# LO Reference and Timing Design Description

020.35.00.00.00-0002 DSN
Status: **RELEASED**

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## Change Record

| Version | Date | Author | Affected Section(s) | Reason |
|---|---|---|---|---|
| A | 2019-07-26 | B. Shillue | All | Initial Draft |
| B | 2022-05-30 | B. Shillue | All | |
| B.1 | 2024-02-29 | B. Shillue | All | |
| C | 2024-02-29 | M. Archuleta | All | Minor formatting and edits; prepared for release. |
| D | 2024-07-11 | B. Shillue | All | Minor clarification after review. |

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# 1 Introduction

## 1.1 Purpose and Scope

The purpose of this document is to define the design of the ngVLA LO Reference and Timing for the Conceptual phase of its development. The LO Reference and Timing consists of Reference and Timing Generation (RTG), Reference and Timing Distribution (RTD), and Antenna Time and Frequency (ATF) subsystems. Thus, the scope of this design document includes all of the local oscillator, time, and frequency services for the array.

Requirements have been flowed down from [AD01-AD11] to inform a pair of Level 2 LO Reference and Timing requirements documents [AD12, AD13]. The purpose of this design document is to describe a design that can meet the requirements as set forth is [AD12] and [AD13].

The design description is a holistic definition of the design, including performance, functional, mechanical, environmental, safety, reliability, availability and maintainability characteristics. The design should also show compliance to external interfaces in cases where the interfaces have a direct impact on the design.

# 2 Related Documents and Drawings

## 2.1 Applicable Documents

The following documents may not be directly referenced herein, but provide necessary context or supporting material.

| Ref. No. | Document Title | Rev/Doc. No. |
|---|---|---|
| AD01 | ngVLA Systems Engineering Management Plan | 020.10.00.00.00-0001 PLA |
| AD02 | ngVLA Requirements Management Plan | 020.10.15.00.00-0001 PLA |
| AD03 | ngVLA System Requirements | 020.10.15.10.00-0003 REQ |
| AD04 | L1 System Environmental Specifications | 020.10.15.10.00-0001 SPE |
| AD05 | L1 System EMI/RFI Requirements | 020.10.15.10.00-0002 REQ |
| AD06 | System-Level Architecture Model | 020.10.20.00.00-0002 DWG |
| AD07 | L1 Safety Specification | 020.80.00.00.00-0001 REQ |
| AD08 | L1 Security Specification | 020.80.00.00.00-0003 REQ |
| AD09 | ngVLA System Electronics Specifications | 020.10.15.10.00-0008 REQ |
| AD10 | Calibration Requirements | 020.22.00.00.00-0001 REQ |
| AD11 | System Technical Budgets | 020.10.25.00.00-0002 DSN |
| AD12 | Antenna Time and Frequency Technical Requirements | 020.30.35.00.00-0004 REQ |
| AD13 | Local Oscillator Reference and Timing: Generation & Distribution Technical Requirements | 020.35.00.00.00-0003 REQ |
| AD14 | ngVLA Risk Register | 020.05.35.00.00-0002 REG |
| AD15 | ngVLA Product Breakdown Structure | 020.10.20.00.00-0004 DSN |
| AD16 | ngVLA Logistics Engineering Management Plan | 020.10.00.00.00-0004 PLA |

## 2.2 Applicable Interface Control Documents

| Ref. No. | Document Title | Rev./Doc. No. |
|---|---|---|
| AD20 | Interface Control Document Between: Antenna Electronics DC Power Supply (PSU) *and* Antenna Electronics Subsystem: section on LO Reference and | 020.10.40.05.00-0006 |

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| --- | --- | --- |
| | Timing and Distribution (RTD) Subsystem (interface 0058) | |
| AD21 | Interface Control Document Between: Antenna Electronics Bins, Modules, and Racks (BMR) *and* Antenna Electronics Subsystem: section on LO Reference and Timing and Distribution (RTD) Subsystem (interface 0064) | 020.10.40.05.00-0040 |
| AD22 | Interface Control Document Between: LO Reference and Timing and Distribution (RTD) Subsystem *and* Antenna Electronics Environmental Control System (EEC) Subsystem | 020.10.40.05.00-0069 |
| AD23 | Interface Control Document Between: Monitor and Control Hardware Interface Layer (HIL)/Monitor and Control Subsystem (MCL) (interface 0077/107) *and* LO Reference and Timing and Distribution (RTD) Subsystem | 020.10.40.05.00-0077 |
| AD24 | Interface Control Document Between Computing/CSP subsystems : section on LO Reference and Timing Generation (RTG) and Distribution (RTD) Subsystems (interface 0099, 0100) and ngVLA Site Buildings (NSB) subsystem | 020.10.40.05.00-0095 |
| AD25 | Interface Control Document Between Monitor and Control System and LO Reference and Timing Generation (RTG) | 020.10.40.05.00-0106 |
| AD26 | Interface Control Document Between Central Fiber Infrastructure (FIB) and LO Reference and Timing Distribution (RTD) | 020.10.40.05.00-0120 |
| AD27 | Interface Control Document Between: Digital Backend Subsystem (DBE) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0152 |
| AD28 | Interface Control Document Between: Central Signal Processing (CSP) and LO Reference and Timing Generation (RTG) | 020.10.40.05.00-0123 |
| AD29 | Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* LO Reference and Timing – Generation (RTG) | 020.10.40.05.00-0124 |
| AD30 | Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0125 |
| AD31 | Interface Control Document Between: Antenna Electronics Integrated Receiver and Downconverters (IRD) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0005 |
| AD32 | Interface Control Document Between: Antenna Electronics DC Power Supply (PSU) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0059 |
| AD34 | Interface Control Document Between: Water Vapor Radiometer (WVR) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0028 |

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|---|---|---|
| AD35 | Interface Control Document Between Antenna Electronics: Bins, Modules, Racks (BMR) *and* Antenna Time and Frequency (interface 0065) | 020.10.40.05.00-0040 |
| AD36 | Interface Control Document Between Antenna Electronics: Antenna Fiber Distribution (AFD) and Antenna Time and Frequency (ATF) (interface 0081) | 020.10.40.05.00-0041 |
| AD37 | Interface Control Document Between Antenna Time and Frequency (ATF) *and* Antenna Electronics Environmental Control System (EEC) | 020.10.40.05.00-0070 |
| AD38 | Interface Control Document Between: Antenna Electronics Monitor and Control Hardware Interface Layer (HIL) *and* Antenna Time and Frequency (ATF) | 020.10.40.05.00-0078 |
| AD39 | Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Antenna Fiber Optic System (AFD) | 020.10.40.05.00-0153 |
| AD40 | Interface Control Document Between: LO Reference and Timing – Distribution (RTD) *and* Water Vapor Radiometer | 020.10.40.05.00-0128 |
| AD41 | Interface Control Document Between: LO Reference and Timing – Generation (RTG) *and* Hardware Interface Layer (HIL) | 020.10.40.05.00-0129 |

## *2.3 Reference Documents*

The following documents are referenced within this text:

| Ref. No. | Document Title | Rev/Doc. No. |
|---|---|---|
| RD01 | Configuration: Reference Design Rev D Description | Next Generation Very Large Array Memo No. 92, https://library.nrao.edu/public/memos/ngvla/NGVLA_92.pdf |
| RD02 | Timing Requirements & Considerations | *ngVLA Electronics Memo#15, https://library.nrao.edu/public/memos/ngvla/NGVLAE_15.pdf* |
| RD03 | ngVLA Antenna Local Oscillator Trade Study | 020.30.35.00.00-0003 REP |
| RD04 | VLA Pie Town Project Handbook | *VLA Technical Reference No. 77, https://library.nrao.edu/public/memos/vla/tech/VLATR_77.pdf* |
| RD05 | S. Durand, J. Jackson, K. Morris, "Phase Coherence of the EVLA Radio Telescope" | EVLA Memo 105, https://library.nrao.edu/public/memos/evla/EVLAM_105.pdf |
| RD06 | W.E. Dumke, "Hydrogen Maser Clock Trip Report and Procurement Recommendation for the VLA and the Proposed VLBI System" | *VLA Electronic Memo#198, Oct. 1980,* https://library.nrao.edu/public/memos/vla/elec/VLAE_198.pdf |

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|---|---|---|
| RD07 | S. Weinreb, C. Moore, "Local Oscillator System Draft" | *VLB Array Memo #62, Jan 1982,* https://library.nrao.edu/public/memos/vlba/main/VLBA_62.pdf |
| RD08 | L.R. D'Addario, A.R. Thompson, S. Weinreb (1985), c. Scott, S. Durand (2014), L. Abeyta (2016), "Hydrogen Maser Frequency Standard Specification A53308N001: VLBA Project," V14 | *VLBA Project Document Archive* |
| RD09 | Tucker, T. K. "Operating and environmental characteristics of sigma tau hydrogen masers used in the very long baseline array (VLBA)." | *Proceedings of the 20th Annual Precise Time and Time Interval Systems and Applications Meeting*. 1988. https://apps.dtic.mil/sti/pdfs/ADA516090.pdf |
| RD10 | Marlow, Bonnie L. Schmittberger, and David R. Scherer. "A review of commercial and emerging atomic frequency standards." | *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 68.6 (2021): 2007-2022.* |
| RD11 | Krehlik, Przemysław, et al. "ELSTAB—Fiber-optic time and frequency distribution technology: A general characterization and fundamental limits." | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control 63.7 (2015): 993-1004.* |
| RD12 | H. Kiuchi, "Frequency transfer subsystem Design description" | *August 2023, 020.10.xx.xx.xx-0001-XXX, Status=Draft* |
| RD13 | Kiuchi, Hitoshi, et al. "High extinction ratio Mach–Zehnder modulator applied to a highly stable optical signal generator." | *IEEE Transactions on Microwave Theory and Techniques* 55.9 (2007): 1964-1972 |
| RD14 | Kiuchi, Hitoshi. "Highly stable millimeter-wave signal distribution with an optical round-trip phase stabilizer." | *IEEE transactions on microwave theory and techniques* 56.6 (2008): 1493-1500 |
| RD15 | Kubo, Derek Y., et al. "Development of a Mach–Zehnder Modulator Photonic Local Oscillator Source." | *IEEE transactions on microwave theory and techniques 61.8 (2013): 3005-3014.* |
| RD16 | Kiuchi, Hitoshi. "Postprocessing phase stabilizer for wide frequency range photonic-microwave signal distribution." | *IEEE Transactions on Terahertz Science and Technology* 7.2 (2017): 177-183. |
| RD17 | Kiuchi, Hitoshi. "Wide-frequency-range phase-locked Photonic-Microwave oscillator operated in a fiber-coupled remote station." | *Journal of Lightwave Technology 37.10 (2019): 2172-2177.* |
| RD18 | H. Kiuchi, "Frequency transfer subsystem Verification report" | *Aug 2023, 020.10.xx.xx.xx-0001-XXX, Status: Draft* |
| RD19 | Miho Fujieda , "Proposal on frequency transfer system with an active phase-noise cancellation for noisy link" | *August 3, 2023, NAOJ Proposal* |
| RD20 | Fujieda, Miho, Motohiro Kumagai, and Shigeo Nagano. "Coherent microwave transfer over a 204-km telecom fiber link by a cascaded system." | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control 57, no. 1 (2009): 168-174.* |
| RD21 | H. Kiuchi, M. Fujieda, "Time transfer subsystem Design description" | *020.10.xx.xx.xx-0001-XXX Status: Draft* |

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| RD22 | M. Fujieda, H. Kiuchi, T. Gotoh, "Proof-of-concept of a fiber-optic timing transmission for a synthesis radio telescope" | *2023, IEEE International Frequency Control Symposium and the European Frequency and Time Forum* |
| RD23 | Rost, M., Fujieda, M., & Piester, D. "Time transfer through optical fibers (TTTOF): progress on calibrated clock comparisons" | *IEEE EFTF-2010 24th European Frequency and Time Forum (pp. 1-8).* |
| RD24 | Fujieda, Miho, et al. "Carrier-phase-based two-way satellite time and frequency transfer." | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control 59.12 (2012): 2625-2630.* |
| RD25 | Fujieda, M., et al. "Carrier-phase two-way satellite frequency transfer over a very long baseline." | *Metrologia 51.3 (2014): 253.* |
| RD26 | Fujieda, Miho, Hitoshi Kiuchi, and Tadahiro Gotoh. "Proof-of-concept of a fiber-optic timing transmission for a synthesis radio telescope" | *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS).* |
| RD27 | R. Selina, B. Shillue, O. Yeste, Ojeda, M. Schiller, "Supporting Spectral Dynamic Range Requirements" | *ngVLA Electronics Memo, in prep* |
| RD28 | JESD204c Primer: What's New and in It for You– Pt 1 | *https://www.analog.com/en/analog-dialogue/articles/jesd204c-primer-part1.html* |
| RD29 | JESD204c Primer: What's New and in It for You– Pt 2 | *https://www.analog.com/en/analog-dialogue/articles/jesd204c-primer-part2.html* |
| RD30 | "What is JESD-204 and Why Should We Pay Attention to It?" Analog Device Technical Article MS-2374, 2013 | *https://www.analog.com/en/technical-articles/what-is-jesd204-and-why-should-we-pay-attention-to-it.html* |
| RD31 | "Clocking Wideband GSPS JESD204B ADCs," Ian Beavers, Matt Felmlee, Analog Device Technical Article | *https://www.analog.com/en/technical-articles/clocking-wideband-gsps-jesd204b-adc.html* |
| RD32 | M. Schiller, "ngVLA LO, IRD, and DBE Timestamping," | *ngVLA Draft memo, Apr 2023* |
| RD33 | Edward c. Liang; "Characterization and modeling of High Q Dielectric Resonators." | *Microwave Journal, November 4 2016.* |
| RD34 | "Fundamentals of Direct Digitial Synthesis (DDS)" | *MT-085, Analog Devices Technical Note, Oct 2008* |
| RD35 | Ken Gentile and Rick Cushing, "A Technical Tutorial on Digital Signal Synthesis" | *Analog Devices, 1999* |
| RD36 | H. T. Nicholas and H. Samueli, "An Analysis of the Output Spectrum of Direct Digital Frequency Synthesizers in the Presence of Phase-Accumulator Truncation" | 41st Annual Symposium on Frequency Control, *Philadelphia, PA, USA,1987, pp. 495-502,* |

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| | | *doi:10.1109/FREQ.1987.201068* |
| RD37 | Personal Communication | *Farron Dacus, Longwing Technology, Nov 2023* |
| RD38 | Braun, Tobias T., Marcel van Delden, Christian Bredendiek, Jan Schoepfel, Stephan Hauptmeier, William Shillue, Thomas Musch, and Nils Pohl. "A phase-locked loop with a jitter of 50 fs for astronomy applications." | International Journal of Microwave and Wireless Technologies *(2023): 1-9.* |
| RD39 | Braun, Tobias T., Marcel van Delden, Christian Bredendiek, Jan Schoepfel, and Nils Pohl. "A low phase noise phase-locked loop with short settling times for automotive radar." | 2021 16th European Microwave Integrated Circuits Conference (EuMIC)*, pp. 205-208. IEEE, 2022.* |
| RD40 | Butler, Bryan, Wayne Koski, EVLA Memo 179. "The New Weather Station for the VLA." (2014) | *https://library.nrao.edu/public/memos/evla/EVLAM_179.pdf* |
| RD41 | Serizawa, Y., et al. "Transmission delay variations in OPGW and overhead fiber-optic cable links." | *IEEE transactions on power delivery* 12.4 (1997): 1415-1421 |
| RD42 | Krehlik, P., K. Turza, and A. Binczewski. "Characterization of the frequency transfer over 300 km of aerial suspended fiber." | *2016 European Frequency and Time Forum (EFTF)*. IEEE, 2016 |
| RD43 | Gozzard, David R., et al. "Characterization of optical frequency transfer over 154 km of aerial fiber." | *Optics letters* 42.11 (2017): 2197-2200 |
| RD44 | Śliwczyński, Łukasz, et al. "Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km." | *Metrologia 50.2 (2013): 133.* |
| RD45 | Ci, C., Wu, H., Tang, R., Liu, B., Chen, X., Zhang, X. S., ... & Zhao, Y. X., "Digital output compensation for precise frequency transfer over commercial fiber link" | *Optoelectronics Letters, 14(2), 109-113.* |
| RD46 | Chen, Y., Dai, H., Si, H., Wang, F., Wang, B., & Wang, L., "Long-Haul High Precision Frequency Dissemination Based on Dispersion Correction" | *IEEE Transactions on Instrumentation and Measurement, 71, 1-7.* |
| RD47 | Xue, W., Zhao, W., Quan, H., Xing, Y., & Zhang, S., "Cascaded microwave frequency transfer over 300-km fiber link with instability at the $10^{-18}$ level" | *2021, Remote Sensing, 13(11), 2182.* |
| RD48 | Lopez, O., Daussy, C., Amy-Klein, A., Chardonnet, C., Narbonneau, F., Lours, M., & Santarelli, G,, "Fiber frequency dissemination with resolution in the 10-18 range" | *2006 IEEE International Frequency Control Symposium and Exposition (pp. 80-82)* |
| RD49 | Newbury, N. R., Williams, P. A., & Swann, W. C., "Coherent transfer of an optical carrier over 251 km" | *Optics Letters*, 2007,32(21), 3056-3058 |
| RD50 | Williams, P. A., Swann, W. C., & Newbury, N. R., "High-stability transfer of an optical frequency over long fiber-optic links" | *JOSA B*, 2008, 25(8), 1284-1293 |
| RD51 | Rubiola, Enrico, and Francois Vernotte. "The companion of Enrico's chart for phase noise and two-sample variances." | *IEEE Transactions on Microwave Theory and Techniques (2023).* |

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| RD52 | Recommendation ITU-T G.8260 (11/2022) "Definitions and terminology for synchronization in packet networks" | *https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.8260-202211-I!!PDF-E&type=items* |
| RD53 | Wu, G., Hu, L., Zhang, H., & Chen, J. (2014)."High-precision two-way optic-fiber time transfer using an improved time code." | *Review of Scientific Instruments, 85(11).* |
| RD54 | Wu, G., Hu, L., Zhang, H., & Chen, J. (2015, April). "A round-trip fiber-optic time transfer system using bidirectional TDM transmission" | *2015 Joint Conference of the IEEE International Frequency Control Symposium & the European Frequency and Time Forum (pp. 773-776). IEEE.* |
| RD55 | Lopez, O., Kéfélian, F., Jiang, H., Haboucha, A., Bercy, A., Stefani, F., ... & Santarelli, G. (2015). "Frequency and time transfer for metrology and beyond using telecommunication network fibres" | *Comptes Rendus Physique, 16(5), 531-539.* |
| RD56 | Zhang, H., Wu, G., Hu, L., Li, X., & Chen, J. (2015). "High-precision time transfer over 2000-km fiber link" | *IEEE Photonics Journal, 7(6), 1-9.* |
| RD57 | Krehlik, P., Śliwczyński, Ł., Buczek, Ł., Kołodziej, J., & Lipiński, M. (2015). "Ultrastable long-distance fibre-optic time transfer: active compensation over a wide range of delays" | *Metrologia, 52(1), 82.* |
| RD58 | Dierikx, Erik F., et al. "White rabbit precision time protocol on long-distance fiber links." | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control 63.7 (2016): 945-952.* |
| RD59 | Lessing, M., Margolis, H. S., Brown, C. T. A., & Marra, G. (2017). "Frequency comb-based time transfer over a 159 km long installed fiber network" | *Applied Physics Letters, 110(22).* |
| RD60 | Vojtech, J., Slapak, M., Skoda, P., Radil, J., Havlis, O., Altmann, M., ... & Cip, O. (2017). "Joint accurate time and stable frequency distribution infrastructure sharing fiber footprint with research network" | *Optical Engineering, 56(2), 027101-027101.* |
| RD61 | Frank, F., Stefani, F., Tuckey, P., & Pottie, P. E. (2018). "A sub-ps stability time transfer method based on optical modems" | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 65(6), 1001-1006.* |
| RD62 | Wang, J., Yue, C., Xi, Y., Sun, Y., Cheng, N., Yang, F., ... & Cai, H. (2020). "Fiber-optic joint time and frequency transfer with the same wavelength" | *Optics Letters, 45(1), 208-211.* |
| RD63 | Wang, J., Fang, S., Sun, Y., Cheng, N., Yang, F., Ying, K., ... & Cai, H. (2021). "Hybrid solution for joint transfer time signal with both RF frequency and optical frequency" | *IEEE Photonics Journal, 13(5), 1-4.* |
| RD64 | Zuo, Faxing, et al. "13,134-km fiber-optic time synchronization." | *Journal of Lightwave Technology 39.20 (2021): 6373-6380.* |
| RD65 | White Rabbit Open Hardware Repository | *https://ohwr.org/project/white-rabbit* |

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| RD66 | Daniluk, Grzegorz. "White Rabbit PTP Core the sub-nanosecond time synchronization over Ethernet." | *Dissertation, Warsaw University of Technology* (2012). |
| RD67 | Jiménez-López, Miguel, et al. "10 gigabit white rabbit: Sub-nanosecond timing and data distribution." | *IEEE Access* 8 (2020): 92999-93010. |
| RD68 | van Tour, C., and J. C. J. Koelemeij, "Sub-Nanosecond Time Accuracy and Frequency Distribution through White Rabbit Ethernet." | https://library.nrao.edu/public/memos/ngvla/NGVLA_22.pdf |
| RD69 | Rizzi, Mattia, et al. "White rabbit clock synchronization: Ultimate limits on close-in phase noise and short-term stability due to FPGA implementation" | *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 65.9 (2018): 1726-1737 |
| RD70 | Lipiński, Maciej, et al. "White rabbit applications and enhancements." | *2018 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS)*. IEEE, 2018 |
| RD71 | Boven, Paul. "DWDM stabilized optics for white rabbit." | *2018 European Frequency and Time Forum (EFTF)* |
| RD72 | Yuan, Xu, and Bo Wang. "Using single wavelength light to improve the synchronization accuracy of the white rabbit system." | *Chinese Optics Letters 15.10 (2017): 101202.* |

# 3 Subsystem Overview

## 3.1 High level description

The LO Reference and Timing (LRT) work element is responsible for supplying accurate and reliable local oscillator, sampler clock, and timing references to the relevant subsystems located at the antennas, and timing for the central signal processor (CSP) and the computing and software (CSW) subsystem.

With the caveat that the diagram below (Figure 1) shows only one ngVLA antenna, and does not show all of the functionality, interfaces, and signal paths of the LO Reference and Timing – it is nevertheless useful in showing at a glance the scope of the subsystem. Everything that is colored red is a deliverable function of the LRT subsystem. The function of the time and frequency transfer is to synchronize the antenna time and frequency with the central time and frequency. Therefore, if more antennas were added to the sketch they would all be mutually coherent.

The LRT subsystem is divided into three work elements:

**Reference and Timing Generation (RTG):** Frequency and Timing sources located centrally or in Standalone remote locations

**Reference and Timing Distribution (RTD):** Optoelectronic modules required to split, distribute, measure, and provide correction for fiber link phase and timing between RTG work element and ATF work element

**Antenna Time and Frequency (ATF):** All antenna-located modules needed to provide LO, digitizer, clocking and references at the antenna

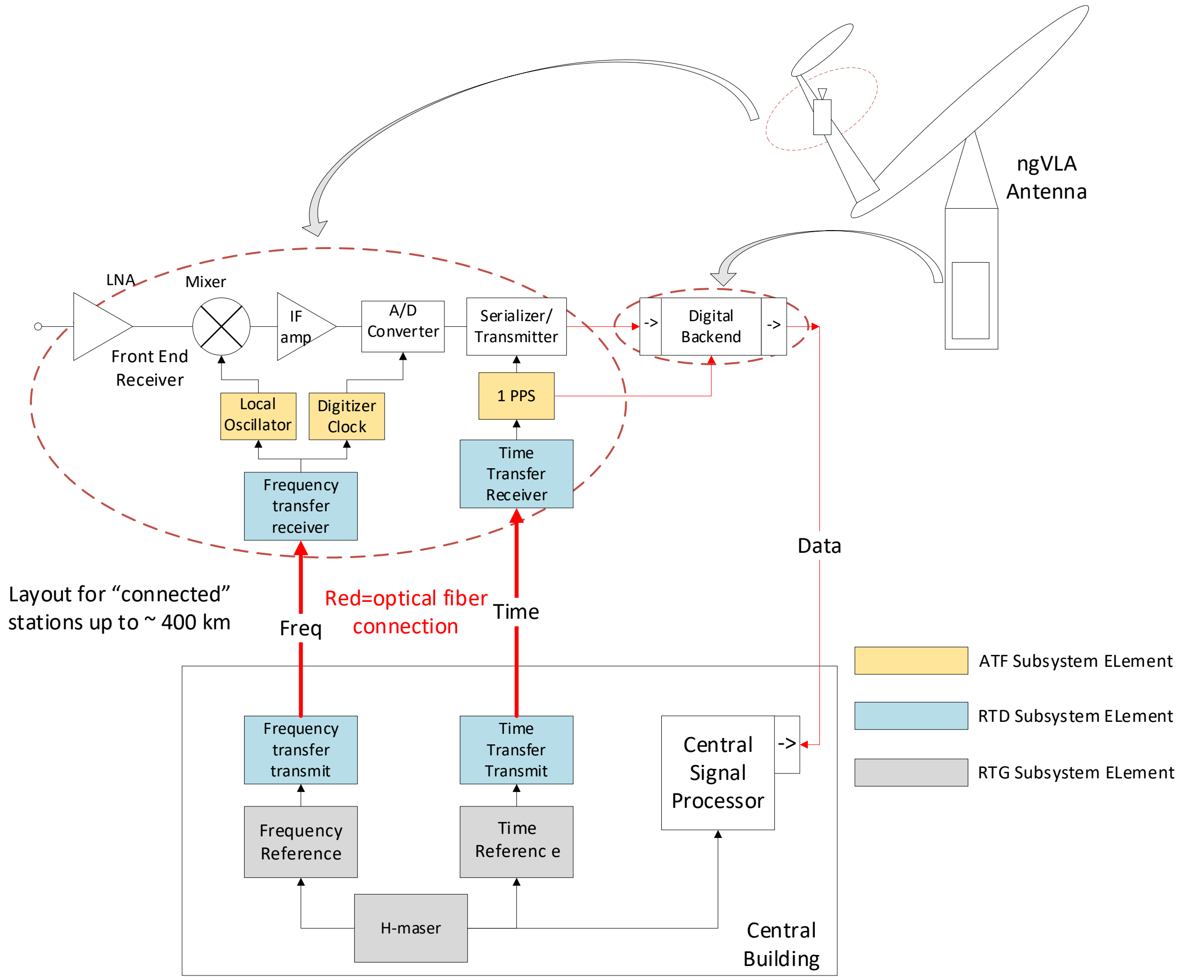


**Figure 1 - LO Reference and Timing subsystem scope**

## 3.2 *Design Driving Requirements*

A subset of the key requirements that drive the design is shown in Table 1 below.

