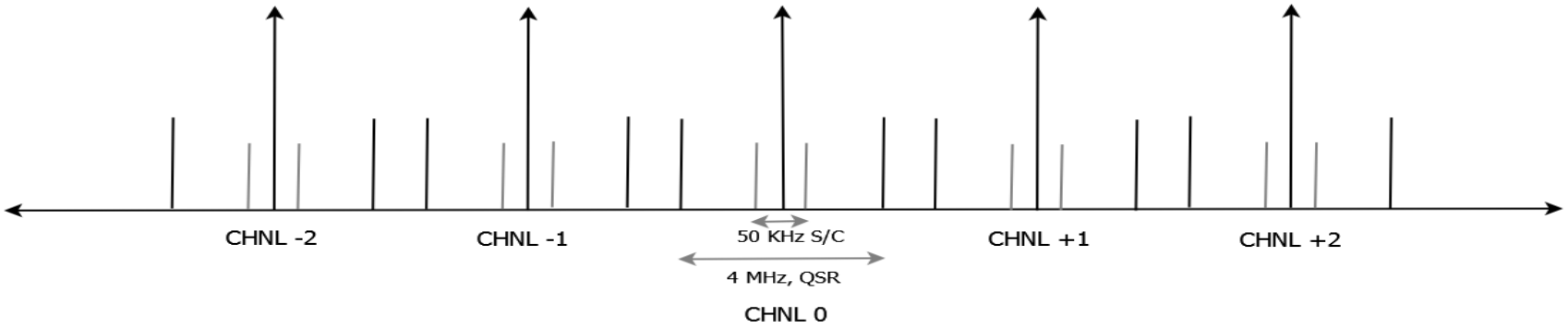
- Hence the optimal algorithms to derive the Differential One-Way delay for S/C and QSR are different.

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..