**Table 1 - Key Antenna Time and Frequency Requirements (Note phase noise and phase drift requirements will be studied further).**

| Parameter | Value | Req. # | Traceability |
|---|---|---|---|
| Maximum Fiber Length | 300km, Goal 1000 km | LRT1120 | SYS1301, RD01 |
| Number of Antennas | RTD subsystem distribution shall be provided to support at least 263 antennas | LRT1100 | SYS1001, SYS1021 |
| Number of Subarrays | Ten, minimum | LRT1140 | SYS0601, SYS0603 |

| Parameter | Value | Req. # | Traceability |
|---|---|---|---|
| Simultaneous LOs | As many as needed to support an entire band | LRT1205 | SYS0903, SYS0905 |
| LO Phase Noise | < 76 fsec | LRT1240 | SYS5001, SYS1503, CAL0314 |
| LO Phase Drift | < 59 fs at 300 s (linear term removed) and < 1500 fs (absolute) | LRT1250 | SYS5001, SYS1504, SYS1505 |
| Return to Phase | Any derived LO or timing signal shall return to phase upon change in frequency from F1 to F2 to F1 | LRT1280 | SYS0602 |
| Timing to CSP | Timing accuracy to CSP (or to date timestamping) shall be within 2 nsec (goal of 1 nsec) | LRT1300 | SYS2002, SYS2003, SYS0404, RD02 |
| LO Spurious Narrowband Tones | < -103.5 dBc within 3.5 GHz of carrier | LRT1500 | [AD31] SYS2104 |
| Mean Time Between Failure/Mean Time Between Maintenance | 1. There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTG subsystem in the Central Electronics Building<br>2. There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTD subsystem in the Central Electronics Building<br>3. There is a minimum MTBF/MTBM of 18520 hours ***total*** for elements of the RTD subsystem located at the antenna<br><br>In each of the three cases above, the sum of MTBFs of all modules and assemblies in the subsystem shall meet these limiting values. | LRT2300, LRT2305, LRT2310, LRT2330 | SYS2610, SYS2605, [AD11] |

### 3.2.1 Maximum Fiber Length

The LRT requirement is for a direct connection of the fiber optic time and frequency service up to at least 300 km with a goal of 1000 km. The maximum distance will be based upon a costed trade study. Beyond 30km, ngVLA will rely on either new trenched fiber or pole strung fiber, either option (especially trenched) carries significant cost. The great distances present infrastructure, installation, and cost challenges. Additionally, beyond 100 km or so, the stations in the MID array are spaced further and further apart and thus the incremental cost of supporting direct fiber connection to the "next" antenna goes up with distance. The scope of the LO Reference and Timing work is to support that fiber optic distance with installed hardware that not only supports the signal transport over the maximum distance, but corrects for phase and timing delays associated with the transport.

### 3.2.2 Number of Antennas

RTD subsystem distribution shall be provided to support up to 263 antennas. Note that the 30 LBS antennas, and possibly additional MID antennas will use a standalone time and frequency design, so the main distribution network from the central building will need to serve <=233 antennas.

### 3.2.3 Number of Subarrays

The RTD subsystem shall support a minimum of ten subarrays. This is one of the main design drivers for the use of a fixed frequency reference frequency transmission to the antenna. Thus, no switching or intelligence is needed at the central building (in the LO Reference and Timing subsystem) to map antennas into subarrays.

### 3.2.4 LO Frequency Table

The requirement for broad frequency coverage, wideband downconverters, and fixed frequency tuning has resulted in a set of nineteen downconverters for RF Bands 2—6 (Band 1 is directly digitized). Each downconverter has a nominally fixed tuned frequency while allowing for application of small offset frequencies. These nominal Loo frequencies are shown in Table 2.

**Table 2 - LO Frequency Table**

| | | RF | | LO | |
|---|---|---|---|---|---|
| RF Band | Module | start (GHz) | stop (GHz) | harmonic | (GHz) |
| 2 | a | 3.5 | 12.3 | 2 | 5.8 |
| | b | | | 4 | 11.6 |
| 3 | a | 12.3 | 20.5 | 5 | 14.5 |
| | b | | | 7 | 20.3 |
| 4 | a | 20.5 | 34 | 8 | 23.2 |
| | b | | | 10 | 29 |
| | c | | | 12 | 34.8 |
| 5 | a | 30.5 | 50.5 | 11 | 31.9 |
| | b | | | 13 | 37.7 |
| | c | | | 15 | 43.5 |
| | d | | | 17 | 49.3 |
| 6 | a | 70 | 116 | 25 | 72.5 |
| | b | | | 27 | 78.3 |
| | c | | | 29 | 84.1 |
| | d | | | 31 | 89.9 |
| | e | | | 33 | 95.7 |
| | f | | | 35 | 101.5 |
| | g | | | 37 | 107.3 |
| | h | | | 39 | 113.1 |

### 3.2.5 Simultaneous LOs

The progression of the baseline design plan for Band 6 from four to eight downconverters, and thus the need for eight simultaneous LOs – was a prime driver for the decision to use fixed frequency LOs (not tunable frequency synthesizers) for the antennas LO [RD03].

### 3.2.6 LO Phase Noise

***Note:*** *the current phase noise requirement will be reviewed to determine if it is too stringent. Any future revision would be subject to formal change processes.*

The requirement is for < 76 fs integrated from 1 Hz to maximum IF frequency offset. The antenna local oscillators are used to downconvert fairly large chunks of RF bandwidth. The maximum IF frequency is 2.9 GHz so any phase noise at offsets from zero to 2.9 GHz will contribute additively to the overall RMS phase noise. In general, oscillators have phase noise that decreases further away from the carrier, and in practice it may be that there are insignificant contributions beyond, say, 10 MHz offset. Nevertheless this needs to be demonstrated and verified. Meeting this requirement means taking into account the contributions from all reference frequencies used to construct the antenna LO, and making careful design of PLLs and offset frequency synthesis. Amongst the subsystems:

**RTG:** maser and central references will be high performance fixed frequency oscillators which should not appreciably drive the final LO phase noise performance.

**RTD**: Long fiber links can add phase noise to distributed oscillators. This affects primarily 0-30 kHz frequency offset ranges

**ATF:** At the antenna, ATF subsystem will lock a fixed frequency low phase noise oscillator to the distributed reference with a narrow band PLL to remove as much of the link noise as possible. Additional offset locking and use of harmonics or multipliers must not add significant phase noise or spurious.

### 3.2.7 LO Phase Drift

***Note:*** *the current phase drift requirement will be reviewed to determine if it is too stringent. Any future revision would be subject to formal change processes.*
< 59 fs at 300 s (linear term removed) and < 1500 fs (absolute)

The requirement is for < 59 fs at 300 s (linear term removed) and < 1500 fs (absolute). The former is 0.03 rad (0.2 deg) at 116 GHz, while the latter is 0.18 rad (1.14 deg) at 116 GHz. These numbers are orders of magnitude less than the uncorrected phase delays, as described below. Thus, a robust method of correcting for the delays is required.

***Uncorrected phase delays:*** The distance from the central building to the most distant antennas connected by fiber is at least 300km. Typically in synthesis arrays the variation in fiber delay can be dominated by above ground antenna fiber runs if the fiber is well-buried at 1m depth or greater. However, for hundreds of km, there will be a non-negligible delay contribution even in the unlikely case that it is all well buried. At a depth of 1m, the underground temperature can vary by about 0.1 deg C per day [RD04], in a mostly linear way since short term fluctuations are attenuated in the soil. For 300km, this is equivalent to 1.5 nsec per day, or about 125 psec per hour. On top of this we can expect something similar to what has been measured on the EVLA which includes above ground fiber, and varies diurnally by about 160 psec peak-to-peak [RD05]. Finally, in the event that there are significant sections of above ground fiber, pole-mounted fiber for instance, then the delay excursions will be much higher (i.e. approximately 50 $\frac{psec}{km^0\text{C}}$ or 5 nsec delay per 10km-10deg exposure).

### 3.2.8 Return to Phase

Any derived LO or timing signal shall return to phase upon change in frequency from $F_1$ to $F_2$ to $F_1$. This means that in the antenna-based frequency synthesis, there shall be no frequency dividers that could lead to phase ambiguous locking. Also, design with direct digital synthesizers shall be done in such a way as to account for the ability to return to phase after frequency switching. The accuracy of the return to phase must be such that the system phase meets baseline stability requirements when the off-state switch is removed from a measured frequency switching time series.

### 3.2.9 Timing to CSP/Antenna

The CSP is responsible for coherent processing of timestamped data. The critical timing accuracy thus is at the location where the timestamp is applied – the digital backend (DBE) subsystem of CSP located at the antenna pedestal. Accurate timing is also required at the digitizer itself which is located at the antenna secondary focus. This document will describe a timing design which transfers central timing (synchronized to a hydrogen maser and referenced to GPS) from the Central Electronics Building (CEB) to the secondary focus at each antenna, and from there to the DBE in the pedestal. This system shall support:

- The overall system requirement of 10 nsec timing accuracy (SYS2002)
- The Central-to-RTD timing accuracy: 2 nsec (LRT1300)
- RTD to DBE timing transfer: 1 nsec (LRT1380)

Additional sources of timing accuracy degradation (including but not limited to GPS measurement accuracy), when added to the 2 nsec distribution timing accuracy, shall not exceed to 10 nsec system timing budget [AD11], [RD02]. (Also see section 5.4.4)

### 3.2.10 Spurious Narrowband Tones

As detailed in [AD01], the local oscillator requirement is to provide a local oscillator for each IRD module in the front end. The LO must be relatively high power (+13 dBm), low phase-noise, and having very low spurious levels, less than -103 dBc/Hz for all frequencies within 3.5 GHz of the carrier.

### 3.2.11 Mean Time Between Failure/Mean Time Between Maintenance

Failures are considered in the same category as maintenance, any equipment status that would require a human intervention to address. Thus, the mean time between maintenance period that covers both preventive maintenance and corrective maintenance such that [AD13], [AD11]:

- There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTG subsystem in the Central Electronics Building
- There is a minimum MTBF/MTBM of 3000 hours ***total*** for elements of the RTD subsystem in the Central Electronics Building
- There is a minimum MTBF/MTBM of 18520 hours ***total*** for elements of the RTD subsystem located at the antenna

In each of the three cases above, the sum of MTBFs of all modules and assemblies in the subsystem shall meet these limiting values.

## 3.3 Key risks

**Fiber Infrastructure and Long Baseline Phase Stability:** On the VLA site, the fiber infrastructure is low risk, insofar as the ngVLA will pursue an installation very similar to what has already been in use for the EVLA. Beyond the VLA site, there is risk due to the fact that as yet there is not a clear understanding of the existing fiber: installed fiber base, existing fiber ownership, opportunities for fiber lease. Additionally, for fiber runs that need to be newly developed, there are issues of cost, rights-of-way, commercial partnerships …etc. Additionally, the long baseline phase stability may depend on whether the distant MID stations are fiber connected or using standalone timing.

**LO Spurious:** The LO Spurious requirement is quite stringent, and will be challenging to meet for all bands over all RF and IF frequency ranges. The presence of low level spurious depends on the detailed design of the LO and how it interfaces with the IRD modules. The mitigation strategy is to conduct early prototyping tests to better assess the probability of the risk, and then conduct a cost/scope assessment if further risk mitigation is required.

## 3.4 Design assumptions

The design of the LO Reference and Timing work element described herein makes the following assumptions:

### 3.4.1 Configuration

- The array consists of 263 antenna stations, 19 in the small baseline array (SBA), 114 in the core, 54 on spiral arms, 46 on MID-baselines, and 30 in the long baseline subarray (LBS).
- The D-Configuration of Antennas is assumed [RD01] (note: future revisions are not expected to alter the recommended design approach set forth here).
- The following table details the Rev D Composition of ngVLA by number and type of antenna, type of connection to fiber networks, and distance from array center. Asterisk signifies area that is subject of further technical-cost study:

**Table 3 - Antenna Configuration**

| Sub-Array | Number of Antennas | Antenna diameter | Trenched fiber | Commercial dark fiber | Internet Service Provider | Distance from Array Center |
|---|---|---|---|---|---|---|
| MA - Core | 114 | 18m | 114 | 0 | 0 | 0–1 km |
| MA - Spiral Arms | 54 | 18m | 54 | 0 | 0 | 1–30 km |
| Mid-Baseline | 46 | 18m | 0 | 30* | 16* | 30–1000 km |
| *Main Array Total* | *214* | | *168* | *30** | *16** | |
| Small Baseline Array (SBA) | 19 | 6m | 19 | 0 | 0 | 0.1 km |
| Long Baseline Subarray (LBS) | 30 | 18m | 0 | 0 | 30 | 1050–5300 km |
| *ngVLA Total* | *263* | | *187* | *30* | *46* | |

### 3.4.2 Fiber Infrastructure

- Fiber connection will be made for all stations up to 300 km. Beyond 300km, additional fiber connection will be made if permitted by cost and technical feasibility.
- LBS and some of the furthest out MID stations will not have a direct connection to the central building for supply of LO and Timing. (Instead local clock and timing and data backhaul by networked fiber). From the table above, the number of antennas currently in this category for the MID array is 16, but a full tradeoff will be conducted prior to the LO Reference and Timing FDR.
- Up to 30km, inclusive of the SBA, Core and Spiral arms, fiber can reach each antenna station in a direct shot with no need for amplification or repeaters.
- From 30km-300km, bidirectional fiber amplifiers (BiDi-EDFAs) and optical-electronic-optical (OEO) repeaters will be required.
- The optical fiber transmission for both the frequency and timing links allows bidirectional transmission

### 3.4.3 Architecture

- Central LO Reference and Timing instrumentation are assumed to be in the same central building as the CSP, but no further assumptions are made as to whether the equipment is in the same room, same racks, sharing floor space, ventilation, power, etc.
- The references are generated and synchronized in the central building, and a frequency reference and timing signal are provided to the CSP. The references are then distributed with all necessary amplification, buffering, splitting, etc., and the required signals are transmitted to each antenna station.
- The central building has space available for housing the central RTG and RTD subsystem equipment and is an RFI shielded structure. Building requirements pertaining to the RTG and RTD subsystem will be included in the ICD with ngVLA Infrastructure group.
- Long Baseline stations have their own central frequency and timing sources, one for each group of three stations at a single site.
- The RTG subsystem is nominally located in the Central Electronics building. Additional versions of the RTG will be located at LBS station location, and possibly for far out MID stations not directly connected to the ngVLA fiber network.
- The RTD subsystem is located at (a) the central building (b) midpoint repeater stations and (c) the antenna stations. For LBS stations and remote MID stations the "central" part of the RTD will be similar but with a much lower fan-out. (For example, at LBS sites, where there are three antenna stations, reference sources and RTD modules will fan-out to each of the three antennas).
- For long baseline array stations, and any other stations not connected to the central building by fiber, the design will be based on a single standalone frequency reference, but will mirror the main array design to the extent possible (i.e. distribution of the reference to local stations)

### 3.4.4 Frequency and Timing transfer

- A central GNSS time standard is co-located with the primary frequency reference
- A system clock is derived from the primary frequency reference, and differences between the system clock and GNSS time will be monitored and logged
- The system clock and frequency reference are distributed to the CSP in the central building
- The system clock and frequency reference are distributed to each antenna station which is connected by fiber, as well as a continuous monitoring of those signals so that fluctuations in the one-way propagation (due especially to thermal effects) can be mitigated.
- The accurate transfer of time and frequency can be made by direct link or by daisy chain
- Additional remote station clocks and frequency reference will be generated for stations that are too distant for connection by fiber

- It is most economical to transfer just one frequency reference
- There is no gain in design simplicity to make the frequency reference tunable, and this would also increase cost, so a fixed frequency reference is transmitted
- Synthesizing the small frequency offset (unique to each antenna) centrally adds cost and technical risk to the design and thus has not been adopted

#### 3.4.5 Antenna Time and Frequency

- The ATF phase noise for local oscillators and digitizers refers to phase noise relative to a "perfect" reference. The assumption is that any opportunity for coherent common mode antenna-to-antenna phase noise is eliminated by (a) very long fiber links, (b) narrow band PLLs at the antenna, and (c) antenna-based frequency offsets.
- A receiver and water vapor radiometer are located on the elevated moving structure of the antenna
- A digital backend is located in the antenna pedestal
- Each antenna station will be equipped with a receiver "package" consisting of six frequency bands, with each band comprising a feed horn and a low-noise cryogenic amplifier assembly. The receivers are located on the feed arm at the secondary focus. Located physically just behind this cryogenic receiver will be additional electronics enclosures housing nineteen highly engineered assemblies that combine the functions of downconversion and digitization (*these are called IRD modules: integrated receiver-digitizer*). The receiver and the additional electronics assemblies have strict size, weight and power limits and are located in a front end enclosure (FEE) that is in an exposed mounting on the telescope near the secondary focus.
- There are 20 IRD modules, 19 of which require a unique LO frequency, and all of which require a digitizer reference frequency

# 4 Product Structure

Product breakdown structure and interface definitions for the RTG, RTD, and ATF subsystems have been flowed down from the system architecture description [*] and N^2 Interface Definitions [*].

## *4.1 Product Context*

### 4.1.1 Product Context RTG

The Reference Timing and Generation subsystem product context diagram is shown in Figure 2. The RTG has five major products as follows:

a. Maser and GNSS sources at the Central Electronics Building to generate a stable common frequency source for the system and to generate an accurate central system clock domain.

b. Fixed frequency transfer sources for the transmission of fixed frequency reference to central signal processor and all antennas.

c. Frequency transfer offset sources: for support of antenna offset frequencies for LO and digitizers – option for central generation (not part of design baseline)

d. Time transfer sources for transmission of various time references for CSP and all connected antennas.

e. Frequency reference and time generation equipment for all stand-alone antennas (antennas not connected via direct fiber to the Central Electronics Building) and for LBS stations.

The RTG also has four major interfaces, with ngVLA Site buildings, Monitor and Control system, Central Signal Processor, and Reference and Timing Distribution.

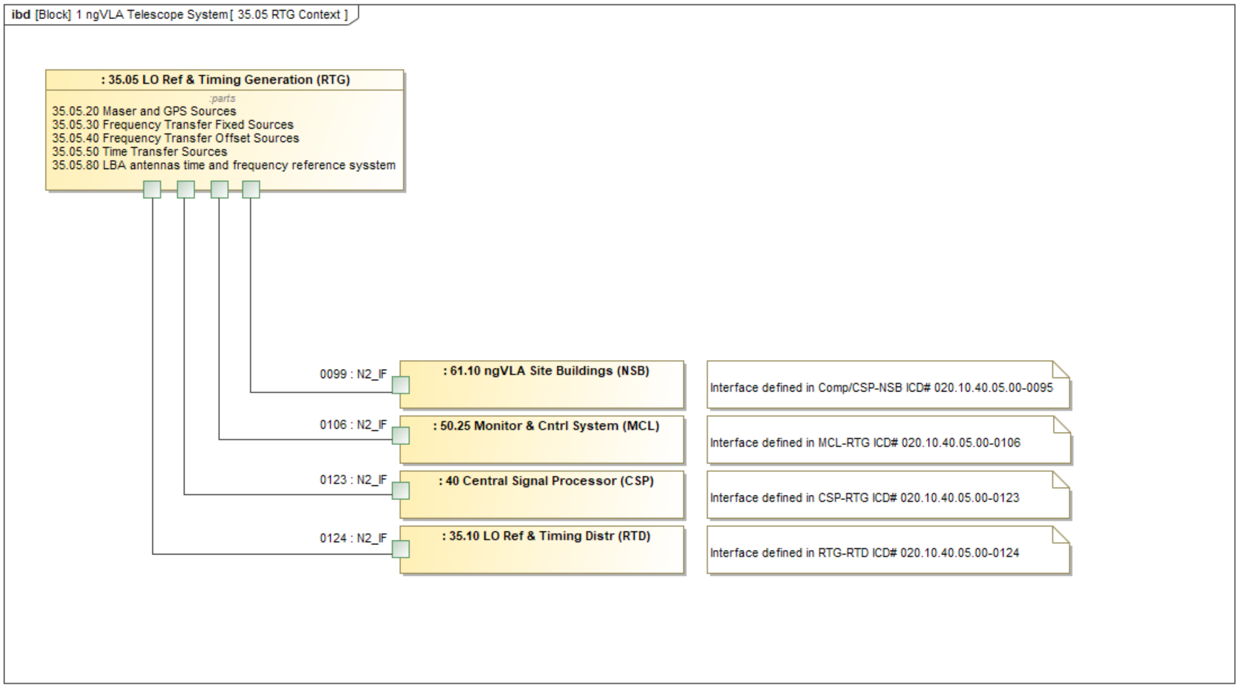


**Figure 2 - Reference and Timing Generation subsystem product breakdown, and interfaces with other antenna subsystems**

### 4.1.2 Product Context RTD

The Reference Timing and Distribution subsystem is shown in Figure 3. The RTD has seven major products including separate product numbers for long haul equipment at a repeater station and long haul repeater equipment located at an antenna station. The RTD also has ten major interfaces, four with Antenna Electronics IPT (BMR, EEC, PSU), three with CSP and Timing IPT (RTG, ATF, DBE), and additional interfaces with ngVLA Site buildings, fiber infrastructure, and HIL/Monitor and Control system. Note that the design assumptions in Section 3.4.5 include

1. digital backend located in antenna pedestal, and
2. receiver and downconverters at secondary focus area.

The current design plan does not include an RTD interface directly with the DBE in the pedestal, but is shown in the diagram as an option for future design flexibility. At the secondary focus front end enclosure, the RTD subsystem terminates at the completion of the round-trip phase correction, and supplies a reference frequency to the ATF subsystem which then generates LO and digitizer clocks.

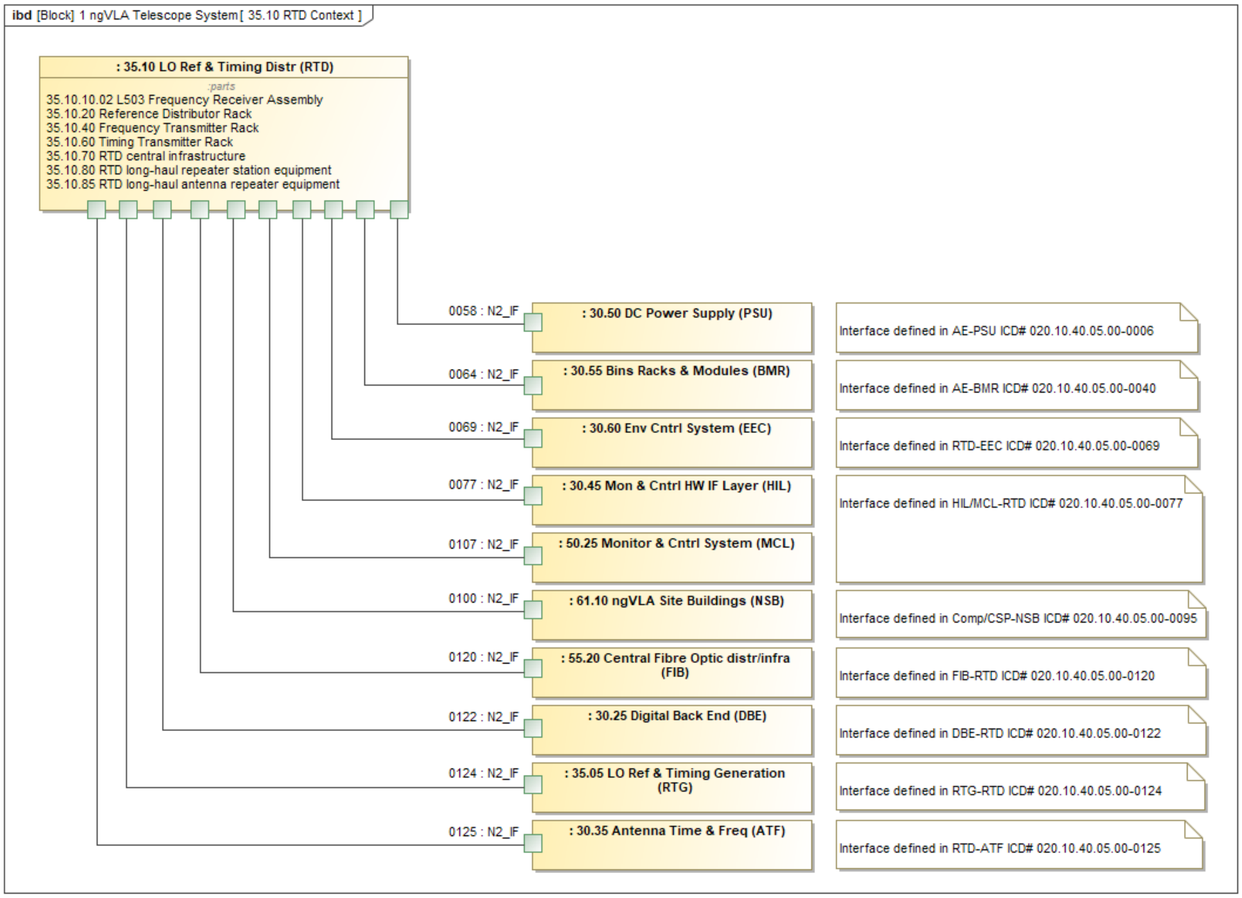


**Figure 3 - Reference and Timing Distribution subsystem product breakdown, interfaces with other antenna subsystems.**

### 4.1.3 Product Context ATF

The Antenna Time and Frequency (ATF) subsystem is shown in Figure 4. The ATF performs the distribution of reference and timing signals for all components located on the antenna. The ATF also applies per antenna small frequency offsets. The supply of the LO and sampling clock for Band 1 to Band 6 receivers (IRDs) is implemented as 20 modules located in the front end enclosure at the secondary focus.

There are nine major associated interface definitions. All of these except for the RTD subsystem are interfaces with the Antenna Electronics IPT which supplies DC power, temperature control, mechanical housings, and a monitor and control hardware layer allowing the ATF equipment to operate with a serialized data interface for monitor and control.

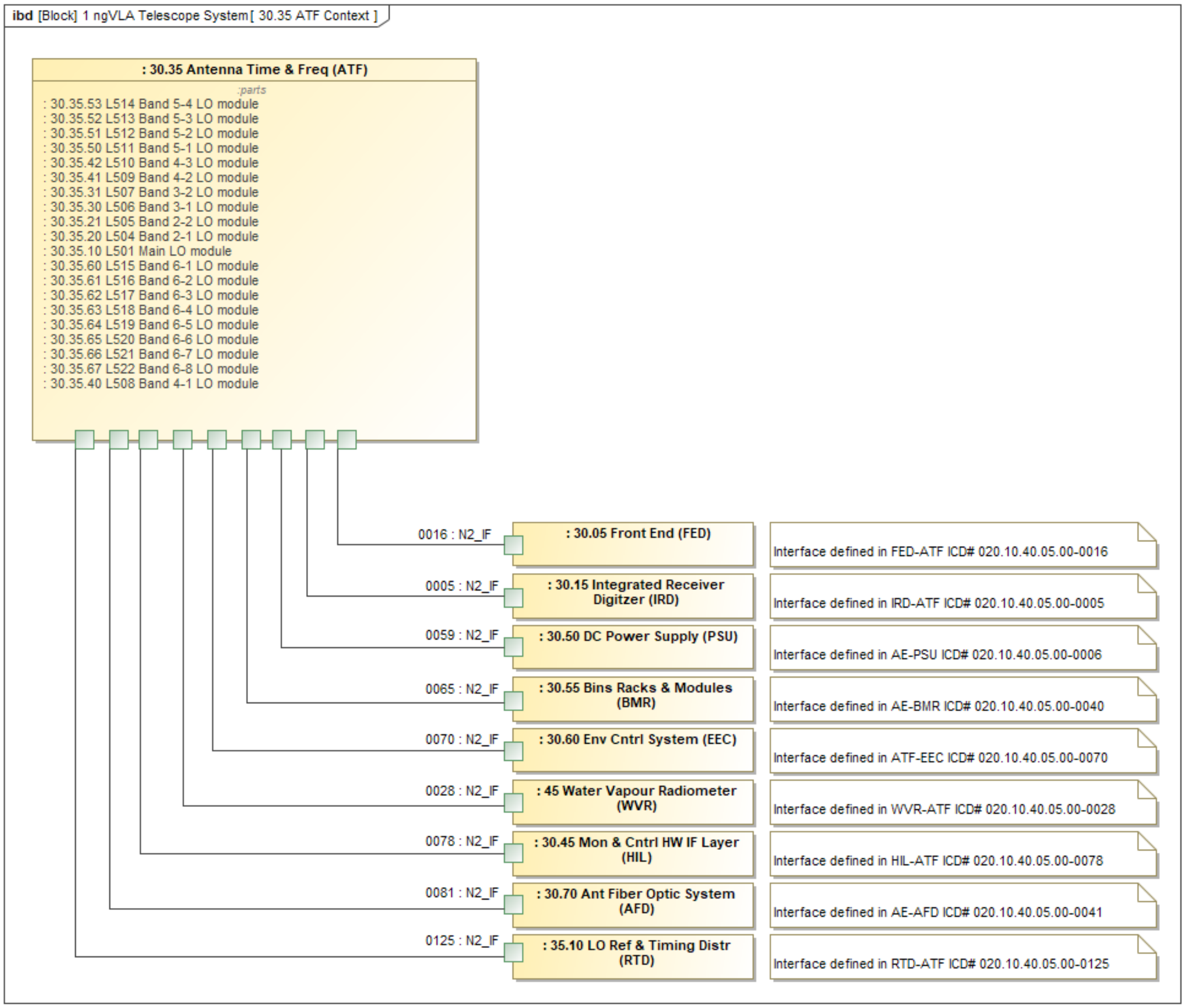


**Figure 4 - Antenna Time and Frequency subsystem product breakdown and interfaces with other antenna subsystems.**

### 4.1.4 Product Breakdown Structure

ngVLA Systems Engineering (SE) has implemented a Product Breakdown Structure (PBS) consisting of five levels [AD15, AD16]:

- Level 1 – Facilities
- Level 2 – System
- Level 3 – Subsystem
- Level 4 – Component
- Level 5 – Part

For LO Reference and Timing a partial listing of the PBS is included below in Table 4. The PBS may be expected to change in the future as the array design matures, so configuration item numbering shown in Table 4 should always be checked against the latest project PBS. The PBS is used throughout the project and support SE processes for document numbering, logistics, inventory, interfaces, modeling and configuration data.

**Table 4 - Partial list of configuration item numbers for the LO Reference and Timing subsystems (Location key: BLD.CEB=Central Elec Building, ANT.FED=Antenna Feed Indexer) (Type key: LRU=Line Replaceable Unit, SRU=Shop Replaceable Unit)**

| Configuration Item Number | Component | Location | Type |
|---|---|---|---|
| 35.00.00.00 | Reference signals | | |
| 35.05.00.00 | LO Reference & Timing - Generation (RTG) ***Subsystem*** | | |
| 35.05.20.00 | Maser and GPS Sources | BLD.CEB | Rack(s) |
| 35.05.20.02 | Hydrogen Maser | BLD.CEB | LRU |
| 35.05.30.00 | Frequency Transfer Fixed Sources | BLD.CEB | Rack |
| 35.05.30.02 | Narrow Linewidth Laser | BLD.CEB | LRU |
| 35.05.30.04 | Fixed Microwave Source | BLD.CEB | LRU |
| 35.05.50.00 | Time Transfer Sources | BLD.CEB | Rack |
| 35.05.50.02 | Timing Laser | BLD.CEB | LRU |
| 35.05.50.04 | Optical Modulator PSK | BLD.CEB | LRU |
| 35.05.50.06 | PN Code-1 Modulator | BLD.CEB | LRU |
| 35.05.80.00 | LBS antennas time and frequency reference system | LBS | Rack |
| | | | |
| 35.10.00.00 | Reference and Timing Generation (RTD) ***Subsystem*** | | |
| 35.10.40.00 | Frequency Transmitter Rack | BLD.CEB | Rack |
| 35.10.40.02 | Frequency Transmitter | BLD.CEB | LRU |
| 35.10.60.00 | Timing Transmitter Rack | BLD.CEB | Rack |
| 35.10.60.02 | Time Transmitter | BLD.CEB | LRU |
| 35.10.60.20 | Timing Controller | BLD.CEB | LRU |
| | | | |
| 30.35.00.00 | Antenna Time and Frequency Subsystem (ATF) ***Subsystem*** | | |
| 30.35.20.00 | L504 Band 2-1 LO | ANT.FED | SRU |
| 30.35.21.00 | L505 Band 2-2 LO | ANT.FED | SRU |
| 30.35.10.00 | L501 LO module | ANT.FED | SRU |

# 5 LO Reference and Timing Design

## *5.1 Summary of Design*

### 5.1.1 Subsystems Descriptions

LO Reference and Timing consists of three separate subsystems:

- Reference and Timing Generation (RTG): A set of reference and timing sources requiring high degree of stability and low phase noise. ***Described in Section 5.2***.
- Reference and Timing Distribution (RTD): The means of transmitting the RTG sources from the central building to the remote antenna while preserving phase and timing accuracy. RTD equipment appears in the central building, on the fiber link, and at the antenna. ***Described in Section 5.3 and 5.4.***
- Antenna Time and Frequency (ATF): Equipment at the antenna which functions to generate the local oscillator and digitizer references and/or sources from the RTD receivers. **Described in Section 5.5.**

Additionally, there is a subset of equipment that is:

- devoted to boosting the time and frequency signals on the long haul fiber links
- supporting the Long Baseline Subarray (LBS), with antenna distances at continental scale

Design provision to support these additional functions is ***described in Section 5.6.***

### 5.1.2 Top Level LRT Design at the Central Building

The top level design if the LRT is shown in Figure 5. A hydrogen maser provides low noise timing (phase-tracked over long term by GPS). Frequency and timing references synchronized with the maser are then impressed on optical fiber, with a frequency source modulating an MZM modulator and a timing source modulating a timing link with pseudo-noise codes.

The frequency link (top) is first split 32 ways after a PM fiber amplifier. Each of the 32 outputs will be a frequency source for up to eight antennas. The figure shows each of the eight frequency transmitters. Each output transmits over a bidirectional link and is the starting point and terminus for a round trip phase measurement of the link. The final element is a wave division multiplexer which combines the frequency transfer and timing transfer onto a single fiber. Each fiber is then mapped to a single antenna.

The timing link (bottom) takes as input the system 1 PPS timing pulse and 10 MHz frequency reference. The key module is called the master modulator/demodulator. The unit applies modulation to each of eight outgoing fibers consisting of a carrier reference encoded with a pseudo-random-noise (PRN) code. These also traverse the fiber in a round trip way with outgoing and incoming fibers diplexed at a circulator. Each return signal is detected and the round-trip time is measured using noise correlation technique. Half of the measured delay is then encoded as an overlay in the packet header of the modulator. Thus, for eight antennas there is one modulator, one PRN code, but eight measured delays encoded in the header. Each remote timing receiver "knows" which timing correction to apply based on configuration assignment.

The figure only shows one each of the frequency transmitter, timing transmitter, and WDM – each of which will occur up to 256 times. (Note: the number of ngVLA antennas is 263 but at least 30 of these comprising the LBS will not be connected to the central time and frequency so the maximum number of links needed is less than or equal to 236).

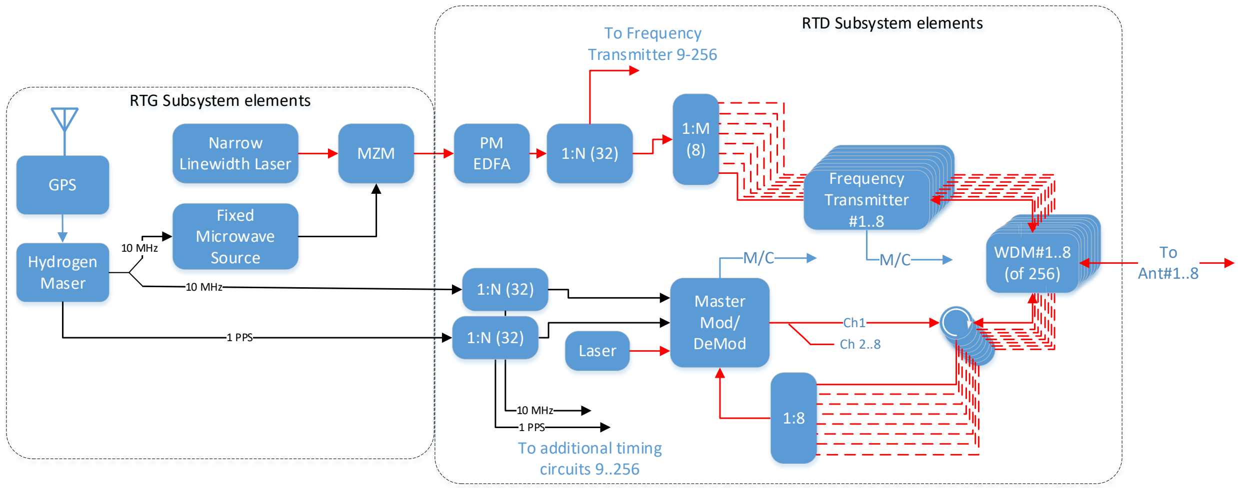


**Figure 5 - Top Level Block Diagram of LRT Design in Central Building**

### 5.1.3 Top Level LRT Design at the Antenna

The top level design for the LRT at the antenna is shown in Figure 6. The following functional blocks are shown in the figure:

- Frequency Receiver: Recovers transmitted frequency reference
- Timing Receiver: Recovers and corrects the transmitted timing pulse
- Frequency Reference Synchronization: Synchronizes antenna references to the transmitted frequency reference
- Timing Reference Synchronization: Develops 1 PPS antenna timing reference by discrete division of the transmitted frequency reference, while continuously measuring timing delay difference from the transmitted/corrected reference. Can be reset to nearest edge of transmitted/corrected reference.
- LO for IRD: Phase locked LO modules for each of nineteen IRD downconverters
- Digitizer/DBE Clocking: Provides JESD204D compliant clock and timing to ADC and DBE

All of the functional blocks shown in Figure 6 will be located in the secondary focus front end enclosure, co-housed with the receiver downconverters. These functional blocks are all discussed in more detail in Sections 5.3, 5.4, and 5.5.

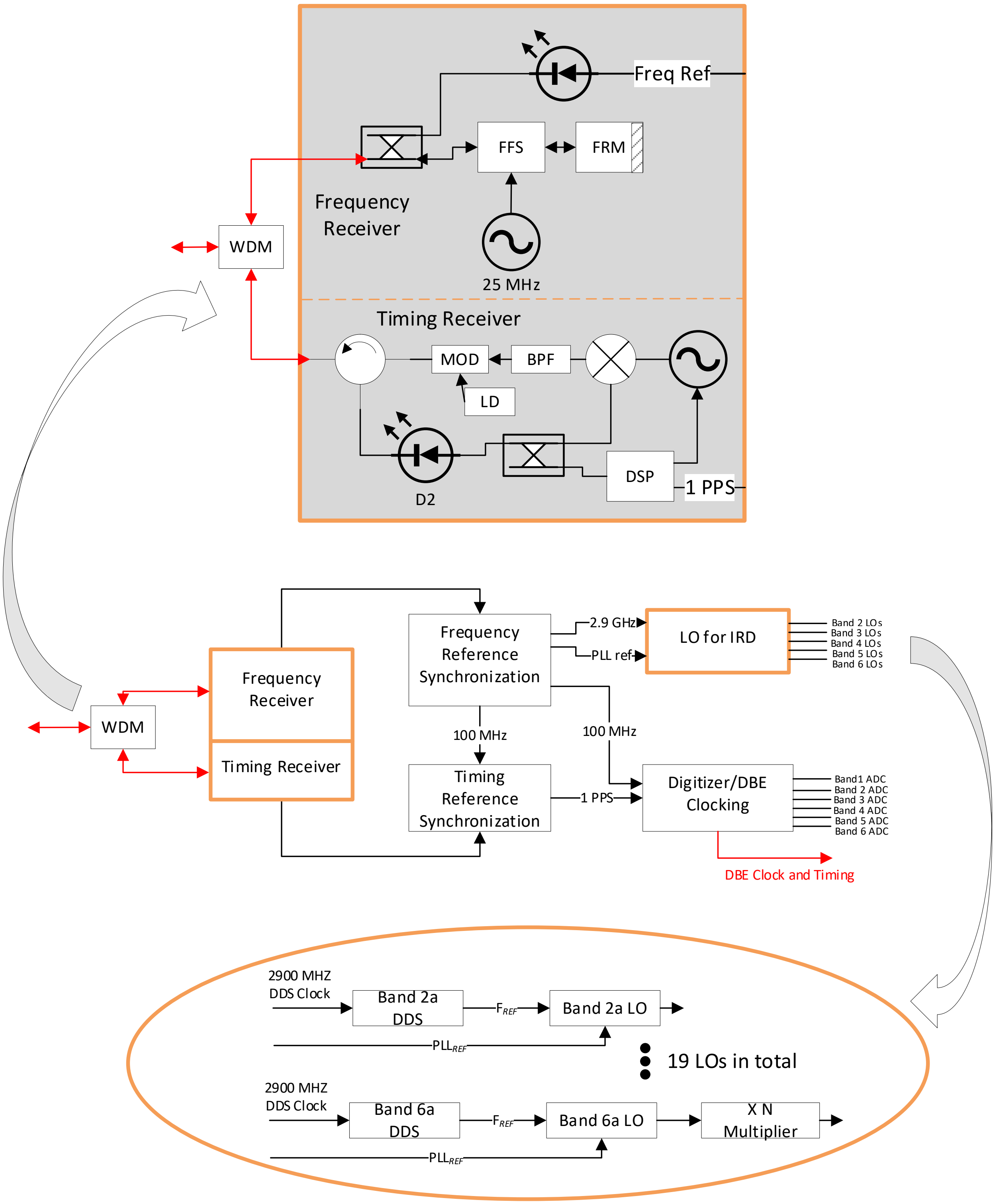


Figure 6 - Top Level Design of LRT at Antenna

### 5.1.4 Physical Design at Secondary Focus

For many reasons the secondary focus front end enclosure has critical size, weight and power requirements. One reason is that the enclosure is on the extended offset feed arm so there is a weight bearing limitation. The size is constrained by a desire to have short waveguide and cable lengths for low loss and low phase drift. And the power is constrained by the need to have tight thermal control. Thus, certain of the physical dimensions have been fixed early in the ngVLA development using careful estimation in cases when the final designs are not necessarily complete. Figure 7 is a rendering of the Front End Enclosure. The six circular apertures are the feed horn covers or lenses which mount flush with the cover of a cryostat. Additionally, four rectangular electronics modules shown as labelled:

- Utility Module: front End power supplies and monitor and control
- L501 Module: LO and Timing reference generation
- SA-501 Module: Band 5 and Band 6 downconverter and digitizer
- SA-502 Module: Band 1--4 downconverter and digitizer.

The front end enclosure is 1800mm wide X 1150mm deep X 600mm tall.

The L501 and SA502 are NRAO in-house mechanical design RFI shielded module with dimensions 508mm x 209 mm X [variable width from 50-150 mm] .

The SA501 is an NRAO in-house mechanical design RFI shielded module with current size of 762mm x 368mm x 99mm.

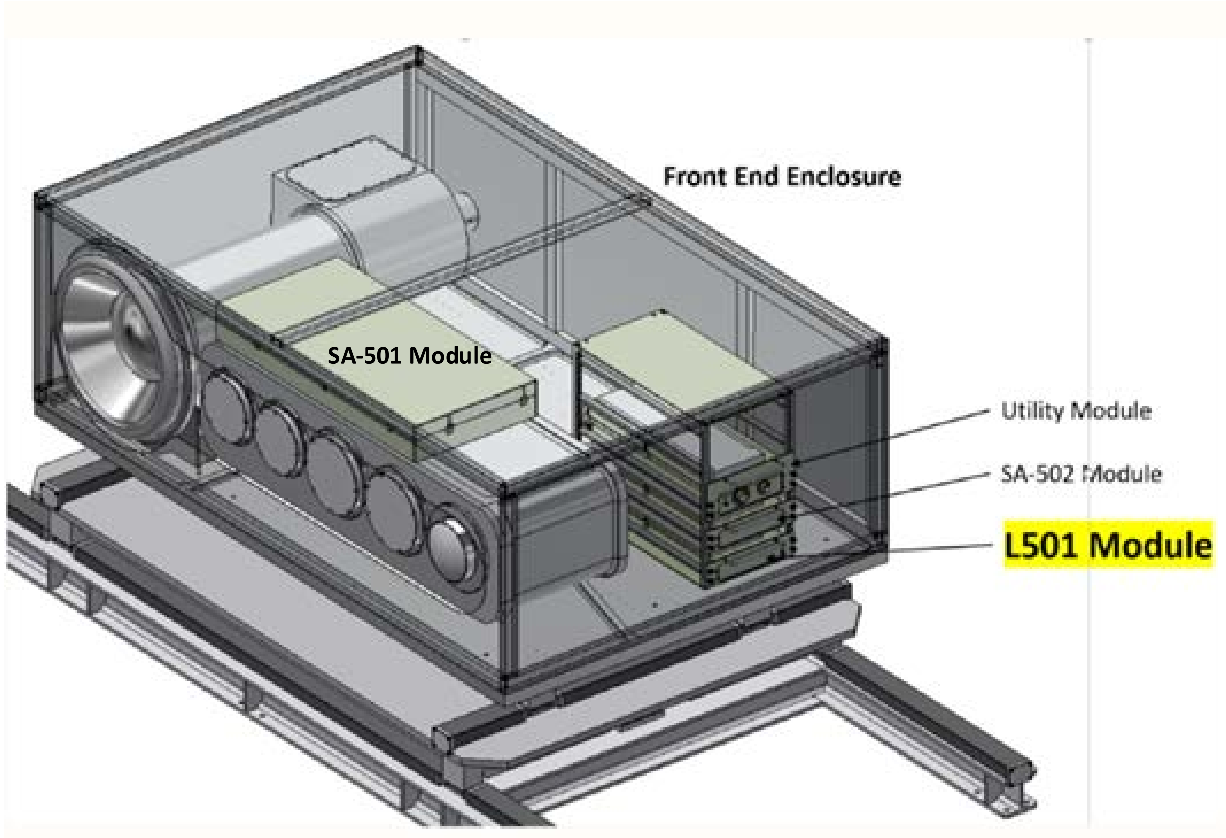


Figure 7 - Physical layout of Front End Enclosure

## 5.2 Central LO (RTG)

### 5.2.1 Driving Requirements

The LO Reference and Timing requirements document [AD13] encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTG subsystem design.

| Parameter | Value | Req. # |
|---|---|---|
| LO Phase Noise | < 76 fsec integrated from 1 Hz to maximum IF frequency offset<br>Goal < 50 fsec | LRT1240 |
| This is the phase noise requirement directly flowed down from Systems Requirements. The phase noise is most important at the antenna local oscillator and digitizer clock. References generated by RTG in the central building must be consistent with meeting the antenna LO phase noise requirement. In most cases the design of a distributed LO or clocking system will utilize phase lock loops or jitter cleaners in the distribution that make parts of the original central source phase noise spectrum irrelevant. So the interpretation of this requirement is that the RTG source phase noise spectrum must be consistent with meeting the overall system phase noise requirement at the antenna. | | |
| | | |
| LO Phase Drift | < 42 fsec at 300 s (linear term removed) | LRT1250 |

| | | |
|---|---|---|
| | < 250 fsec absolute | |
| This requirement is for applicable to the entire distributed LO system for ngVLA. Most significant sources of LO phase drift may be expected to be incurred in the RTD and ATF subsystems. What is important for the RTG subsystem is that the frequency references be reasonable compact and well-regulated thermally, with careful attention to cables and/or components that could cause spurious thermal phase drifts. Additionally, the central reference source frequency stability should meet this requirement, in anticipation of the need for far-out ngVLA antennas stations to run on independent frequency sources (i.e. H-maser). | | |
| | | |
| RTD Input Frequency Accuracy from RTG | The frequency reference supplied from RTG to the RTD subsystem must have long term accuracy from T=1 to 1000 seconds<br>T=1 sec AV<=2e-13<br>T=100 sec AV<=1e-14<br>T=1e3 sec AV<=2e-15 | LRT5220 |
| This requirement pertains specifically to the need to maintain adequate coherence when there are far-out antennas that are not sharing a single frequency source. Thus, the RTG source must have very high coherence. The stability set forth here is meant require "hydrogen maser or better" stability. (It is estimated that an H-maser will give from 1-3% coherence loss at 116 GHz) | | |
| | | |
| RTD Frequency Input Stability from RTG | Phase Noise at offset frequency from 1 Hz to 100 MHz < 50 fsec, goal < 30 fsec rms integrated phase noise | LRT5230 |
| Note that the transfer of RTG oscillator stability to RTD and thence to ATF subsystem depends on the phase lock loop bandwidths at each stage. This requirement specifies 100 MHz offset frequency in case the antenna PLL locks to the fiber frequency transfer with such a wide bandwidth. If in the final design the PLL bandwidth is less than this then the upper frequency bound of the offset frequency in this requirement may be derated. | | |
| | | |
| RTD Timing Stability from RTG | Timing accuracy to RTD shall be within 0.3 nsec. | LRT1350 |
| For an overall timestamp accuracy of 10 nsec, each part of the timing transfer chain must be well controlled. This requirement stipulates that between the creation of the reference point for the central timing pulse and the input of the RTD, the accuracy shall be 0.3 nsec. As an example, this is equivalent to ~ 10cm cable length. Common mode paths and calibration can be used to meet this requirement. | | |
| | | |
| Timing to CSP | Timing accuracy to CSP shall be within 2 nsec (goal of 1 nsec)<br><br>(Relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging)<br><br>Note: If data timestamps are tagged at the antenna, this requirement can be relaxed | LRT1300 |
| At this point in the project it is firmly planned that timestamps will be applied at the telescope. Therefore, the timing accuracy of 2 nsec shall be applicable to the DBE input rather than the central CSP. In fact, the central CSP does not currently envisage the need of any timing input from RTG, but rather can rely on network time. If a future need arises it will be simple to make a 1 PPS available to CSP by a short fiber connection via same method as will be in use for the station timing transfer. | | |

| | | |
| --- | --- | --- |
| Availability | The MTBF and MTTR for the RTG and central RTD parts are TBD. They should support a system budget to achieve 95% system availability | LRT2305 |
| The RTG shall be designed with some combination of hot-spare, hot-swap, redundant and backup power, as needed to meet this requirement. | | |
| | | |
| Mean Time Between Failure/Mean Time Between Maintenance | The RTG and RTD subsystem shall have a MTBM of 3000 hours (Note: these values will be derived from a reliability analysis, driven by maintenance workload requirements)<br>Here failures are considered in the same category as maintenance, any equipment status that would require a human intervention to address | LRT2305, LRT2310 |
| | | |
| Network Time to MCL/HIL | RTG to supply timing signal for PTP network timing | LRT1330 |
| | | |

Note that the RTG subsystem establishes central time and frequency functions but does not provide tuning, offset frequencies, or switching. Thus, the critical requirements listed above mainly concern with: noise, stability, and accuracy; rather than, say: tuning ranges, return-to-phase, and switching times. These latter types of requirements will be more prominent in the RTD and ATF subsystems.