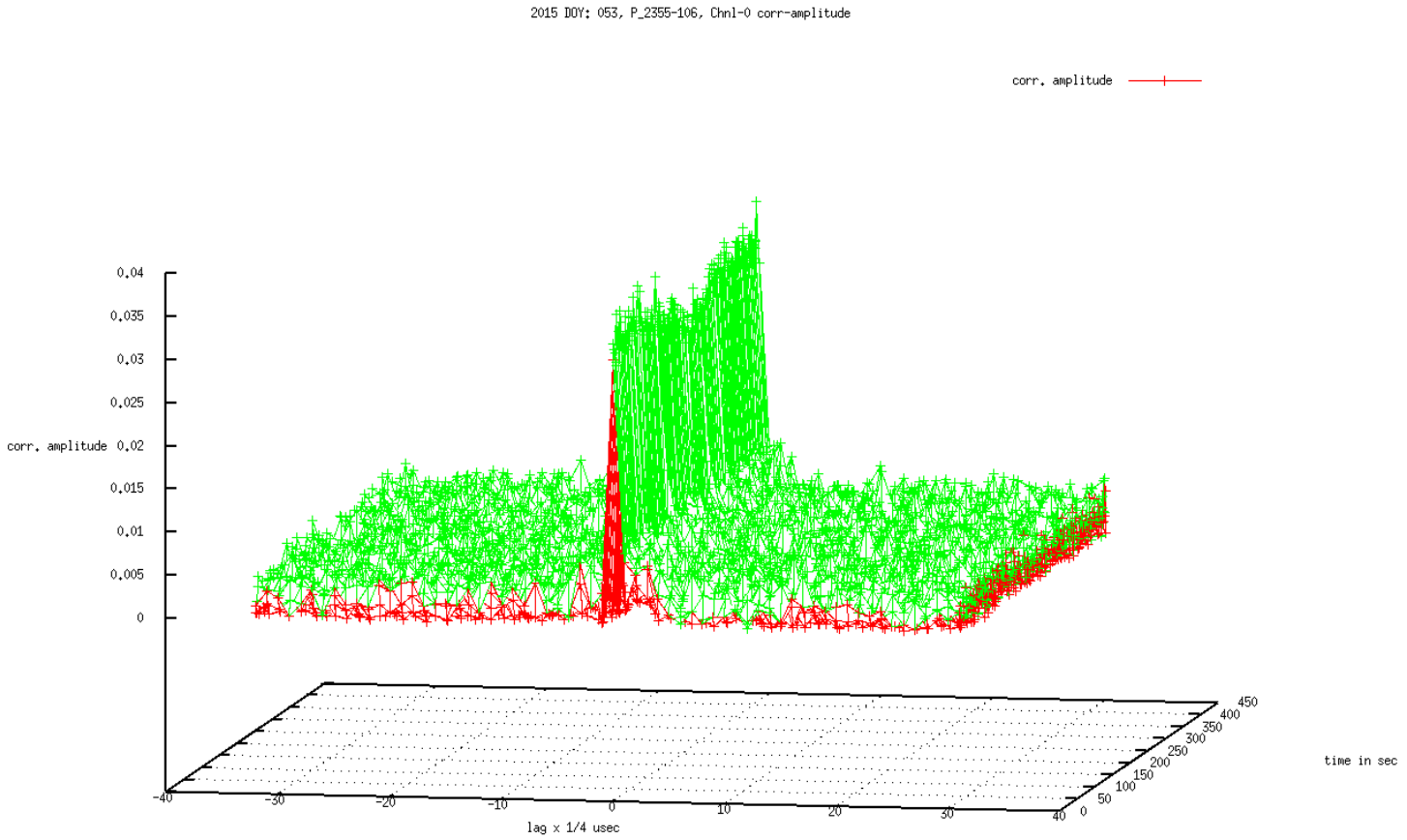
Delta-DOR Correlator

- 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

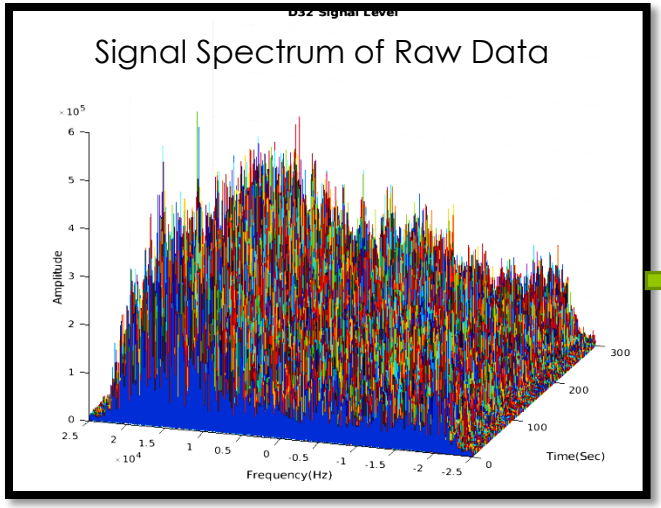
Sample First-level Correlation Results



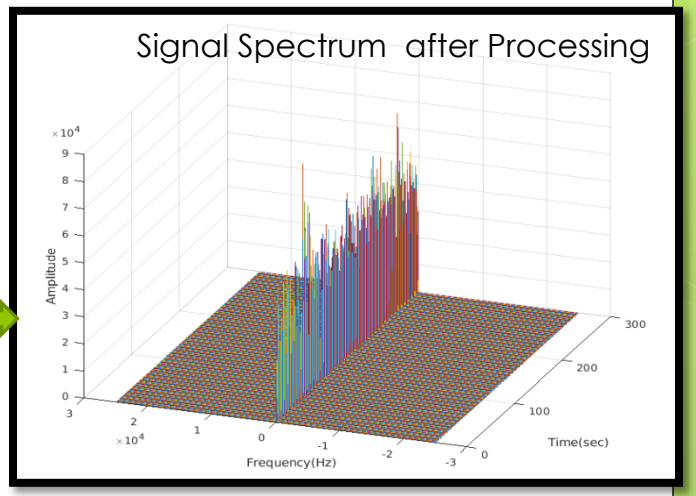
S/C Correlation

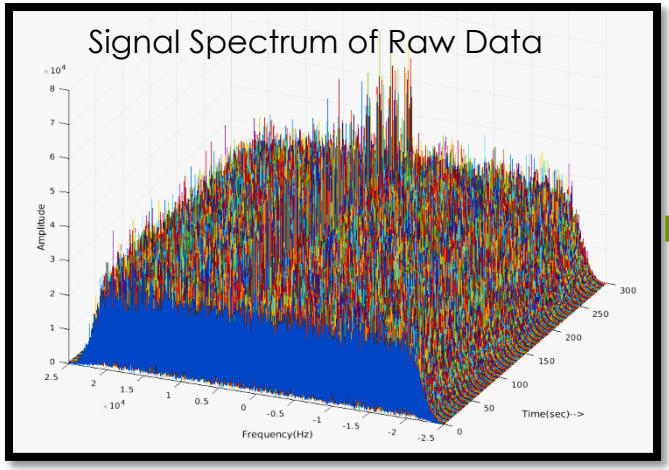
- General PLL based approaches such as Analog / Digital PLL, AGC-based PLL approach, Complex-Filtering, Windowing-based Digital Filtering method etc., alone were not sufficient to handle the OUTER channels (+2, -2 harmonics) noisy-data processing.
- Evolved our own approach to doing accurate phase measurement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

Outermost S/C Channel Processing

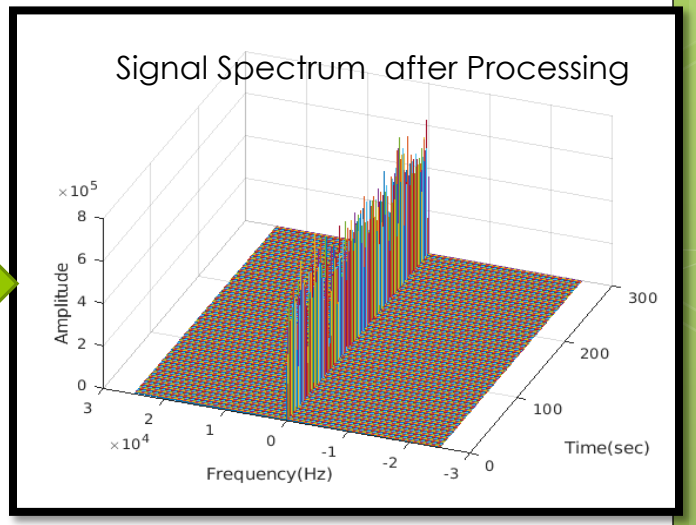


Exact Signal Extraction From D32 +2 Channel Extraction





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.

Correlator Status

- 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.
  - Further improvement is however being worked-on.

On Collaboration..

- Discussion Forum on VLBI for sharing technical knowledge
- VLBI for S/C navigation with more than 2 participating stations
- 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