### 5.2.2 Proposed Block Diagram

A proposed block diagram for the RTG subsystem is shown in Figure 8. The primary functions involve the synchronization and distribution of the 10 MHz frequency reference and the 1 PPS timing signal.

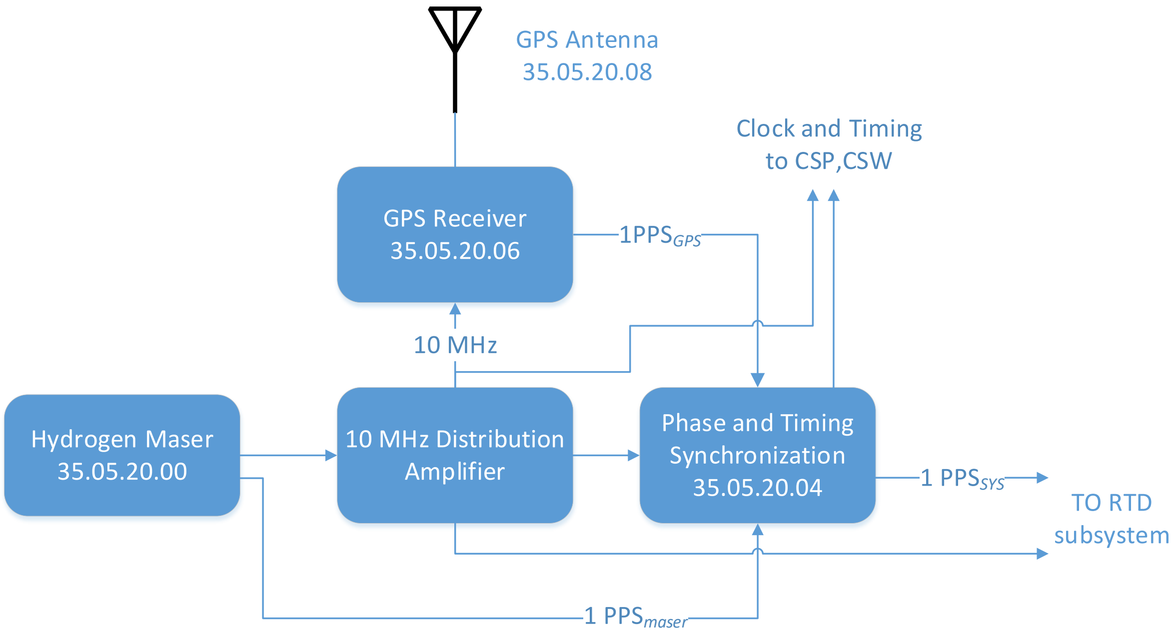


**Figure 8 - Block Diagram of RTG subsystem**

The hydrogen maser provides the highly coherent frequency reference which is distributed via the RTD subsystem to all antennas. In addition, the H-maser will provide a 1 PPS output synchronized with the 10 MHz maser output frequency. Separately, a GPS receiver measures time of day and produces its own 1 PPS. The $1PPS_{maser}$ and $1PPS_{GPS}$ will, in general, track each other but with a slow drift. This drift can be monitored by counters in the "Phase and Timing Sync" module. This module can reset the $1PPS_{SYS}$ as needed (between observations) to the nearest H-maser clock edge to the $1PPS_{GPS}$. Thus, at all times, the 1 PPS remains synchronized with an H-maser clock edge. The frequency reference, 1 PPS, and timecode will be made available to the CSP and CSW subsystems as needed. It is not expected that cable lengths for 1 PPS will be critical for timing in the central building (since timestamping is done at the antenna), however, if needed these cable lengths can be calibrated or compensated.

Note: some or all of the functionality outside of the box labeled "Hydrogen Maser" (as shown in Figure 8, may be included as part of the as-delivered H-maser assemblies. Both of the leading maser manufacturers, Microchip and T4Science, have extensive capability in other timing products.)

### 5.2.3 GNSS Receiver

GNSS receivers are ubiquitous and relatively inexpensive. A unit will be chosen that has the required timing accuracy, data formats, remote interface, and signal input/output options. As an example, the Septentrio PolaRx5TR could be a placeholder until the full ngVLA specification and interface requirements are defined.

### 5.2.4 H-Maser

For ngVLA antenna that are part of the long baseline array, the baselines are continental in length and a direct real-time frequency transfer by optical fiber would be prohibitively expensive and would have significant technical challenges even if it were not too costly. This is also the case for far out stations of the mid-baseline array. A decision on fiber frequency transfer to these stations will be made on a cost-performance tradeoff. In both cases (a) all of the long baseline array antennas and (b) the furthest-out stations of the MID array, the best alternative is the use of standalone timing based on a hydrogen maser for long term stability. Of course, the central building will also have a hydrogen maser. And as a note, the long baseline array consists of thirty antennas in ten groups of three. Each group of three requiring only one hydrogen maser with time and frequency transfer between each antenna in these groups of three.

Active hydrogen masers are the only viable commercial clock that will provide the coherence level which will allow ngVLA to meet the ambitious frequency stability requirements (i.e. LRT1250, LRT5220 as detailed above).

Hydrogen masers are: expensive, full rack size, heavy, have good reliability, have few (2) well established vendors, require a controlled environment, and provide excellent performance. In addition, there is a long NRAO institutional use of H-masers that is well documented [RD06-RD09].

### 5.2.5 Alternatives to H-maser

Alternatives to H-maser have been considered. We first consider commercially available clock/sources. Referring to Table 5, the first line is the hydrogen maser. Each of the next eight successive lines is another commercial RF source. Each also has a higher Allan deviation and would therefore not qualify for a standalone ngVLA frequency source. The last two are the cryogenic sapphire oscillator (CSO) and optical clocks. The former is like the H-maser a commercially available source that has been developed over decades. These are available commercially from two companies: QuantX and FEMTO engineering. However, note that the Allan deviation is worse than the H-maser above 100 seconds, and in addition these are more complex, require more maintenance, and are more expensive than H-masers. Finally, optical clocks have long been projected to become superior to microwave sources (like H-masers) on short time scales, but as yet have not been developed to be both portable and commercial. This category of advanced commercial optical clock is on the near horizon [RD10] and would offer superior stability, but (a) the cost may initially be prohibitive and (b) the performance reliability in terms of guaranteed continuous operation would not initially be expected to compete with H-masers.

**Table 5 - Commercial and future sources of highly coherent microwave frequency sources**

| Type of Oscillator | Product name | $\sigma_y(T)$ $T = 1s$ | $\sigma_y(T)$ $T = 100s$ | $\sigma_y(T)$ $T = 1\,day$ | Reference |
|---|---|---|---|---|---|
| Active Hydrogen Maser | iMaser3000 | 8e-14 | 3e-15 | 1e-16 | https://www.t4science.ch/ |
| Passive Hydrogen Maser | PHM | 7e-13 | 8e-13 | 1e-14 | Space.leonardo.com |
| Cold Rubidium | Spectra Dynamics cRb | 5e-13 | 8e-14 | 3e-15 | https://spectradynamics.com |
| Cold Rubidium | Tiqker Cold Rubidium | 3e-13 | 3e-14 | < 5e-15 | https://www.infleqtion.com/tiqker |
| Cold Rubidium | QuantX Cold Rb | 3e-13 | 3e-14 | ~3e-15 | www.quantxlabs.com |

| Type of Oscillator | Product name | $\sigma_y(T)$ $T = 1s$ | $\sigma_y(T)$ $T = 100s$ | $\sigma_y(T)$ $T = 1\ day$ | Reference |
|---|---|---|---|---|---|
| Cesium Clock | Oscilloquartz OSA 3235B | 1.2e-11 | 2.7e-12 | 8.5e-14 | www.oscilloquartz.com |
| Chip Scale Atomic Clock | Microchip SA55 | 3e-11 | 3e-12 | 2.5e-11 | www.microchip.com |
| Rubidium | Accubeat AR133 | 5e-12 | 2.5e-12 | 2e-12 | www.accubeat.com |
| OCXO | Vectron OX-175 | 3.3e-12 | 7e-12 | 5e-9 | www.vectron.com |
| OCXO | Accubeat USO | 5e-13 | 5e-14 | 8e-12 | https://www.accubeat.com/uso |
| Cryogenic Sapphire Oscillator | QuantX Labs | 6e-16 | 8e-16 | >1e-14 | www.quantxlabs.com (and FEMTO engineering) |
| Optical Clocks | research | <=1e-14 | --- | --- | [RD10] |

All of the sources listed in Table 5 are standalone clocks. There is one further possibility which is to use a clock delivered by two-way-satellite time and frequency transfer. In this case a two-way phase measurement is made between the central and remote station and this can be used to steer an oscillator at the remote station. These have not been thoroughly investigated. However, to our knowledge no such system has been built that could meet the remote station performance of an H-maser. And these would require considerable development and operational cost in any case.

### 5.2.6 H-Maser Peformance/Cost/Procurement

Costs of hydrogen masers is approximately $300K. This is based on historical purchases rather than new or recent quotations. New units have very good reliability, design redundancy and 20 year design lifetime.

### 5.2.7 RTG for Standalone Stations

For standalone stations, the RTG block diagram will be largely unchanged. All of the blocks from Figure 8 remain, and only the interfaces change: no CSP interface; RTD interface will be different since there will be a maximum of three antennas per H-maser for the ngVLA long baseline array.

### 5.2.8 Hydrogen Maser Allan Deviation and Coherence Loss

There are two known manufacturers of state-of-the-art active hydrogen masers. Form published datasheets we plot the Allan deviations below.

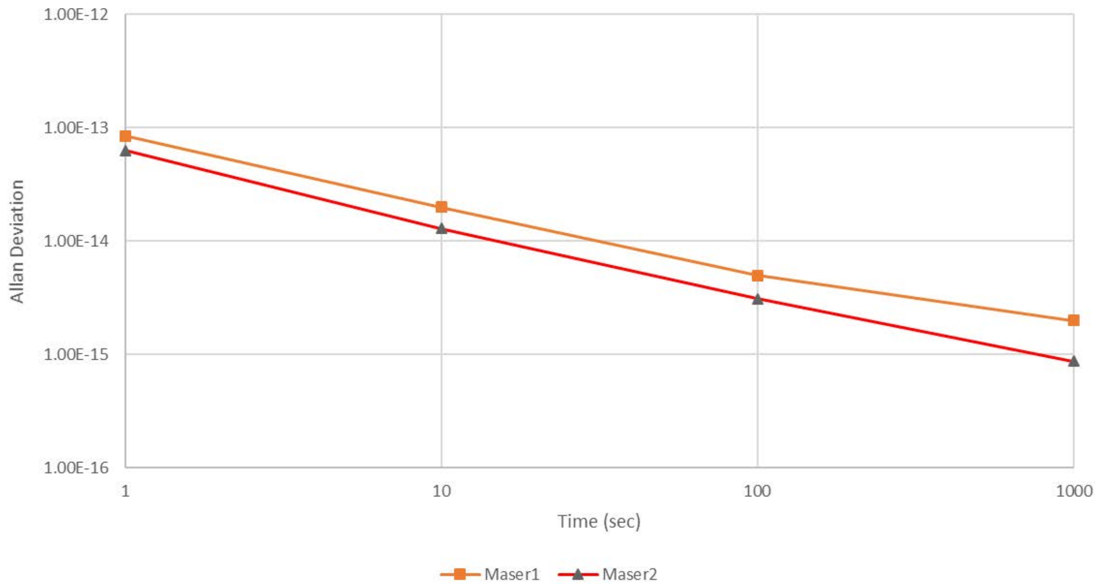


Figure 9 - Allan deviation of H-masers from datasheet

These curves can be roughly approximated by the equations:

$$ADEV = \sqrt{\alpha_p}/_{\tau} + \sqrt{\alpha_f}/_{\sqrt{\tau}}$$

And for the top curve $\sqrt{\alpha_p}$=$\sqrt{\alpha_f}$=3e-14, and for the bottom curve $\sqrt{\alpha_p}$=3e-14, $\sqrt{\alpha_f}$=5e-14
Then the combined expression for coherence degradation due to both white frequency noise and white phase noise:

$$L_C = \left[\frac{\alpha_p}{6} + \frac{\alpha_f * T}{12}\right] * \omega_0^2$$

For the bottom curve there is a 1% coherence loss at 300 seconds integration time, and for the top curve there is a 3% coherence loss at 300 seconds integration time.

## 5.3 Frequency Transfer (RTD)

A frequency transfer system is required to supply a reference frequency to each antenna station. The antennas are linked to the central building by fiber optic. The frequency reference is delivered to the antenna by fiber, while a measure of the round trip phase is recorded for downstream compensation (assuming the one-way phase is exactly half of the two-way phase). For the set of antennas for which the distance and cost to connect via fiber is too high, these antennas will similarly be provided a transmitted frequency reference from an independent frequency source.

### 5.3.1 Frequency Transfer Key Perfomance Requirements

The LO Reference and Timing requirements document [AD13] encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTD frequency transfer subsystem design.

<table>
<tr><th>Parameter</th><th>Value</th><th>Req.#</th></tr>
<tr><td>LO Phase Noise</td><td>< 76 fsec integrated from 1 Hz to maximum IF frequency offset<br><br>Goal < 50 fsec</td><td>LRT1240</td></tr>
<tr><td colspan="3">This is the phase noise requirement directly flowed down from Systems Requirements. The phase noise is most important at the antenna local oscillator and digitizer clock. References provided by RTG in the central building must be consistent with ultimately meeting the antenna LO phase noise requirement. In most cases the design of a distributed LO or clocking system will utilize phase lock loops or jitter cleaners in the distribution that make parts of the original central source phase noise spectrum irrelevant. So the interpretation of this requirement is:<br>a) The RTG source phase noise spectrum provided as input to RTD frequency transfer subsystem must be consistent with ultimately meeting the overall system phase noise requirement at the antenna.<br>b) The RTD frequency transfer subsystem must transfer the phase noise from the central building to the antenna, over an appropriate portion of the frequency spectrum. For instance, if the output of the RTD frequency transfer subsystem at the antenna is used to lock an antenna local oscillator with a PLL bandwidth of 1 kHz, then the RTD phase noise spectrum used in verification of this requirement is DC-1 kHz. Phase noise above 1 kHz that is effectively filtered out may be ignored.</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>LO Phase Drift</td><td>< 59 fsec at 300 s (linear term removed)<br><br>< 1500 fsec absolute<br><br>RTD allocation presently 42 fsec at 300 sec</td><td>LRT1250</td></tr>
<tr><td colspan="3">This requirement is for applicable to the entire distributed LO system for ngVLA. Most significant sources of LO phase drift may be expected to be incurred in the RTD and ATF subsystems. In particular, in the RTD subsystem it is necessary to compensate for phase drift associated with the fiber link. The requirements noted above are applicable after the compensation is applied.<br><br>These requirements come from SYS1504, 1505, 5001 in “ngVLA System Requirements,” NRAO Doc# 020.10.15.10.00-0003-REQ:<br><br>SYS1504 The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds.<br><br>SYS1505 The absolute phase drift per antenna over 300 seconds shall not exceed 4 psec. Goal to meet this specification over 1000 seconds.<br><br>SYS1501 takes the relative (95 fsec) and absolute (4000 fsec) drifts and allocates them to different subsystems. The frequency transfer subsystem is allocated 1/5th of the total rms noise (i.e. 95/sqrt(5)=42 fsec) for residual noise and about ten percent of the absolute drift budget (4000 psec/sqrt(10) ~ 1.25 psec.) The LO is allocated 42 fsec also. The root sum of RTD and LO is then 59 fsec.<br><br>For absolute drift over 1000 seconds, $\tau = 1500$ fsec is equivalent to .0078 rad of phase scaled to a frequency of 1 GHz. For the frequency transfer system, the allowable absolute phase in 1000s will scale with the transmitted frequency: $\emptyset_{rad} \leq .0078 * f_{GHz}$</td></tr>
</table>

### 5.3.2 Frequency transfer design assumptions

- It is most economical to transfer just one frequency reference
- There is no gain in design simplicity to make the frequency reference tunable, and this would also increase cost, so a fixed frequency reference is transmitted

- Synthesizing the small frequency offset (unique to each antenna) centrally adds cost and technical risk to the design and thus has not been adopted
- The system clock and frequency reference are distributed to each antenna station which is connected by fiber, as well as a continuous monitoring of those signals so that fluctuations in the one-way propagation (due especially to thermal effects) can be mitigated.
- The accurate transfer of time and frequency can be made by direct link or by daisy chain
- Additional remote station clocks and frequency reference will be generated for stations that are too distant for connection by fiber
- There is no gain in design simplicity to make the frequency reference tunable, and this would also increase cost, so a fixed frequency reference is transmitted

### 5.3.3 Frequency Transfer Block Diagrams

The sketch below is included to capture the top level assumptions such as:

- 263 antennas grouped into the SBA, Central Core, Spiral Arms, MID-array and Long Baseline Subarray
- Long Baseline antennas and some MID antennas with standalone timing
- All other antennas with centralized common timing
- Frequency and 1 PPS timing references transferred from timing source to antenna

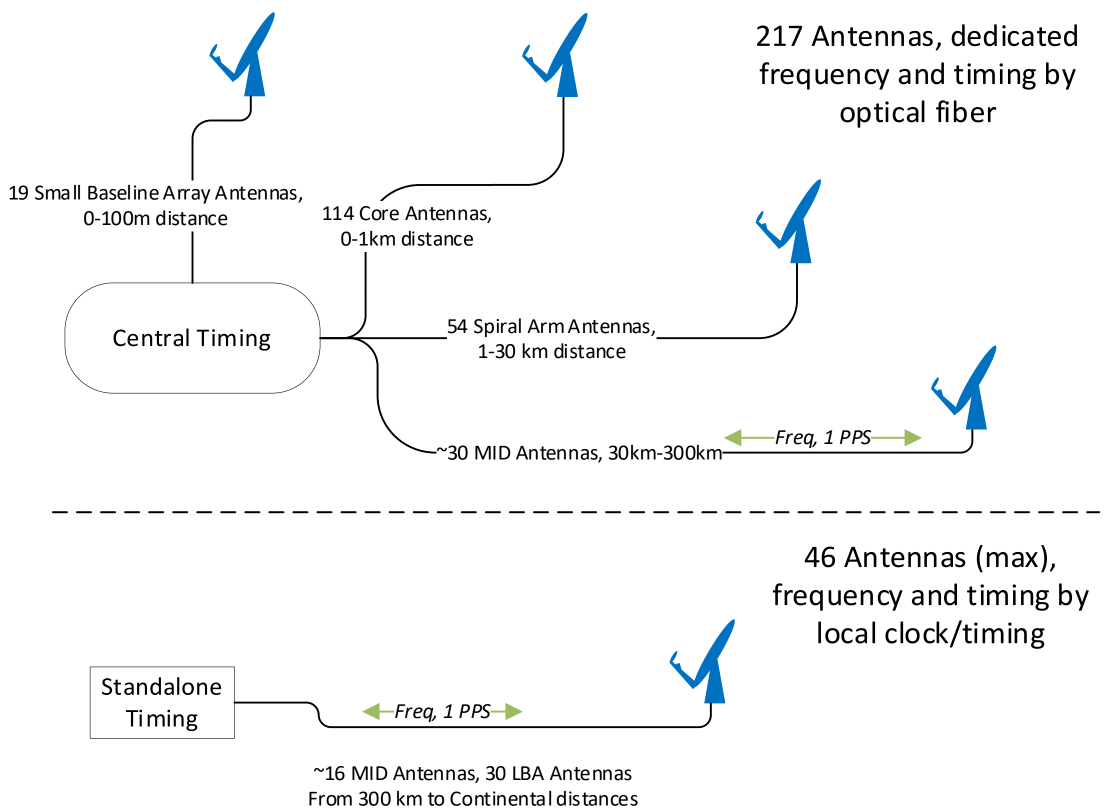


**Figure 10 - Top Level frequency and timing transfer block diagram**

The frequency transfer is based on a frequency reference input (from the maser source), which is then upconverted to a microwave reference frequency and transmitted by optical fiber to the antenna, where it is received. The round-trip phase of the transmitted frequency reference is measured and recorded.

This measured data is then available for an offline correction of the one-way phase. This relies on the assumption that the fiber link is perfectly reciprocal so that the one way phase is half of the round trip phase. The link design is made in such a way as to minimize any non-reciprocities.

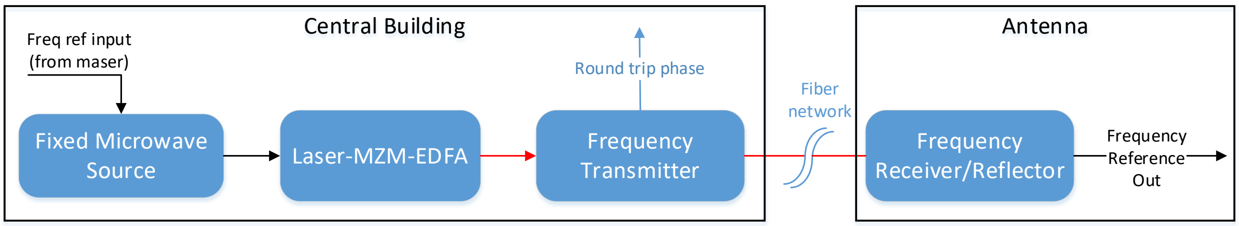


**Figure 11 - Frequency transfer simplified block diagram: single link. Narrow linewidth laser, MZM modulator, and Erbium-doped fiber amplifier (EDFA) is shown as a single block.**

The design is easily extrapolated to as many antennas as necessary by separating the laser source, MZM and fiber amplifiers from the transmitter modules. The transmitter module prototype and concept groups eight modules into one assembly. Therefore a 32-way split ahead of this stage will allow for distribution to 256 antennas – more than enough for the SBA, core, spiral arms, and MID-array.

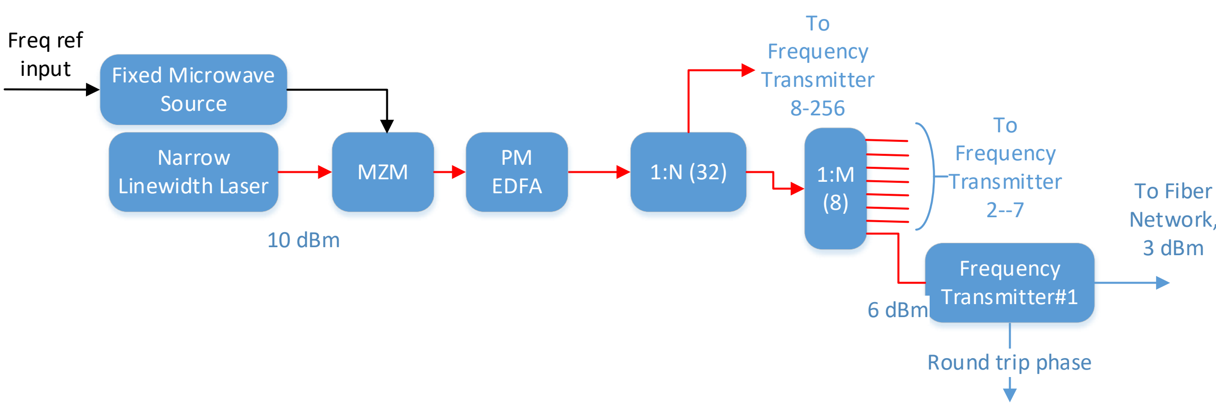


**Figure 12 - Frequency transfer block diagram showing distribution from one fiber to 256**

For stations that have independent timing, there are two possible configurations. For LBS there are ten sites with three antennas each. Thus, a single central maser source, fixed microwave source (FMS), narrow linewidth laser (NLL), MZM, and EDFA will be copied as shown above. The splitter network is reduced from 256-way to 3-way, and the fiber network consists of three fibers of modest length one to each antenna. For isolated MID antennas, the same set of modules maser, FMS, NLL, MZM, EDFA is used with a single (relatively short) fiber to the antenna. This is a conservative design in that it provides for a round trip phase correction when in fact the fiber paths are quite short and the correction may not always be needed.

### 5.3.4 Frequency transfer for Long Haul Links

The use of the term "long-haul links" here refers to antenna stations in the MID array for which we consider the possibility of direct connection by fiber. For these stations the fiber distance from the central building could be anywhere from 30 km to ~800 km. A few issues that arise from the longer links:

a) Dispersion: Chromatic dispersion and polarization mode dispersion can both impact the long-haul performance

b) Distance, delay, and bandwidth: the round-trip delay limits the speed with which either an active correction or an offline correction can compensate for disturbance or fluctuations. The servo bandwidth limit is:

$$f = \frac{1}{4\tau} = \frac{nc}{4L} = 112\frac{kHz}{km},$$

where n is the fiber index of ~1.5, c is the speed of light, and L is the fiber length.

c) Signal-to-Noise: the lightwave signal power in the link is important for good signal fidelity at the antenna-located receiver, and at the round-trip receiver in the central building. Prior work has found that bidirectional amplification is needed at approximately every 50-80 km [RD12].

### 5.3.5 Frequency Transfer Design

A complete description of the proposed NAOJ system is included as [RD12].

The technique relies upon the transmission of a reference frequency encoded on fiber as a pair of lightwaves spaced by the reference frequency. Generally, when a laser is modulated by a reference frequency the laser will develop upper and lower sidebands and thus there are three lightwaves: carrier plus two sidebands. The drawback to this technique is that when photodetecting to receive the reference frequency, the upper sideband beating against the carrier and lower sideband beating against the carrier add as phasors. When the length of the fiber weighted by the amount of chromatic dispersion in the fiber reaches a certain limit, then the phasors add in opposition and the output is suppressed. For this reason, the proposed design eliminates the carrier and simply propagates the upper and lower sideband. This removes the distance limit imposed by chromatic dispersion. The detected frequency is twice the modulating frequency.

The key device, called a Mach-Zender modulator (MZM), essentially acts as a photonic frequency doubler when used in "null bias" mode. This technique works well up to ~50 GHz, and beyond that can be limited by the modulator bandwidth. However, above 50 GHz, the "full bias" mode can be used to generate 2nd order sidebands, and the central laser lightwave must then be suppressed by optical filtering. In this case the MZM acts as a frequency quadrupler with output to 100 GHz. A schematic representation is shown in Figure 13.

Proof of concept tests at NAOJ have been completed at 22 GHz, 80 GHz and 100 GHz. The stability results do not appear to depend strongly on the transmission frequency. As detailed in [RD12], the frequency transfer susbsystem design consists of the following features:

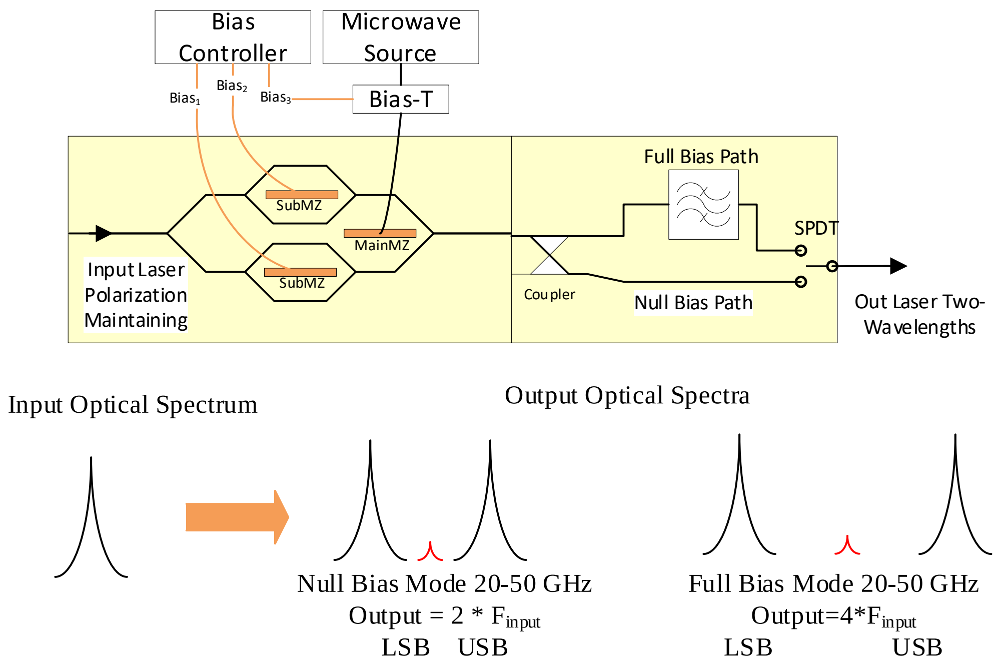


**Figure 13 – MZM Laser Modulator schematic supporting both null bias (20-50 GHz) and ful-bias (50-100 GHz) modes of operation.**

- Two lightwaves are sent to the telescope, with the MZM output passing through a polarizing beamsplitter as shown in Figure 14.

- At the terminating point of the link (in the secondary focus front end enclosure), the two lightwaves are frequency shifted by 50 MHz (by a FFS: fiber frequency shifter, shift occurs 25 MHz in each direction), reflected by a faraday rotator mirror (FRM) and returned to the central building.

- In the central building transmitter module, the returning lightwaves are combined with a sample of the outgoing lightwaves.

- Thus, four lightwaves are collected, a pair closely (50 MHz) spaced at the lower sideband lightwave frequency, and a pair closely (50 MHz) spaced at the upper sideband lightwave frequency.

- These pairs are then separated and detected. Importantly, it can be shown that the detected phase difference between the two pairs is equivalent to the round-trip phase fluctuation at the original reference frequency. The separation of the pairs is accomplished by an optical filter. This round-trip phase detection is called the ***double difference phase detection technique***.

- Note that ngVLA intends to transmit one reference frequency only, so the additional circuit selecting null-bias or full-bias is not strictly needed. (The current plan is to transmit 23.2 GHz)

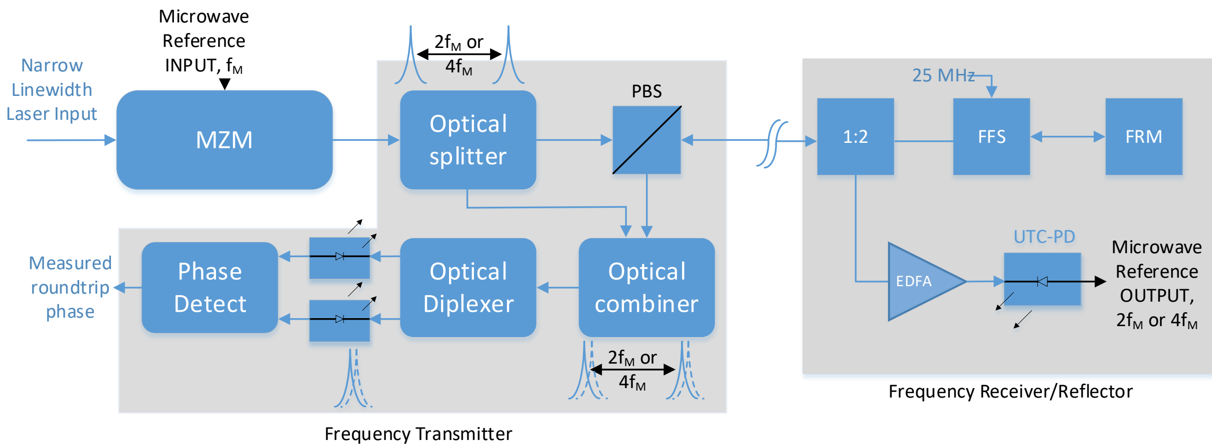


**Figure 14 - Double difference phase detector with transfer frequency transmitter and receiver/reflector. (PBS = Polarizing Beamsplitter)**

The technique has been developed over many years at NAOJ. There is prior work on the development as follows:

**Table 6 - Prior work on the Dual-difference technique with Offline compensation**

| Year | | Reference | Description |
|---|---|---|---|
| 2007 | | [RD13] | Introduced the Mach-Zehnder Modulator as a photonic signal source for up to 100 GHz |
| 2008 | | [RD14] | Introduced the concept of dual difference phase measurement |
| 2013 | | [RD15] | Reported on fully packaged and engineered MZM signal source for DC-130 GHz topical signal transmission |
| 2017 | | [RD16] | Demonstrated dual-difference detector with high accuracy for offline phase compensation |
| 2019 | | [RD17] | Demonstrated technique for locking high frequency oscillators and for implementing long haul fiber repeaters |

### 5.3.6 Frequency transfer: Performance

#### *5.3.6.1 Summary of the NAOJ References*

Performance in the laboratory and in the field of the frequency transfer system is discussed at some length in [RD12] and [RD18]. For purposes of summarizing those results, the Allan deviation performance data is collected onto a single plot as shown in Figure 15 below.

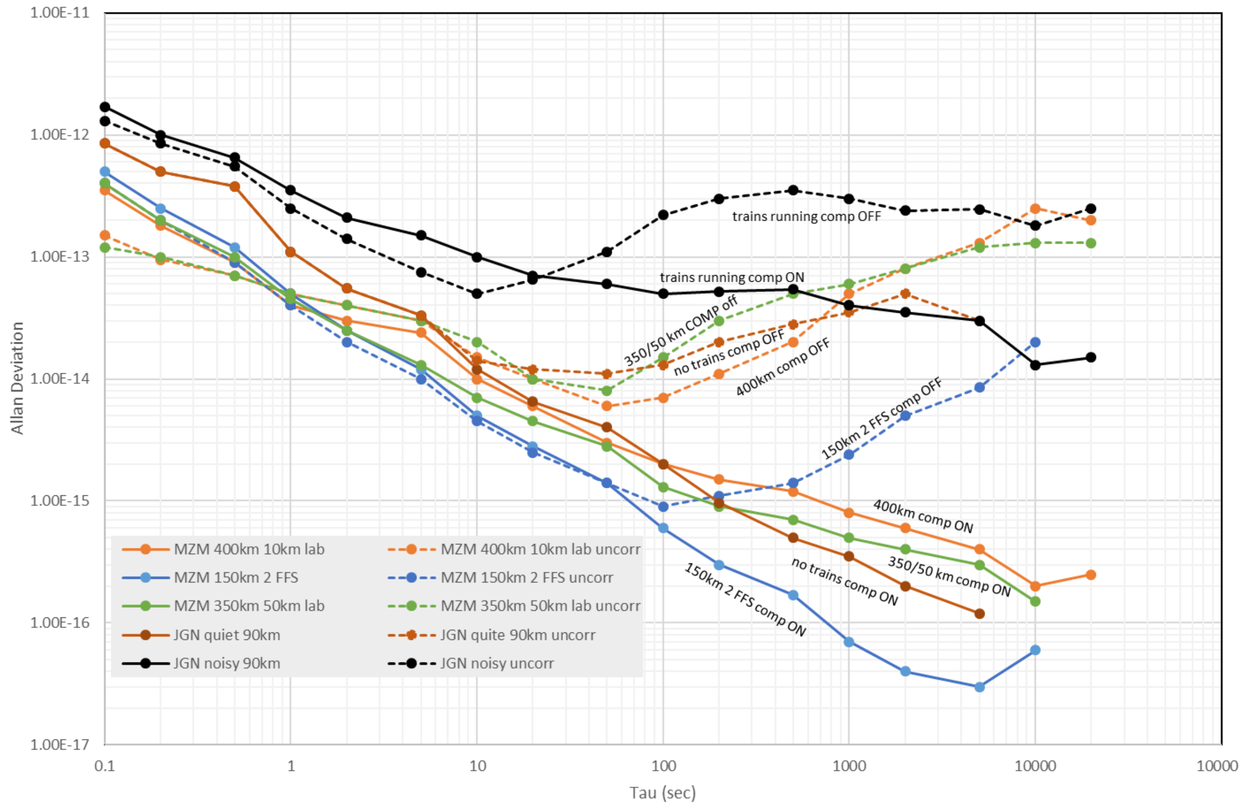


**Figure 15 - Allan Deviation performance of dual-difference frequency transfer technique under several measurement conditions as detailed in Table 7 - Test conditions for tests plotted in Figure 15**

**Table 7 - Test conditions for tests plotted in Figure 15**

| | |
|---|---|
| MZM 400km 10 km lab | MZM frequency source 100 GHz tested in lab with two arms, one at 400km and one at 10 km |
| MZM 150km 2 FFS | MZM frequency source 100 GHz tested in lab with two arms, one at 150km and one short fiber |
| MZM 350km 50km lab | MZM frequency source 100 GHz tested in lab with two arms, one at 350km and one at 50 km |
| JGN quiet 90km | MZM frequency source 100 GHz tested in Tokyo subway with one arm at 90 km: trains not running, quiet morning hours |
| JGN noisy 90km | MZM frequency source 100 GHz tested in Tokyo subway with one arm at 90 km: train running, busy daytime hours |

As was discussed in section 6.1, the requirement is likely to be met at L=100 km and less, but with some degradation possible at longer link distances. A notable result from Figure 15 is that when the trains were running, the offline compensation system did not work well. It is difficult to make a clear conclusion about what this means for the ngVLA long haul links. The noisy Tokyo subway may be a more difficult environment than the long-haul links in the USA southwestern desert regions, even in the case of aerial fiber links (the JGN testbed consists of an installed fiber link in the Tokyo subway with a combination of aerial fiber and fiber routed alongside the railroad tracks [RD12]). Further work will study this more closely and either aim to:

- Quantify the environmental noise level which we expect to be present for ngVLA MID links
- Improve the result with the present system as necessary
- Propose an alternate system that could be used in particular for the ngVLA MID long-haul links

##### *5.3.6.2 Compliance versus ngVLA requirement*

A dataset was provided to NRAO from NAOJ with raw test data of a laboratory measurement with a single fiber link of 250 km. The test setup is shown in Figure 16.

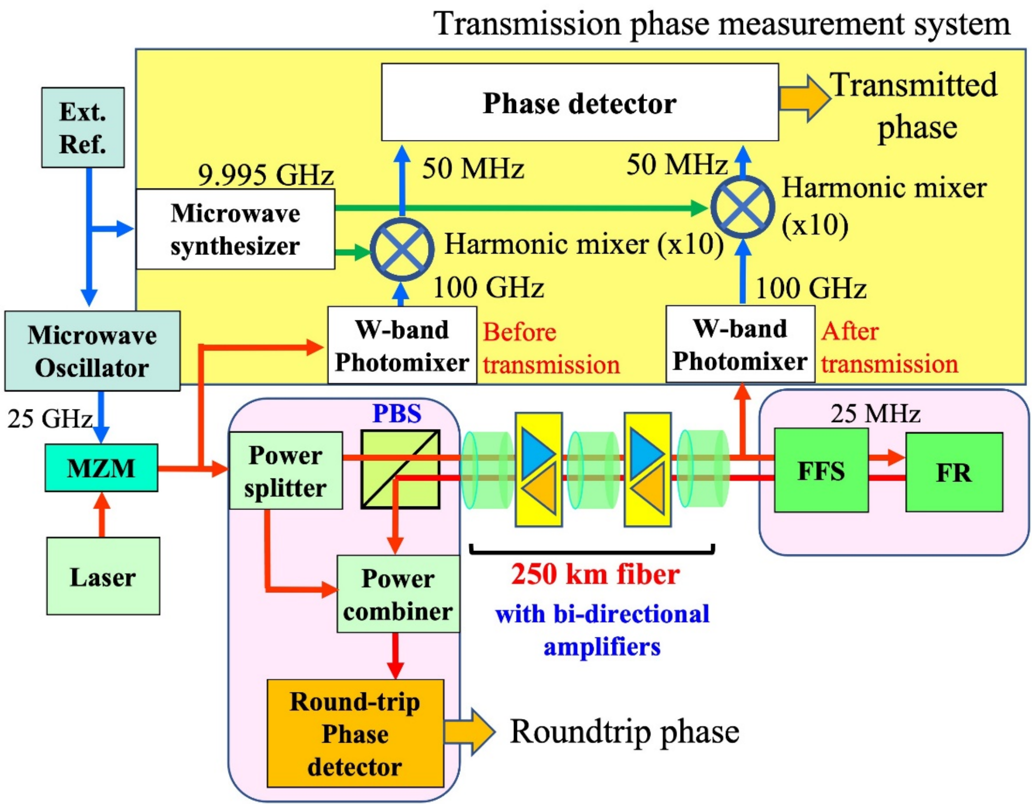


Figure 16 - NAOJ 250km laboratory frequency transfer measurement

The one-way phase is measured at 100 GHz using direct microwave measurement of the reference frequency and analog phase detection. The round-trip phase is measured in the NAOJ digital phase detect system.

The measured one-way phase is processed by subtracting half of the round-trip phase, resulting in a residual delay (see Figure 17) bracketed by +/- 400 fsec and having a small nonlinear probably diurnal) component.

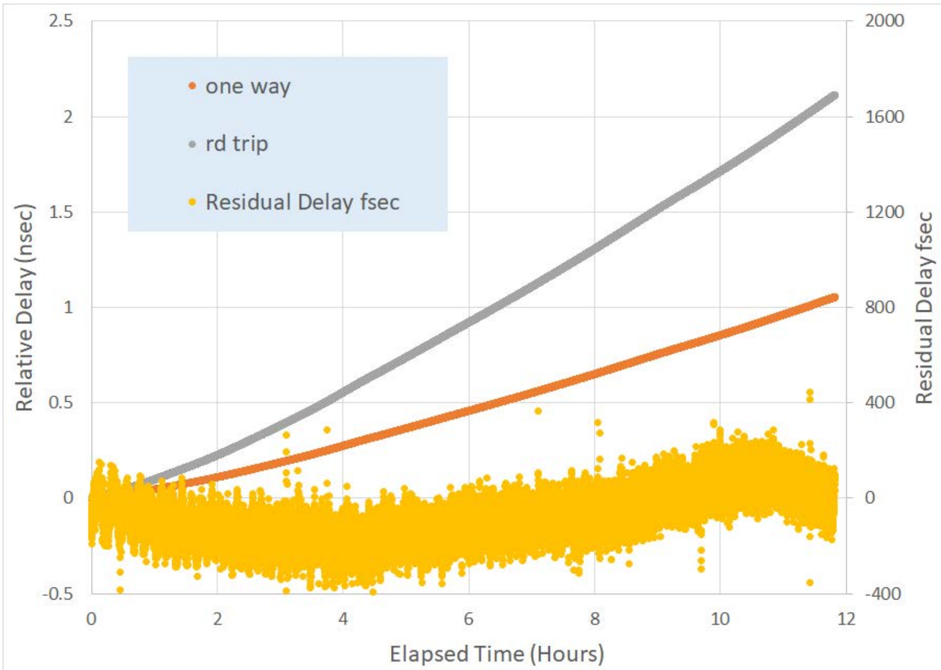


**Figure 17 - 250km fiber laboratory testbed, 12-hour measurement of one-way, round-trip and residual delay**

The Allan Variance of the residual is plotted in Figure 18.

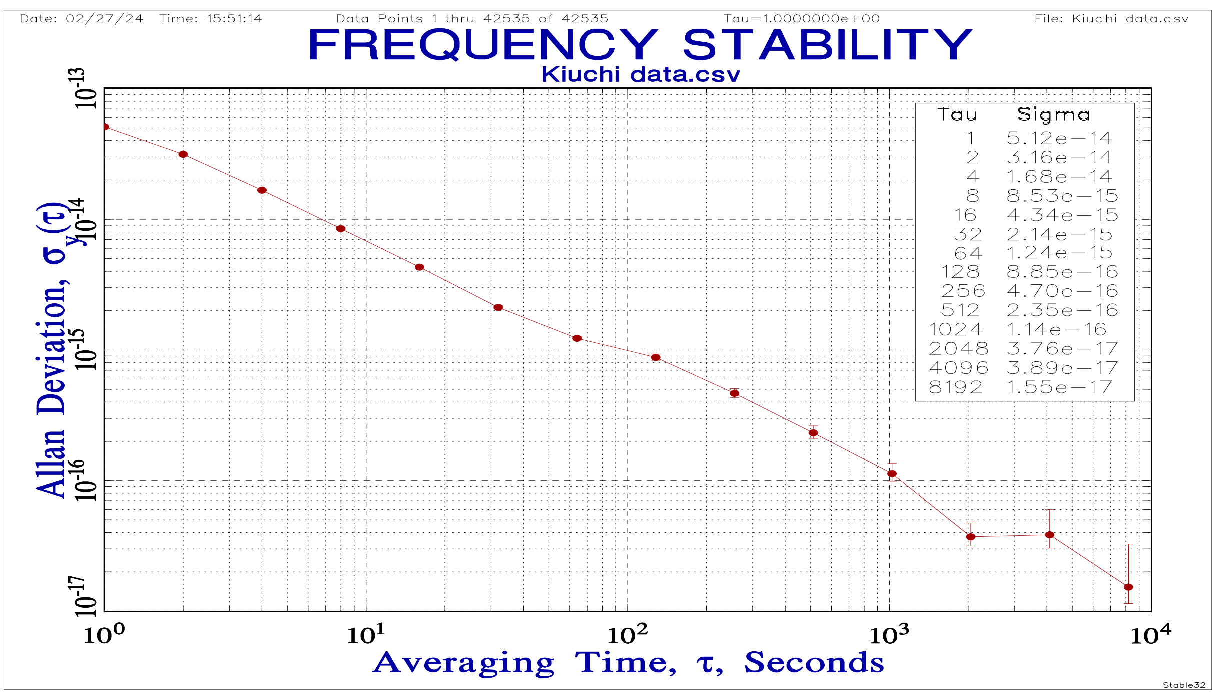


**Figure 18 - Allan Variance of residual delay error for 250-km link**

Next this residual delay error is processed according to the ngVLA requirement definition:

From [AD03]:

The delay/phase **drift** requirement refers to the two-point Allan Standard Deviation with a fixed averaging time, τ, of 10 seconds, and intervals, T, between 20 and 300 seconds.

$\sigma^2(2,T,\tau) = 0.5 * <[\phi_\tau(t+T) - \phi_\tau (t)]^2>$

$\phi_\tau$ is the average of the absolute or differential phase over time τ = 10 seconds; < … > means the average over the data sample which should extend to 10 or 20 times the largest value of the sampling interval T that is used.

Note that this usage of the name "Allan variance" and other related terms is somewhat nonstandard. Strictly speaking, the Allan variance refers to the two-sample variance of fractional frequency and was introduced by David Allan in his studies of oscillator stability. Here the same formalism is used and the name Allan variance extended to mean the two-sample variance of phase and of gain.

This quantity has been calculated versus T with the following result:

| T (sec) | 10 | 20 | 100 | 300 | 1000 |
|---|---|---|---|---|---|
| *σ(2,100,10)* | 19 fsec | 23 fsec | 51 fsec | 53 fsec | 54 fsec |

This is slightly above the 42 fsec requirement at 300 sec. However, considering that the ngVLA overall drift requirement per antenna is 95 fsec this could be considered a promising result. More characterization of the frequency transfer system in different environments will be needed. Some of this has already begun and is discussed in [RD18].

### 5.3.7 Frequency transfer: Alternatives for Long Links

A specific proposal for frequency transfer over long links (especially when the noise level is high) has already been made available by NAOJ scientist Miho Fujieda [RD19]. This proposal was developed after tests of the dual-difference offline compensation system failed under the most difficult conditions during the Tokyo subway testing reported in section 5.3.6 and [RD18]. However, the proposal is modeled after prior work reported in [RD20] which demonstrated active suppression of fiber noise in a noisy environment. This prior work demonstrated that cancellation of the phase noise can be made by a factor of 45 dB, effectively reducing daily variations of 12-meters in effective path length (~40nsec) to less than 2 psec.

### 5.3.8 Frequency transfer: Risks

Major risks for this subsystem have been identified and are summarized briefly below. These are periodically assessed for tracking within the project risk register.

Table 8 - Most significant risks for RTD frequency Transfer

| Risk | Description | Scale |
|---|---|---|
| Long baseline phase stability | For MID antennas at 50km-800 km distance, the phase drift requirement is difficult to meet | High |
| MZM Optical Signal Generator | Custom design requires institutional or commercial vendor | Med |
| Custom design | Requires internal manpower or institutional collaboration | Med |
| Long term availability of optical components and FPGAs | Considering long lifetime of array | Low |
| Partner risk | NAOJ and NRAO collaboration depends on separate funding sources (and timelines) and mutual goodwill | Med |

For the long baseline phase stability risk, due to its high-risk rating, our ongoing development plan through the preliminary design phase will include mitigations for this risk, including:

(a) Continued study of the configuration design via a Fiber Working Group
(b) Study of the extend of environmentally induced fiber noise and drift representative of the actual transmission cables (Buried and Aerial cables)
(c) Frequency transfer stability measurement test using actual transmission cables
(d) Integration test with other subsystems and using actual ngVLA prototype antenna (including compatibility with transmission phase compensation software)

### 5.3.9 Frequency transfer: Major Interfaces

a) Central Station:

- The round-trip phase measurement data is provided to CSP. The format and transmission method for this data transfer need to be defined
- Interface with RTG subsystem: input frequency reference signal definition: amplitude, stability, phase noise, frequency
- Interface with MCL: monitor and control protocol, cabling, and definition of monitor and control points for all LRUs. Definition of equipment states, mode, and data logging requirements.
- Interface with FIB: Interface with fiber optic cabling to site
- Interface with NSB: Rack footprints, mechanical interfaces, air flow needs, cable trays, AC power, UPS power

b) Antenna Station

- Interface with ATF: definition of frequency reference output power level, stability, and phase noise

- Interface with DBE: Definition of any signal or clocking needed by DBE and provided by RTD

- Interface with AFD: Antenna Fiber routing definition for RTD

c) Repeater Stations

- Interface with FIB: Enclosure and Rack requirements, temperature control and air flow requirements, and cable routing

### 5.3.10 Frequency Transfer Functional Requirements

A functional overview of the RTD subsystem is shown in Figure 19.

The frequency reference and timing reference are the primary inputs. These are distributed to each antenna and a return signal is measured to form a round trip measurement. An antenna specific frequency offset is added to LO and digitizer clocks at the antenna. Round trip and hardware monitoring is implemented at the central building, repeater stations, and antenna station.

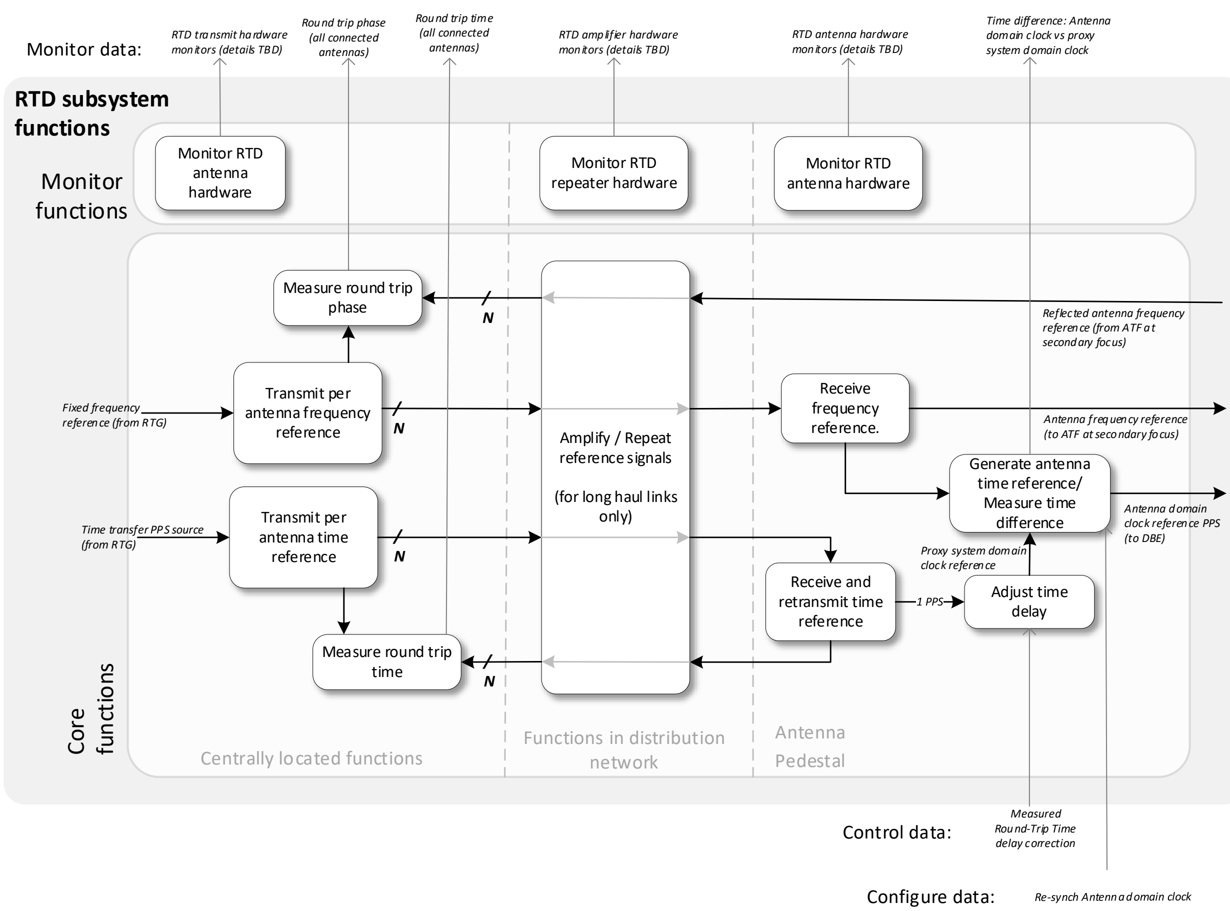


**Figure 19 - Functional overview: LO Reference and Timing Distribution (RTD) Subsystem.**

The frequency transfer portion of the RTD is discussed here (timing transfer is discussed in 5.4.11). The functional requirements are listed below:

A. **Set Frequency reference:** As shown in Figure 11 and Figure 12, the frequency reference is currently envisioned as a fixed frequency reference directly phase-locked to the central references which in turn are locked to a central H-maser. Thus, there is no need to "Set" the frequency in the context if frequency tuning. This function will thus be implemented and confirmed by an ON/OFF command, setting and monitoring power level, and monitoring status of phase locking.

B. **Transmit reference:** As shown in Figure 20, the frequency transmission to each antenna is functionally accomplished by means of a transmitter module. The transmitter module has a frequency reference input and a narrow linewidth laser input. The MZM module converts these to the desired two-wavelength optical spectrum, which is then split into enough outputs (~256 for the central RTD) to form one input for each transmitter module. The 1:256 splitter will include an optical shutter so output can be nulled if needed for any of the transmitter inputs.

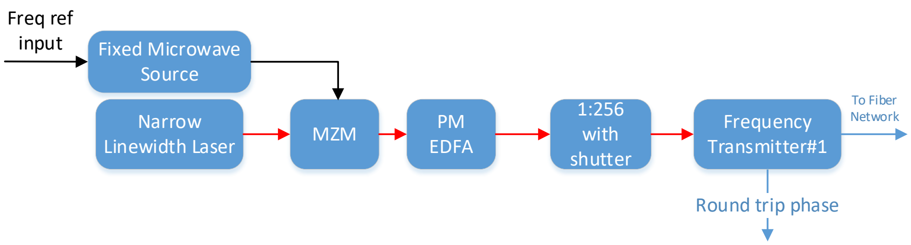


Figure 20 - Functional implementation of frequency reference transmission

C. **Measure round trip phase:** When the fiber network is terminated in a frequency receiver/reflector for fiber distances up to several hundred km, then the transmitter module measures the round trip phase and provides this as an output to the monitor and control subsystem.

D. **Amplify/Repeat Reference:** To overcome fiber attenuation and possibly other effects like dispersion, it is necessary to either bidirectionally amplify the round-trip traveling lightwaves, or photodetect and re-transmit as a repeater. These amplify or repeat stations are expected to be required on links exceeding 80 km and occur at approximately 80 km intervals. The functional implementation of a bidirectional amplifier module is shown in Figure 22. The hardware is commercially available, and highly reliable.

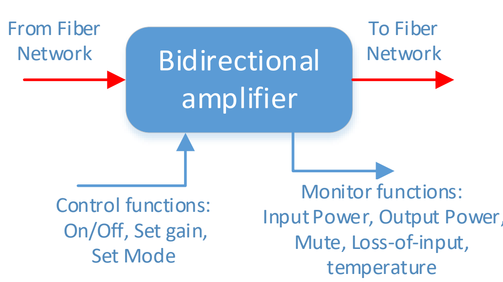


Figure 21 - Bidirectional amplifier functional implementation

The hardware to implement a full repeater is more extensive. However, the need for a full repeater has not yet been confirmed, and would only be needed in a few special cases for very long-haul links in the MID-array.

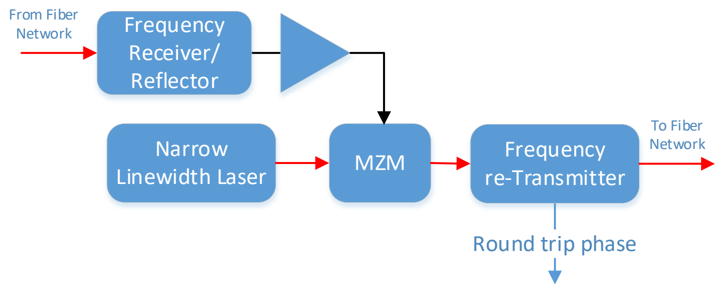


**Figure 22 - Full repeater implementation**

E. **Receive reference:** The frequency receiver is implemented as shown in Figure 14.

## 5.4 *Timing Transfer (RTD)*

### 5.4.1 Key Requirements of Time Transfer

The LO Reference and Timing requirements document [AD13] encompasses all of the requirements for the RTG and RTD subsystems. Here we extract a subset of these requirements that are considered driving requirements for the RTD frequency transfer subsystem design.

**Table 9 - Key Requirements for Time Transfer**

| Parameter | Value | Req. # |
|---|---|---|
| Timing to RTD | Timing accuracy to RTD used for digital timestamping shall be within 2 nsec (goal of 1 nsec): Relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging<br><br>***Note1:*** data timestamps are tagged at the antenna, therefore this requirement is met by providing accurate timing ***to the antenna***<br><br>***Note 2:*** An additional 1 nsec budget is allocated for the RTD-DBE fiber transfer at the antenna | LRT1300 |
| The data timestamping is planned for the antenna rather than central building. The CSP clock domain will be a virtual clock determined by the timestamps and the antenna delay models, with one antenna (per subarray) selected as the reference antenna. | | |
| | | |
| Antenna Timing | The antenna clock domain shall be stable relative to the antenna LO reference to within 1 ns.<br>This requirement supports synchronization of LO, digitizer and antenna timing signal. | LRT1357 |
| The design calls for the antenna station 1 PPS to be derived directly from the frequency reference. This requirement defines the required accuracy of that division. | | |
| Subarray Timing | Timing correction of at least one antenna per subarray shall be supplied by measurement or active correction to within 2 nsec for support of accurate data timestamping. | LRT1360 |

| | | |
|---|---|---|
| | The requirement is relative to the central system clock on short timescales and relative to the absolute timing standard over 1-day averaging. | |
| Since there is a flexible subarraying requirement, and each subarray requires at least one antenna with 2 nsec accuracy, the design presented herein provides for the accurate transfer of 1 PPS timing to ***all*** antennas. | | |

### 5.4.2 Timing Transfer Assumptions

- A central GNSS time standard is co-located with the primary frequency reference
- A system clock is derived from the primary frequency reference, and differences between the system clock and GNSS time will be monitored and logged
- The system clock and frequency reference are distributed to each antenna station which is connected by fiber, as well as a continuous monitoring of those signals so that fluctuations in the one-way propagation (due especially to thermal effects) can be mitigated.
- The accurate transfer of time and frequency can be made by direct link or by daisy chain
- Additional remote station clocks and frequency reference will be generated for stations that are too distant for connection by fiber
- From [RD03], the system will have multiple timing domains (discussed further in 5.4.3)
    - Central System Clock
    - Antenna Clock
    - Station clocks: replicas of the central clock needed for outlying stations
    - CSP Timing Domain
    - Network Time Domain
- The System clock runs open loop on the primary frequency reference and is periodically synchronized with GPS
- The antenna clock runs open loop on the distributed frequency reference and is periodically synchronized with the distributed central timing reference
- Critical timing is preserved from RTG to RTD to ATF to DBE where data timestamping occurs.

### 5.4.3 ngVLA Timing Overview

The overall ngVLA timing design is shown in Figure 23. The following time domains are depicted:

- $\mathcal{T}_{SYS}$ : Central maser
- $\mathcal{T}_{SYS\{1..j\}}$ : Standalone maser { for remote LBS sites, and for remote standalone stations}
- $\mathcal{T}_{SYSn'}$ : recovered time at antenna
- $\mathcal{T}_{ANTj}$ : antenna station timing domain
- $\mathcal{T}_{CSP}$ : CSP domain
- $\mathcal{T}_{NET}$: network time domain

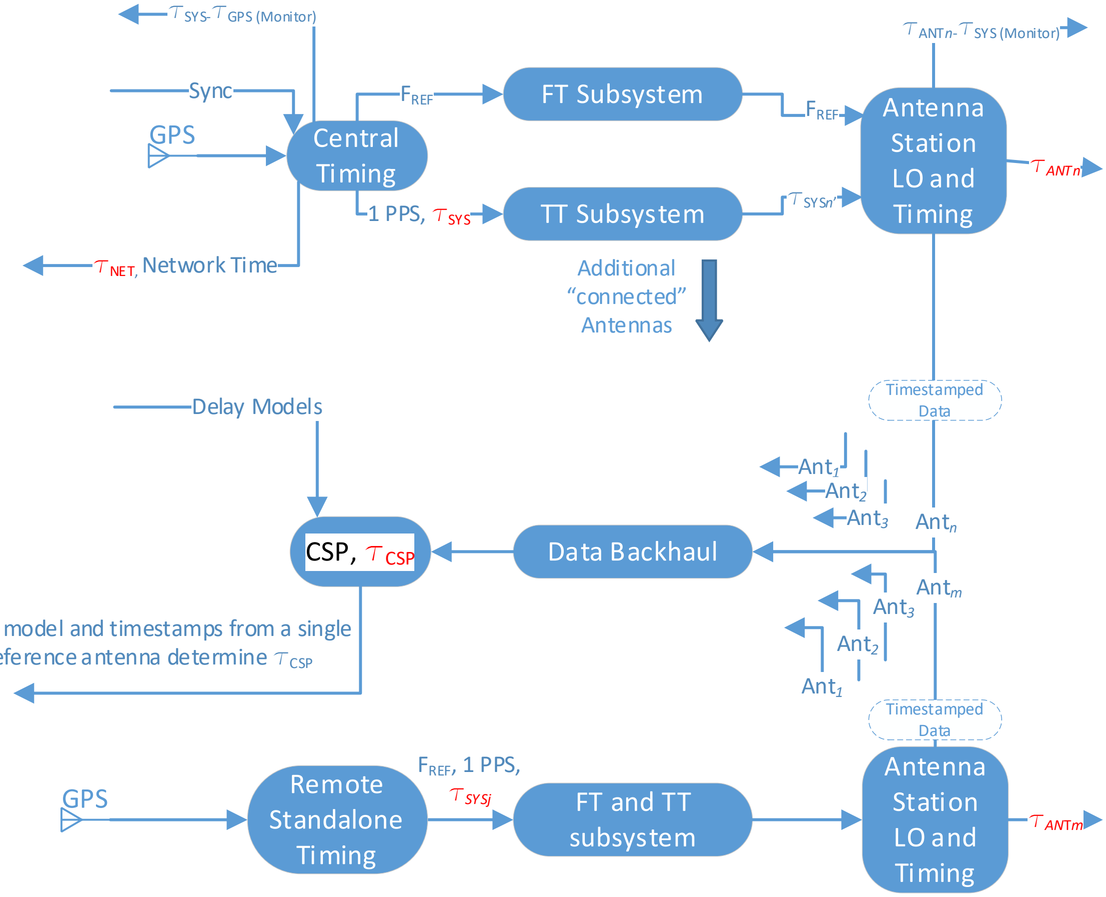


**Figure 23 - ngVLA Timing Design**

The figure depicts, at top, the central timing hub which is part of the RTG subsystem. This relies on a hydrogen maser for short term stability and GPS for long term stability, and forms $\tau_{SYS}$, the central time domain for the connected element array. Any longer term drift between GPS and maser is handled by continuous monitoring with the availability of a reset SYNC command which resets the system clock to coincide with the nearest H-maser zero crossing to the GPS 1 PPS pulse. This is shown below in Figure 24.

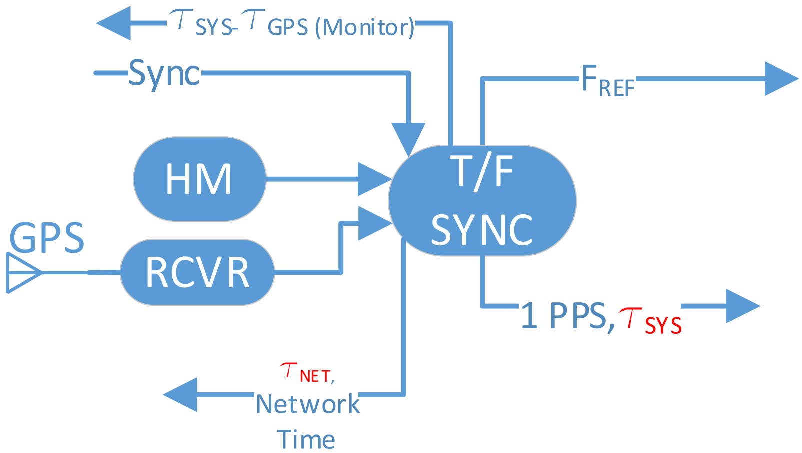


**Figure 24 - Central Timing. HM=Hydrogen Maser**

The $\tau_{SYS}$ is then transferred to the antenna by use of a time transfer transmitter/receiver pair (denoted "TT subsystem" in Figure 23). The resulting output called $\tau_{SYS'}$ should track $\tau_{SYS}$ closely as the time transfer system removes the effect of the one-way fiber propagation. Just as $\tau_{SYS}$ tracks the H-maser in the short term and can be re-synchronized to GPS time over the long term, likewise at the antenna station the $\tau_{ANT}$ tracks the frequency references on short time scales and can be resynchronized to the $\tau_{SYS'}$ over the long term. In this way, the $\tau_{ANT}$ (1 PPS) timing is synchronized with the local oscillators and digitizer clock guaranteeing a fixed number of samples between every 1 PPS edge. Details of this implementation are shown in Figure 25.

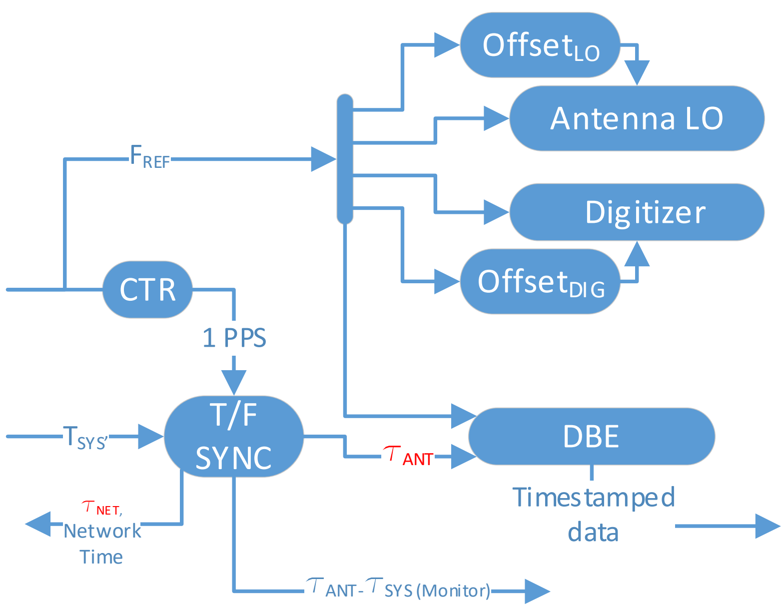


**Figure 25 - Detail of Timing Distribution at Antenna Stations**

Referring again to Figure 23, the timestamped data is then sent back to the central building. The CSP will then create a virtual clock domain, $\tau_{CSP}$, comprising one reference antenna path (per subarray) with delays applied on a per-antenna basis according to the system delay model. Remote standalone timing is handled in much the same way as central timing, with a H-maser and GPS reference transmitted to the antenna station to provide a baseline for the antenna station timestamping.

### 5.4.4 Timing Performance Budget

A timing performance budget has been developed and set forth in [RD02].

**Table 10 - Timing Performance Budget**

| Sub-System Timing Precision Allocation | Sub-system | Error (nsec) | Notes | Timing reference planes for measurement |
|---|---|---|---|---|
| Measurement Error: System Domain Clock Drift vs GPS Time | RTG | 1.67 | GPS timing error long term average | Maser 1 PPS output versus GPS 1 PPS |
| Uncorrected Time Drift from System Domain Clock (RTG) to CSP | RTG | 0.00 | CSP time domain is derived from DBE timestamping | N/A |
| Uncorrected Time Drift between System Domain Clock (RTG) and Time Distribution System (RTD) | RTD | 0.30 | Assumes short cable lengths in temp controlled environment | Maser 1 PPS output versus RTD 1 PPS input to time transmitter |
| Uncorrected Time Drift from System Domain Clock (RTG) to Reference Antenna Domain Clock (RTD) | RTD | 2.00 | Residual after round-trip correction of timing signal | Maser 1 PPS output to corrected 1 PPS output of Timing Receiver |
| Antenna Structural & Electronic Delay Drift (preceding digitizer) | ANT, SBA | 0.05 | 4 psec over 300 sec (48 psec/hr.), combined across all systems in an antenna, between astronomical calibrations. | N/A for LRT subsystem |
| DBE Time Error w.r.t. Antenna Domain Clock | ATF/DBE | 1.00 | Assumes JESD 204D timestamping of digitized data | 1 PPS timing input to ADC JESD clocking circuit versus 1 PPS delivered through 25m optical fiber to the DBE |
| Other Delay Model Errors | ONL | 1.00 | | N/A for LRT subsystem |
| | | | | |
| **Sub-System Error Sub-total** | | **2.98** | **RSS Combination of Independent Errors** | |
| | | **6.02** | **Linear Sum of Correlated Errors (worst case)** | |
| Margin - only true if terms are independent. | | 9.55 | (Aiming towards 1 nsec goal in allocations) | |
| **System-level Total Error Budget** | | **10.0** | **RSS Combination of Errors** | |

The budget shows how potential sources of timing inaccuracy are accounted for within the overall systems timing budget of 10 nsec (SYS2002). Note: shaded lines in the table refer to subsystems within LO Reference and Timing design described in this document.

For purposes of test and verification it is necessary to have a well-defined test point for the timing signals described in Table 10. A description of the reference planes appears as column five in the table.

### 5.4.5 Time Transfer subsystem design

In its simplest form, the timing link consisting of a transmitter and receiver across the fiber optic link, with central 1 PPS input synchronized with H-maser (in the $\tau_{SYS}$ domain, 5.4.3) and the 1 PPS Output (in the $\tau_{SYS'}$ domain, see 5.4.3), nominally synchronized with the 1 PPS input - Figure 26.

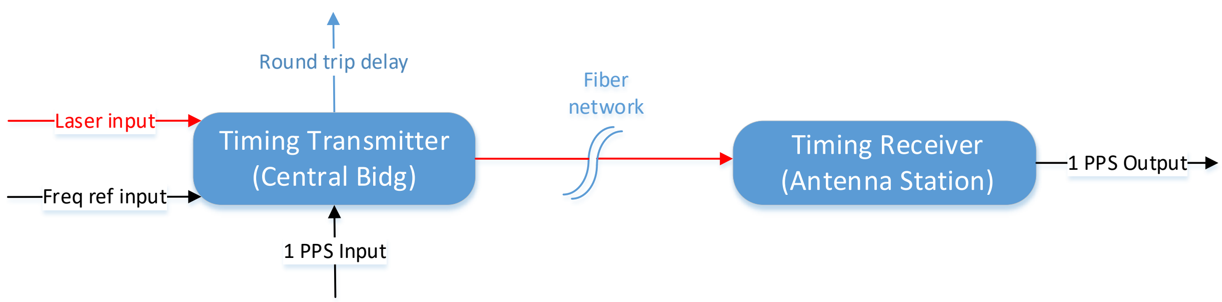


**Figure 26 - Timing Link Block diagram (red=fiber, black=electronic)**

The timing link can be further detailed to show how it is combined with the frequency transfer link onto a single optical fiber per antenna. The two links are wavelength separated by a wave division multiplexer (WDM) on each end of the fiber. WDMs provide high isolation even for closely spaced wavelengths (with wave spacing generally determined by the ITU frequency grid). Having the two links on closely spaced ITU channels may have some small benefit in reducing any second order effect between the links due to chromatic dispersion, though in principle the concept will work with wide spacing.

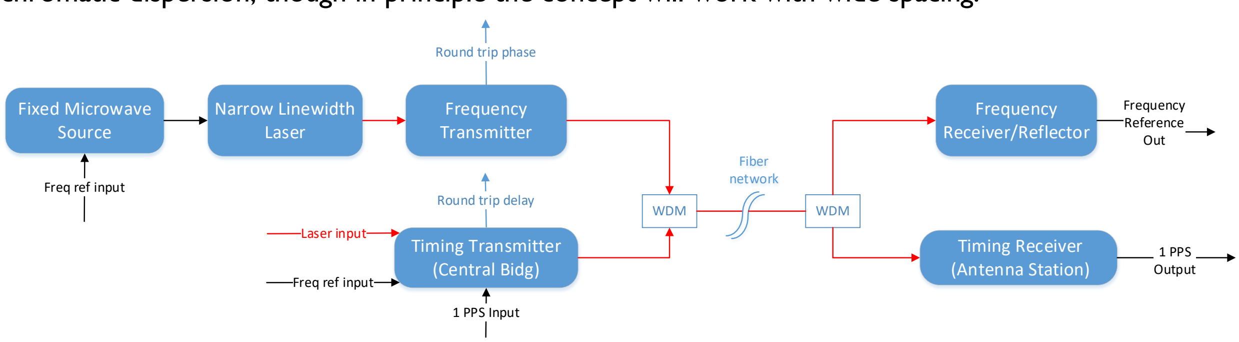


**Figure 27 - Frequency transfer and Timing transfer on single optical fiber. (Red=optical fiber, black=electronic)**

Similarly to the proposed frequency transfer design (i.e. Figure 12), the timing transfer design is easily scalable, and Figure 28 shows the timing transmitter design concept scaled for distribution to a large (i.e. N=256) number of antennas as needed for ngVLA.

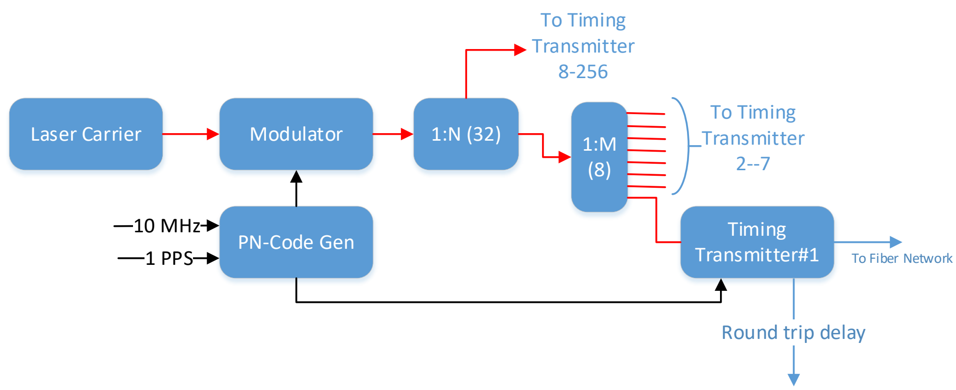


**Figure 28 - Timing transmitter design scaled for ngVLA distribution**

Note that the laser, modulator and PN-code can be notionally shared by all transmitters and the "Transmitter #N" module or circuit function is to measure delay by correlating the outgoing vs return signal.

### 5.4.6 Time Transfer: NAOJ Method

A time transfer method is proposed by the NAOJ team utilizing a pseudo-random noise (PRN) codes to modulate in a binary offset carrier system [RD21, RD22]. Correlation of the noise code after a round-trip determines accurately the two-way delay. The measured delay is then transmitted as an overlay in the same link so that the 1 PPS timing signal at the receive end can synchronize with central timing. This concept is based on several prior successful works by the NAOJ researchers on two-way timing long haul transfer by satellite and optical fiber [RD23, RD24, RD25]. The updated NAOJ concept has now been prototyped and tested successfully in an urban (Tokyo) fiber link.

Some features of the proposed system are:

- High measurement precision
- Straightforward signal processing by digital electronics
- Binary offset carrier approach, similar to GPS systems
- high chip rate for sub-nsec precision (10 psec accuracy)
- Accuracy of timing to meet ngVLA 2 nsec requirement
- Cost effective system: central system can support multiple channels per card and receive module is compact and simple
- Max distance >= 300 km (what is limit?)
- Same wavelength both directions to minimize chromatic dispersion effects at long haul
- One-way delay is measured and transmitted to remote system
- Compatibility with (NAOJ proposed) frequency transfer subsystem
- Transmission delay measured by XF correlator with a IQ mixer

#### *5.4.6.1 Concept*

The proposed time transfer concept is shown in Figure 29. The bidirectional link is shown in red with $\lambda_1$ indicating that the same wavelength is used in each direction. Rather than multiplexing the optical wavelength, instead the RF wavelength is multiplexed, with $f_1$ outgoing and $f_2$ return. The optical wavelength being the same in both directions eliminated any source of error from chromatic dispersion.

The RF wavelengths are separated by several tens of MHz which is enough to isolate the outgoing from the return signals. Further information about the modulation and the signal processing is included in the references [RD21, RD22]. Preliminary results indicate accuracy of 0.4 nsec or less for link lengths up to 90 km [RD21].

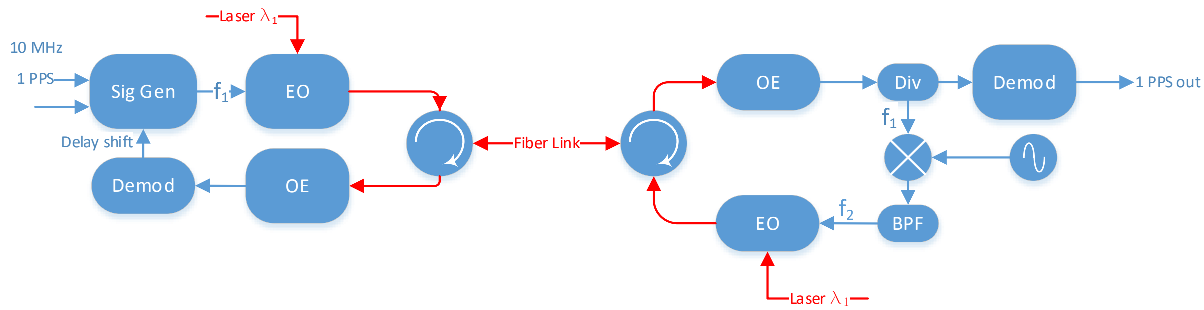


**Figure 29 - Proposed NAOJ time transfer concept**

#### 5.4.6.2 *Hardware*

Optical components are commercial off the shelf. Electronic digital signal processing is via low-cost field Programmable Gate Arrays (FPGAs).

### 5.4.7 Timing Transfer Performance

An early prototype system at NAOJ (utilizing equivalent wavelengths in each direction with analog signal) measured less than 1 nsec timing accuracy for several link configurations and lengths up to 250 km [RD21]. A subsequent test with BOC signaling and a correlation demodulator for several fiber lengths including the 90 km subway link had timing accuracy better than 500psec [RD26].
Additionally, a test was performed with a mm-scale air gap stretcher to measure the time delay resolution, and the result was linear delay measured vs displacement with ~psec level resolution.

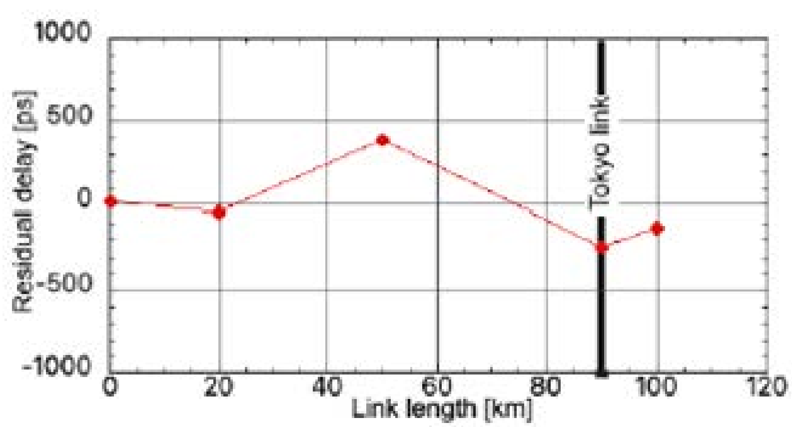


**Figure 30 - Delay measurement accuracy versus link length in preliminary measurement of the BOC correlation timing link**

### 5.4.8 Timing Transfer for Long Haul Links

The NAOJ technique has been demonstrated in a 90km noisy link and a 250km laboratory link. It thus appears well-suited for the long haul ngVLA links to MID antennas.

### 5.4.9 Timing Transfer Risk

Like frequency transfer, there is performance risk in the performance of the system to the ngVLA requirements in particular for the long haul links to distant MID stations. Other risks like procurement, reliability, component lifetime are not high risk and are not unique compared to other parts of the ngVLA system. The development of the major parts of the time transfer (like frequency transfer) by collaborating partner NAOJ implies some risks associated with common funding and scheduling, as well as interface compatibility risks.

### 5.4.10 Interfaces

The timing transfer has the following interfaces:

- 10 MHz signal input from RTG subsystem
- 1 PPS timing signal input from RTG subsystem
- Fiber optic distribution and cabling in the central building and repeater stations (FIB subsystem)
- Interface with ATF subsystem at antenna side, 1 PPS output signal
- Monitor and Control interface at Central building and antenna (MCL subsystem)
- Rack (mechanical) and environmental (temperature, air flow,…) interface with Central building and Antenna Electronics

### 5.4.11 Functional Requirements of RTD

A functional overview of the RTD subsystem is shown in Figure 19. The functional tasks of the timing transfer are:

A. **Establish time reference:** By a clock edge of the 1 PPS timing signal coming from the RTG via H-Maser and GPS. This cable will be kept short but can have a calibrated delay.

B. **Transmit reference:** As shown in Figure 29Figure 20, the timing transmission to each antenna is functionally accomplished by means of a modulator/transmitter. The preliminary design allows simultaneous transmit to eight antennas, with up to 32 units needed for <= 256 antennas in the connected array.

**C. Amplify/Repeat Reference:** As needed for long links, via same method as used for the frequency transfer. With both on one fiber, the amplification is also common.

D. **Detect Remote 1 PPS:** signal pulse is detected and retransmitted back to central building (Figure 29).

E. **Measure and Correct 1 PPS:** Measured round trip delay information is continuously sent to receiver in packet header, then is removed (as half of round delay) from recovered pulse. This link compensated 1 PPS is then made available to the ATF subsystem.

## *5.5 Antenna Time and Frequency (ATF)*

### 5.5.1 Key Requirements of Antenna Time and Frequency

The Antenna Time and Frequency requirements document [AD12] encompasses all of the requirements for the ATF subsystem. Here we extract a subset of these requirements that are considered driving requirements for the ATF subsystem design.

**Table 11 - Key Requirements for Antenna Time and Frequency**

<table>
<tr><th>Parameter</th><th>Value</th><th>Req. #</th></tr>
<tr><td>LO Phase Noise</td><td>< 76 fsec integrated from 1 Hz to maximum IF frequency offset<br><br>Goal < 50 fsec</td><td>ATF1240</td></tr>
<tr><td colspan="3">This is the phase noise requirement directly flowed down from Systems Requirements. The phase noise is most important at the antenna local oscillator and digitizer clock. References provided by RTD subsystem and transferred to ATF subsystem must be consistent with ultimately meeting the antenna LO phase noise requirement. In most cases the design of a distributed LO or clocking system will utilize phase lock loops or jitter cleaners in the distribution that make parts of the original central source phase noise spectrum irrelevant. So the interpretation of this requirement is:<br><br>(a) The RTD phase noise spectrum provided as input to ATF subsystem must be consistent with ultimately meeting the overall system phase noise requirement at the antenna.<br><br>The ATF subsystem must provide frequency sources and frequency references such that the total LO integrated phase noise requirement ATF1240 is met</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>LO Phase Drift</td><td>< 59 fsec at 300 s for output of ATF including the RTD distribution<br><br>< 42 fsec for ATF subsystem alone<br><br>(linear term removed)<br><br>< 250 fsec absolute</td><td>ATF1250</td></tr>
<tr><td colspan="3">This requirement is for applicable to the entire distributed LO system for ngVLA. Most significant sources of LO phase drift may be expected to be incurred in the RTD and ATF subsystems. In particular, in the RTD subsystem it is necessary to compensate for phase drift associated with the fiber link. The requirements noted above are applicable after any round trip compensation is applied.<br><br>These requirements come from SYS1504, 1505, 5001 in “ngVLA System Requirements,” NRAO Doc# 020.10.15.10.00-0003 REQ:<br><br>SYS1504 The (relative) system phase drift residual shall not exceed 95 fsec rms per antenna over 300 seconds. Goal to meet this specification over a period of 1000 seconds.<br><br>SYS1505 The absolute phase drift per antenna over 300 seconds shall not exceed 4 psec. Goal to meet this specification over 1000 seconds.<br><br>SYS5001 takes the relative (95 fsec) and absolute (4000 fsec) drifts and allocates them to different subsystems. The Antenna Time and Frequency subsystem is allocated 1/5th of the total rms noise (i.e. 95/sqrt(5)=42 fsec) for residual noise. The requirement ATF 1250 takes into account the need to verify the phase drift with and without the RTD frequency drift subsystem. For phase drift between two LO units measured without fiber</td></tr>
</table>

optic distribution, the phase drift requirement is 42 fsec. Including the fiber optic distribution (and compensation) the requirement is 42 fsec $*\sqrt{2}$ = 59 fsec.

For absolute drift over 1000 seconds, $\tau = 250$ fsec is equivalent to .0.17 rad of phase scaled to the maximum LO frequency of 113.1 GHz.

| | | |
|---|---|---|
| Spurious Narrowband Tones | Spurious narrowband tones introduced in the LO spectrum may be expected to pass directly to the receive path. These tones shall contribute no more than -43 dB/MHz relative to the system noise level in the IF receive path.<br>***Derived requirement (see below)***<br>Within 3.5 GHz of carrier < –103 dBc<br>Beyond 3.5 GHz from carrier < –48 dBc | ATF1500 |

- Assume that the LO power is + 10 dBm.
- Further assume that the receive signal path noise floor is low ~ –80 dBm/Mhz. The requirement sets the spurious at –43 dB relative to this level, or –123 dBm/MHz.

If the conversion efficiency of spurious inputs at the LO port were about the same as inputs at the RF port, then we would need to suppress those spurious inputs by 10 + 123 = 133 dBc. Direct port-to-port leakage of the tone is likely to be less significant than downconversion, and in any case the spurs we are currently concerned with lie well outside the IF baseband frequency range, and will be significantly attenuated by the baseband signal path if not downconverted first.

This downconverted LO path can be mitigated by the use of balanced mixers, anti-alias filtering, and the use of saturated amplification in the receiver LO path. These details may be different depending on the LO frequency and receiver or downconverter band.

For instance, the anti-aliasing filters will suppress signals more than ~3.5 GHz away from the primary LO by at least 55 dB (IRD062x). Second, the mixers will likely all be balanced, which should suppress LO noise and inputs by another 15 dB or so. Finally, LO buffer amps inside the IRD modules will likely be run in compression, which would tend to suppress weak signals which are present on top of the primary LO. We can conjecture an additional 15 dB (TBC) for this effect. So, with these effects we can relax our spurious LO tone suppression spec (for signal beyond 3.5 GHz) to 133–55–15–15 = –48 dBc. Or, for tones close (within 3.5 GHz) to the carrier –103 dBc.

| | | |
|---|---|---|
| LO Frequency Ranges | LO frequencies shall be provided to support downconversion (except instances of direct conversion). | ATF1200 |

These shall fall in or near to the range of sky frequencies required for ngVLA: 1.2–8 GHz, 8–50 GHz, and 70–116 GHz. Fixed or tunable LOs must allow for continuous frequency coverage across these spans. Additionally, the design plan must allow for simultaneously multiple LOs in a given receiver band so that the full available instantaneous downstream processing bandwidth can be achieved, and so that discontinuous portions of a band may be selected.

| | | |
|---|---|---|
| LO Frequency Table | Given the overall frequency ranges covered by ngVLA, the detailed design of the Front End receiver and downconverter spanning this range will determine the specific LO tunings for each downconverter (IRD module) and receiver band. | ATF1205 |

A tuning plan, or table, with required amplitudes and frequencies will be specified in the ICD between the ATF and the IRD. The current working version of this frequency table is shown below:

| RF Band | Module | RF start (GHz) | stop (GHz) | LO harmonic | (GHz) |
|---|---|---|---|---|---|
| 2 | a | 3.5 | 12.3 | 2 | 5.8 |
| | b | | | 4 | 11.6 |
| 3 | a | 12.3 | 20.5 | 5 | 14.5 |
| | b | | | 7 | 20.3 |
| 4 | a | 20.5 | 34 | 8 | 23.2 |
| | b | | | 10 | 29 |
| | c | | | 12 | 34.8 |
| 5 | a | 30.5 | 50.5 | 11 | 31.9 |
| | b | | | 13 | 37.7 |
| | c | | | 15 | 43.5 |
| | d | | | 17 | 49.3 |
| 6 | a | 70 | 116 | 25 | 72.5 |
| | b | | | 27 | 78.3 |
| | c | | | 29 | 84.1 |
| | d | | | 31 | 89.9 |
| | e | | | 33 | 95.7 |
| | f | | | 35 | 101.5 |
| | g | | | 37 | 107.3 |
| | h | | | 39 | 113.1 |

| | | |
|---|---|---|
| LO Frequency Offsets | Nominal LO frequencies must be capable of frequency offsetting on a per antenna basis. | ATF1210 |

The considerations around the implementation of this requirement are detailed in [RD27]. Each antenna station will incorporate a fixed frequency offset that is a multiple of a small fixed offset. The current design value of this fundamental offset is 15.68 kHz. Thus, an antenna will have its LO offset by an amount of m*15.68 kHz, where m is an index representing the antenna station and can take on values m= –131, –130,…, –1,0,1,…130,131 for an overall offset range of +/-131*15.68 kHz equals +/- 2.054 MHz. Similarly, the digitizer clock shall offset by the same amount.

Since bands 2–6 all have more than one LO, it is noted that the fixed offset attached to each LO in a particular band results in a different ratio between the offset and the LO frequency. This has implications for the LO design and is not a requirement but rather a system design choice subject to review and/or change.

Also, it is noted that the incremental assignment of offsets to stations applies only within a single science subarray. Thus, only when all antennas are in a single subarray would the full +/- 2.054 MHz tuning range be used. This, and the fact that subarrays can be re-assigned amongst sets of antenna stations, means that the fixed offset to applicable to a particular station must be tunable to any of the values for m= –131, –130,…, –1,0,1,…130,131.

| | | |
|---|---|---|
| Digitizer/ Sampler Frequency | The Digitizer, or Sampler, implementation depends on the Front End design. The ATF must supply a digitizer frequency, or a reference frequency, as necessary, to support the Front End implementation. | ATF1208 |

Specific frequency (-ies) required for support of digitizers will be communicated to ATF via Antenna Electronics IRD group by means of ICD between ATF and IRD [AD20].

| | | |
|---|---|---|
| Digitizer/ Frequency Offsets | The Digitizer must be capable of frequency offsetting on a per antenna basis. | ATF1215 |
| Digitizer/Sampler Frequency Offsets: not a strict requirement but per [SYS2015] a desirable feature. See especially the discussion in [RD27]. The implementation of offsets will be detailed in the ICD between ATF and IRD [AD31], as well as the ICD between ATF and DBE [AD27]. A potential implementation is as follows:<br><br>Each antenna station will incorporate a fixed frequency offset to the digitizer (or digitizer reference) that is a multiple of a small fixed offset. The current design value of this fundamental offset is 15.68 kHz [see RD 56]. If the offset is to be applied to a reference to the digitizer that is fractionally related to the digitizer clock frequency, then the offset shall be applied as the same fraction multiplied by 15.68 kHz. Thus, an antenna will have its digitizer offset by an amount of m*15.68 kHz, where m is an index representing the antenna station and can take on values m= –131, –130,…, –1,0,1,…130,131 for an overall offset range of +/-131*15.68 kHz equals +/- 2.054 MHz.<br><br>Also, it is noted that the incremental assignment of offsets to stations applies only within a single science subarray. Thus, only when all antennas are in a single subarray would the full +/- 2.054 MHz tuning range be used. This, and the fact that subarrays can be re-assigned amongst sets of antenna stations, means that the fixed offset to applicable to a particular station must be tunable to any of the values for m= –131, –130,…, –1,0,1,…130,131. | | |
| | | |
| Digitizer JESD Clocking | LO and Timing requirements for support of commercial digitizer chosen for implementation in IRD modules must support the relevant JESD technical standard | ATF1290 |
| JESD204D is expected to be the standard of the eventual ngVLA digitizer. This standard is not published yet. However, clock and timing requirements are expected to be similar to the published JESD204C standard which is described in [RD28], [RD29]. | | |

### 5.5.2 Assumptions

Please see Section 5.1.3 for the top level context for the ATF subsystem. The following list of assumptions pertain to the Antenna Time and Frequency Subsystem:

- The ATF phase noise for local oscillators and digitizers refers to phase noise relative to a "perfect" reference. In certain interferometer array configurations, the phase noise between oscillators at different antennas may have the desirable quality of being mutually coherent in certain regimes if they have a common (central) frequency reference. However, for ngVLA the array configuration negates much of that possible advantage. First, many of the links are long haul > 100 km. For long haul links the round-trip phase correction bandwidth is limited by the reciprocal lightwave travel time. The reference clocks traveling to each antenna are thus susceptible to added noise from the links above this limited correction bandwidth which is an uncorrelated noise. The antenna oscillators will thus require very narrow band PLLs and must have very good near-in phase noise without much "assistance" from the central oscillator. Stated more simply: ***Any opportunity for coherent common mode antenna-to-antenna phase noise is eliminated by (a) very long fiber links, (b) narrow band PLLs at the antenna, and (c) antenna-based frequency offsets.***
- A receiver and water vapor radiometer are located on the elevated moving structure of the antenna
- A digital backend is located in the antenna pedestal.

- Each antenna station will be equipped with a receiver "package" consisting of six frequency bands, with each band comprising a feed horn and a low-noise cryogenic amplifier assembly. The receivers are located on the feed arm at the secondary focus. Located physically just behind this cryogenic receiver will be an additional electronics enclosures housing nineteen highly engineered assemblies that combine the functions of downconversion and digitization (these are called IRD modules: integrated receiver-digitizer). The receiver and the additional electronics assemblies have strict size, weight and power limits and are located in a front end enclosure (SFE) that is in an exposed mounting on the telescope near the secondary focus.
- There are 20 IRD modules, 19 of which require a unique LO frequency, and all of which require a digitizer reference frequency.

### 5.5.3 Overview

The distribution of frequency and timing reference has been covered in Sections 5.3 and Section 5.4. In this section what will be discussed is what frequency reference and timing circuits are implemented at the antenna to compete the requirements for local oscillator, digitizer clock, and timing references.

### 5.5.4 Top Level Design

A top level view of the Antenna, Time and Frequency subsystem design is shown in Figure 31. To each telescope there are two optical fibers, one carrying the frequency reference (F) and one for the timing reference (T) (note: alternatively, these could be on two adjacent wavelengths on one fiber). The fiber destination includes the secondary focus and the pedestal. There is a coupler at the base of the telescope that taps off to the pedestal, and the main path continues up the telescope to the secondary focus. The fibers are terminated by modules L503 and L501 in the pedestal and the secondary focus, respectively.

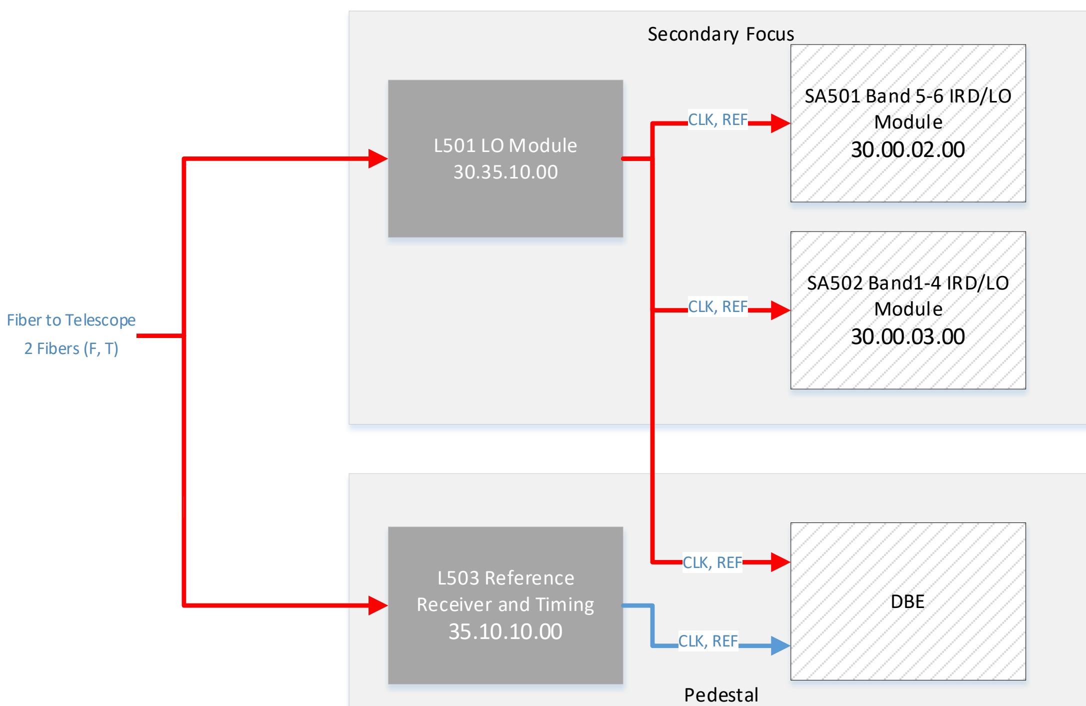


**Figure 31 - Top Level view of ATF subsystem design**

**L501 module:** Converts time and frequency references from optical to electronic. Provides return of both time and frequency references on the same fiber. Perform signal processing functions on frequency reference to:

- Use recovered frequency reference $f_{HI}$ to synchronize low frequency crystal oscillators
- Use recovered clock to synchronize and lock clock for direct digital synthesizers used for frequency offsets
- Supply common clock and timing for multiple LO and digitizers, including clock and timing satisfying JESD requirements
- Derive 1 PPS timing pulse synchronized with the recovered frequency reference (called the station 1 PPS)

Perform signal processing function on time reference to:

- Compare and record difference between the station 1 PPS with the 1 PPS recovered from the timing receiver (which in turn tracks the central 1 PPS)
- Implement a reset circuit which will reset the station 1 PPS so that its rising edge is synchronized with the closest rising edge of $f_{HI}$ to the rising edge of the station 1 PPS.
- Provide timing pulse input to the LO and digitizer signal processing

And then finally, coherent copies of certain clock and timing signals needed for the JESD receiver in the DBE will be transmitted by optical fiber from the L501 to the DBE.

**L503 module:** Converts time and frequency references from optical to electronic to be used as redundant copies in the pedestal as needed. Provides frequency and timing reference to any other modules in the pedestal as needed.

### 5.5.5 Antenna Time Domain

As discussed in section 5.5.4, section 5.4.3, Figure 23, and Figure 25 – the antenna station timing pulse is synchronized with the recovered frequency reference, which guarantees that there will always be a discrete number of samples between any two timing pulses. Over longer time intervals the degree with which it tracks the distributed and recovered central timing pulse is continuously monitored. If the station timing pulse drifts too far from the central pulse then it can be reset to the recovered central timing pulse (to within a clock cycle of $f_{HI}$). Note that the station timing pulse is derived from the centrally transmitted reference frequency, yet the actual LO and digitizer frequencies both have offset frequencies associated with them. However, because these offsets are restricted to multiples of 1 Hz and are sourced by DDS's which have clocks that are also derived from the station reference, there should still always be a discrete number of samples between station 1 PPS pulses.

### 5.5.6 Front End Enclosure Design

We discuss next the electronics in the secondary focus located Front End Enclosure (see top half of Figure 31). Here and in the next few sections will detail the conceptual design for the L501, and the ATF portions of the SA501 and SA502 modules. Mainly, this means providing detail about the design of the LO and digitizer sources and their synchronization. This is sketched in more detail in Figure 32. Also note that the physical design of these modules was described in section 5.1.4.

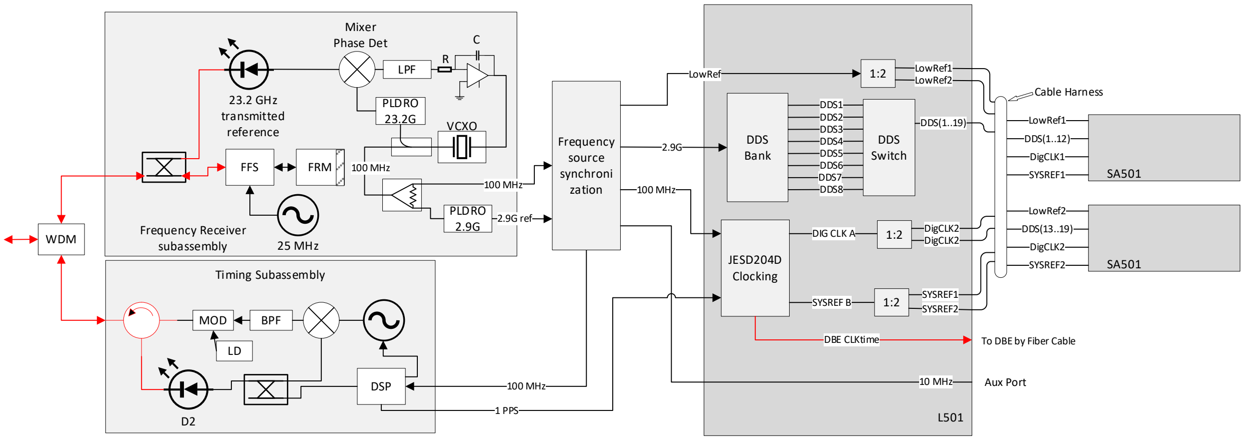


**Figure 32 - Antenna Time and Frequency modules in the Front End Enclosure**

As shown in the figure, a single optical fiber input carries the input lightwaves for the frequency transfer receiver and the timing transfer receiver. These are described in sections 5.3 and 5.4. the output of the frequency receiver is the antenna frequency reference 23.2 GHz. The frequency receiver assembly locks a local 23.2 GHz PLDRO to the transmitted reference in a narrow band phase lock loop. The 100 MHZ voltage controlled crystal oscillator (VCXO) in that loop is then used to produce a 2.9 GHz output reference that is also locked to the transmitted reference. The 100 MHz and 2.9 GHz references are then applied to the input of a synchronization module which produces additional outputs at 10 MHz, 90.3125 MHz, and all are phase aligned with the 2.9 GHz input. An additional 100 MHz output clock from the synchronizer module goes to the timing subassembly where the closest clock edge to the centrally transmitted (and corrected) 1 PPS is used to form the antenna station 1 PPS.

With all of the timing and references thus derived, they are applied as follows:

- A low frequency (90.3125 MHZ) reference is split and sent to both the SA501 and SA502 module
- JESD204 clock and SYSREF digitizer signals are split and sent one each to SA501 and SA502
- Eight DDS outputs are mapped to as many of eight out of 19 total LO modules in SA501 and SA502. DBE clock and timing is sent by optical fiber to DBE
- An auxiliary 10 MHz synchronized to the antenna frequency reference is available as a module output for testing purposes

### 5.5.7 1st LO Design

The local oscillators for ngVLA must provide for nominally fixed frequency operation at each of nineteen frequencies all at harmonic multiples of 2.9 GHz. This is shown schematically in Figure 33 (and the LO frequencies appear in tabular form in Table 11). At each of these fixed frequencies there is a small offset tuning requirement as well. The requirement is for the provision of discrete tuning steps indexed by antenna, so that each antenna has a slightly different overall LO frequency. The LO tuning offset maximum is +/- 2.05 MHz ($F_{Max_{offset}} = \frac{N_{ant}-1}{2} * 15.68\ kHz = 2.054\ MHz$).

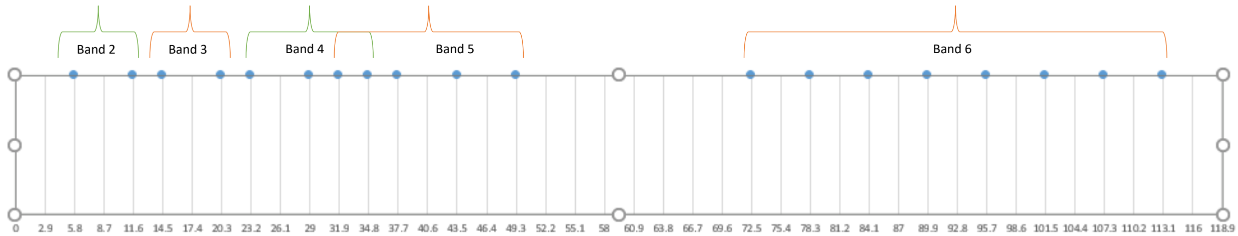


**Figure 33- LO frequencies and Receiver Band Groupings**

Several concept are being considered in the detailed implementation of the LO. We present below the detailed implementation of ***one*** of these concepts. In this concept, each LO is derived from a phase locked DRO oscillator roughly in the range of 5-20 GHz. For LO frequencies above 20 GHz conventional active multipliers are used to reach the higher frequencies. One consideration in the design was that the application of the required "small" frequency offset ruled out schemes in which crystal oscillators were directly multiplied to the GHz range. For Band 2, the push tuning of a crystal would be > 300 ppm resulting in poor phase noise performance. Three approaches have been identified to work around this issue:

- Offset phase locking using multiplied crystal and DDS
- Switched crystal scheme
- Directly multiplied DDS

Demonstration units for each of these approaches will be bench tested in FY2024. For CDR, we have assumed the first approach (offset phase locking) because it offers a good combination of reasonably low performance risk, realizability, simplicity, and is an approach that can be extended to Bands 2—6.

A generic schematic for the envisioned "offset-locked DRO" is shown in Figure 34. Note that there are two inputs: 2900 MHz and 90.3125 MHz. The first one, 2900 MHz, is derived directly from the transmitted central frequency reference by locking a cleanup oscillator to this frequency with a narrow loop bandwidth. This frequency is used as the clock for a direct digital synthesizer (DDS), and the frequency plan (for all 19 LOs) can then be arranged so that the required output frequency of the DDS is kept always below 100 MHz. The combination of high clock frequency and relatively low DDS output frequency will keep spurious signals at a lower level. The second reference is at frequency close to but not exactly a subharmonic of 2900 MHz – in this case 90.3125 MHz is "close" to 2900 MHz/32 or 90.625 MHz. This second reference frequency drives a sampling phase detector which essentially acts as a subharmonic mixer. With this offset locking topology:

- The DDS can easily provide the required small frequency offsets
- Spurious signals can be kept low
- A single crystal (90.3125 MHz) with optimally low phase noise can be used for all LO modules

There are of course still technical risk as even low spurs can exceed the ngVLA requirement, and the required ~$10^{-4}$ tuning range required of the DROs will lead to some phase noise degradation.

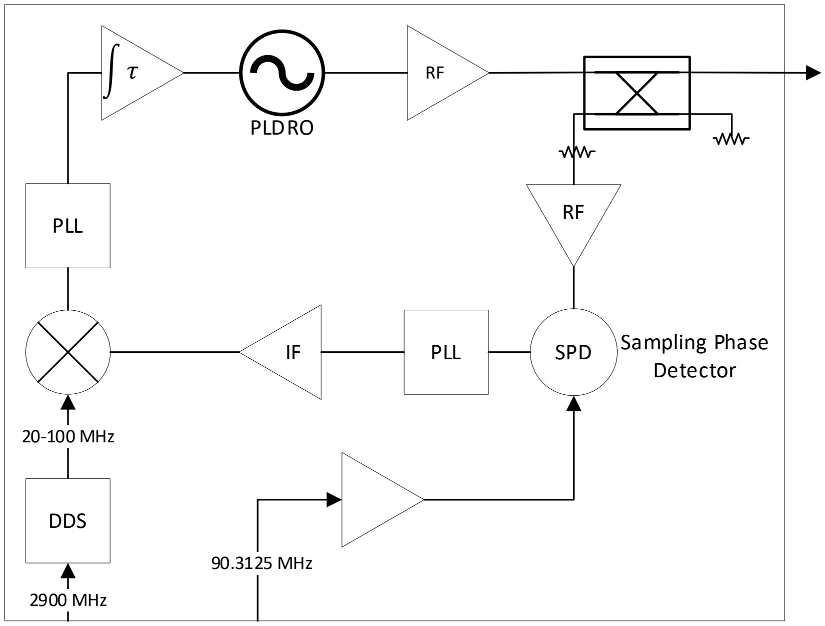


**Figure 34 - Generic schematic for "offset locked DRO"**

### 5.5.8 Synchronization of References

The two references shown in Figure 34, as well as additional references at 10 MHz and 100 MHz for the IRD/ADC modules can be derived and locked to the centrally transmitted reference frequency as shown in Figure 35. The frequency receiver subassembly produces 2.9 GHz and 100 MHz locked in a narrow bandwidth to the central reference. Additional circuitry then produces synchronized frequencies at 10 MHz and 90.3125 MHz. (Note: Figure 35 is a notional way of synchronizing 10 MHz, 90.3125 MHz, and 100 MHz from 2.9 GHz. It may not represent an optimal or final design.)

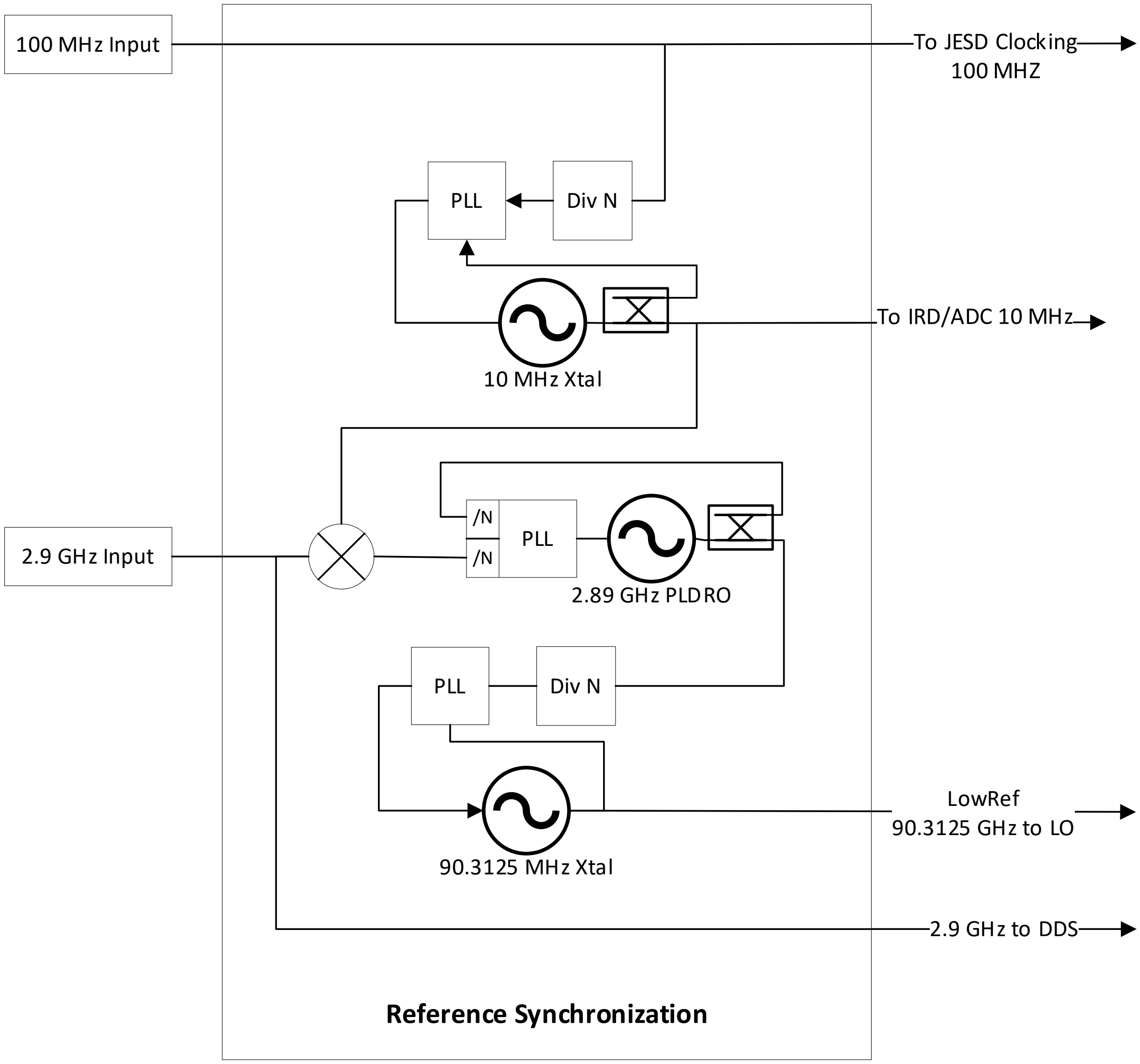


**Figure 35 - Synchronization of reference signals**

### 5.5.9 Digitizer Clock and Timing

The IRD modules also require input for the digitizer clock and the SYSREF signal that is required for JESD support [RD30, RD31].

The LO module is an offset locked PLDRO as described above and shown in Figure 34. Additionally, a digitizer clock and SYSREF signal is provided by commercial chips TI LMK04828 and TI LMX2594, as suggested in [RD32]. These parts would be suitable for providing signaling to currently available COTS ADC such as TI ADC12DJ5200RF. For future parts that may be selected as the ngVLA digitizer, these clock driver parts or future upgrades are expected to also be available. In any case, it is important that a frequency reference source (100 MHz) and timing signal (1 PPS) that are synchronized with the antenna frequency and timing are supplied as inputs.

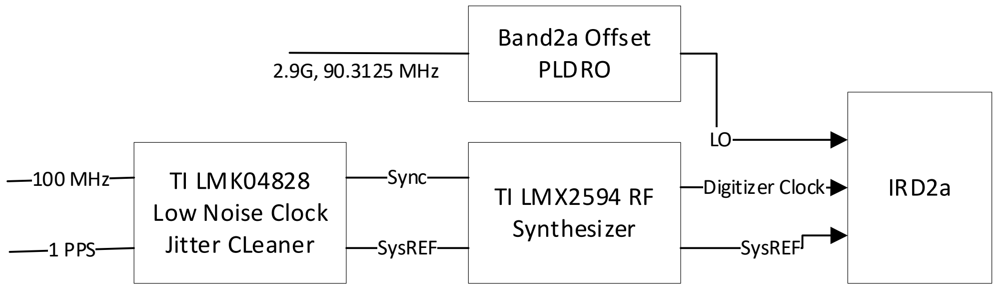


Figure 36 - Clock and Timing circuit for ngVLA digitizer

### 5.5.10 LO and Digitizer Offsets

In Figure 34, the DDS provides an offset to the LO frequency which is shown as being between 20 and 100 MHz. Table 12 shows how this can then be implemented for each receiving band – with DDS frequency in column 6. In addition to these nominal DDS offset frequencies, however, there will also be an additional antenna-dependent "small offset." These will be at frequencies given by

$$F_{OFFSET} = m * F_{STEP}, \text{ m=\{-131..-1,0,1,...+131\}}$$

Where m is the antenna index and $F_{STEP}$ is a small offset step size governed by the following considerations [RD27]:

- Large enough to cover the IRD tuning hole
- Multiple of 1 Hz
- Multiple of 56 Hz
- Ideally at or near the DBE maximum spectral resolution of 15.625 Hz
- Not too much bigger than that so as not to impact sub-band filter design requirement

Table 12 - Nominal DDS Frequency by Band

| BAND | X2.9G | LO Freq | MULT | DRO freq | DDS frequency |
|---|---|---|---|---|---|
| 2 | 2 | 5800 | 1 | 5800 | 20 |
| 2 | 4 | 11600 | 1 | 11600 | 40 |
| 3 | 5 | 14500 | 1 | 14500 | 50 |
| 3 | 7 | 20300 | 2 | 10150 | 35 |
| 4 | 8 | 23200 | 2 | 11600 | 40 |
| 4 | 10 | 29000 | 2 | 14500 | 50 |
| 4 | 12 | 34800 | 3 | 11600 | 40 |
| 5 | 11 | 31900 | 2 | 15950 | 55 |
| 5 | 13 | 37700 | 2 | 18850 | 65 |
| 5 | 15 | 43500 | 3 | 14500 | 50 |
| 5 | 17 | 49300 | 3 | 16433.33 | 86.77083333 |
| 6 | 25 | 72500 | 6 | 12083.33 | 71.77083333 |
| 6 | 27 | 78300 | 6 | 13050 | 45 |
| 6 | 29 | 84100 | 6 | 14016.67 | 18.22916667 |
| 6 | 31 | 89900 | 6 | 14983.33 | 81.77083333 |
| 6 | 33 | 95700 | 6 | 15950 | 55 |
| 6 | 35 | 101500 | 6 | 16916.67 | 28.22916667 |
| 6 | 37 | 107300 | 6 | 17883.33 | 1.458333333 |
| 6 | 39 | 113100 | 6 | 18850 | 65 |

Choosing 15.68 kHz (280th harmonic of 56 Hz), the total offset range from is then +/-2.054 MHz.
DDS devices can be tuned to exact frequencies only at multiples of the DDS frequency resolution which is given by $\frac{f_{CLK}}{2^N}$. For our chosen clock frequency of 2.9 GHz, and for typical DDS word sizes of 24, 32, and 48 bits the resolution would be 172.85 Hz, 0.675 Hz, and 1.03e-5 Hz (respectively) – but note that these are all truncated numbers. In general, the tuning step size is not an even number of Hz much less a multiple of 56 Hz. Therefore, the application of the offset frequencies will contain a frequency inaccuracy that is at most half of the frequency tuning resolution, i.e. 86.42 Hz for N=24 bits, 0.337 Hz for N=32 bits, and 5.15e-6 Hz for N=48 bits. Possible remedies for this include:

(a) Dither the offset frequency to achieve the exact frequency after averaging. Careful choice of the dither frequency step size and the dithering rate could be design issues, as well as the possible generation of spurious signals.

(b) Modify the clock frequency to be a perfect multiple of $56*2^N$. For instance, if $f_{CLK}$ were 939.524096 MHz, then the frequency resolution step size for 24 bits is exactly 56 Hz. Obviously it would also work for 32 and 48 bits, with exact multiples of 56 Hz being available but with finer frequency resolution. The tradeoff in this case would be that there would need to be a clock generator DDS to generate this special clock frequency, and it would likely need to incorporate fast dithering to achieve the exact frequency. Spurious and/or filtering could be potential issues with this approach.

(c) Accept the inexact frequency synthesis as something we can live with. This would involve choosing the DDS with enough bits that we could live with the maximum frequency error. The system requirement for absolute drift of the 1st LO and digitizer clock is 250 fsec in a 300s period. Table 13 shows the computed absolute phase drift incurred in 300sec for a DDS with 24, 32, or 48 bits. Columns are included for the minimum and maximum LO frequency as well as the digitizer clock frequency. For a 48-bit DDS, the digitizer clock and all LO frequencies except 5.8 GHz would still meet the absolute phase drift requirement. For 5.8 GHz the excess drift over the requirement is almost negligibly small. ***So, we could probably live with a 48-bit DDS and no further correction. However, due to the fact that we have knowledge of the frequency error, downstream compensation in the signal processing chain could be implemented to remove this particular drift term.***

**Table 13 - Absolute phase drift incurred (in 300s) due to deviation from desired LO/digitizer frequency**

| | | Minimum LO frequency=5.8 GHz | | Maximum LO Frequency=113.1 GHz | | Digitizer Clock = 7 Gs/s | |
|---|---|---|---|---|---|---|---|
| | Max deviation from desired (Hz) | Fractional frequency deviation | Drift in 300s | Fractional frequency deviation | | Fractional frequency deviation | |
| 24-bit DDS | 86.42 | 1.49e-8 | **4.47 usec** | 7.64e-10 | **0.22 usec** | 1.23e-8 | **3.70 usec** |
| 32-bit DDS | 0.337 | 5.81e-11 | **17.4 nsec** | 2.98e-12 | **0.89 fsec** | 4.81e-11 | **14.4 nsec** |
| 48-bit DDS | 5.15e-6 | 8.88e-16 | **266 fsec** | 4.55e-17 | **13.6 fsec** | 7.36e-16 | **220 fsec** |

### 5.5.11 1st LO Design Choices

Although the conceptual design calls for an offset locked LO as shown in Figure 34, there are several other aspects of the design that are discussed in the next few sections:

- Choice of oscillator
- Direct Digital Synthesizer Considerations
- Frequency multipliers and amplifiers
- Band 6 Implementation

Recall that ngVLA requires 19 local oscillators in 5 Bands, one per IRD module. The Band Plan is repeated here for reference:

Table 14 - Band plan for 1st Local Oscillator

| RF Band | Module | Start (GHz) | Stop (GHz) | LO (GHz) |
|---|---|---|---|---|
| 1 | a | 1.2 | 3.5 | |
| 2 | a | 3.5 | 12.3 | 5.8 |
| | b | | | 11.6 |
| 3 | a | 12.3 | 20.5 | 14.5 |
| | b | | | 20.3 |
| 4 | a | 20.5 | 34 | 23.2 |
| | b | | | 29 |
| | c | | | 34.8 |
| 5 | a | 30.5 | 50.5 | 31.9 |
| | b | | | 37.7 |
| | c | | | 43.5 |
| | d | | | 49.3 |
| 6 | a | 70 | 116 | 72.5 |
| | b | | | 78.3 |
| | c | | | 84.1 |
| | d | | | 89.9 |
| | e | | | 95.7 |
| | f | | | 101.5 |
| | g | | | 107.3 |
| | h | | | 113.1 |

#### *5.5.11.1 1st LO Oscillators*

There are multiple choices for VCOs in the LO system. Some driving features are tuning range, power consumption, spurs, and of course, phase noise. YIG oscillators have large tuning ranges and are typically tuned by an electromagnet. Permanent magnet YIGs use a permanent magnet to bias the magnetic field to the center of its range. A small electromagnet then either adds or subtracts from the field to tune the oscillator. They are available in small 0.625 inch by 0.5 inch tall cylindrical packages with output frequencies up to about 16 GHz and typically consume about 700 mW. Larger packages (1.25" x 2.8") with similar power consumption can reach about 44 GHz with an included doubler. They exhibit a loaded Q of typically a few hundred. They are current controlled oscillators. The free running phase noise is about -100 dBc/Hz at 100 kHz offset. Higher frequency YIGs usually require a large electromagnet and therefore more power to operate, but can work up to over 40 GHz.

Dielectric Resonance Oscillators (DROs) are voltage controlled oscillators that utilize a ceramic resonator coupled to microstrip structures in a transistor oscillator. Q's as high as 10,000 are possible. Tuning ranges are limited, but can be tuned to the offset ranges we require in ngVLA. Power consumption is around 5 watts. Phase noise in a typical 14 GHz oscillator is about -115 dBc/Hz at 100 kHz offset. DROs are available with fundamental outputs up to about 15 GHz. DROs can also produce spurs [RD33].

With the combination of lower phase noise and lower power the DRO oscillator is a better choice for the ngVLA (fixed frequency) LO.

#### *5.5.11.2 DDS Considerations*

From the requirements, the LOs will be required to tune according to:

$$F_{LO}=F_C+/- (n*0.00001568) \text{ GHz}$$
where $F_{LO}$ = Band Center Frequency
where (1<=n<=132)

That is to say that each LO shall be tunable in discrete steps as far as +/-~2.07 MHz from the center of the band. For direct digital synthesizers (DDS), exact frequencies are synthesized only at $f_{CLK}/2^N$ where fCLK is the DDS clock frequency and N is the number of bits in the DDS. Therefore, exact frequency steps of 15.68 kHz generally cannot be obtained. Depending on "N", and the tuning resolution of the DDS, there will therefore be an offset on the order of microhertz between the ideal LO frequency and the actual frequency (discussed further in 5.5.10).

Using a DDS in order to generate the offsets required by ngVLA poses some issues. Foremost is the generation of spurs. Phase truncation spurs result from the truncation of the phase word. The magnitude and distribution of phase truncation spurs is dependent on three factors [RD34, RD35]:

- Accumulator size (A bits)
- Phase Word size (P bits) – the number of bits after truncation
- Tuning Word

Certain tuning words yield no phase truncation spurs at all while others yield the maximum possible. If A-P >= 4, spur level van be approximated by:

-6.02*P dBc (below tuning word frequency)

So using the device AD9914 as an example, we have:

A=32
P=12
So, A-P=20
Therefore, -6.02(12) = -72.24dBc

So, ideally, the spur level will be no greater than -72.24 dBc. Calculating the exact amplitude and frequency of the spurs is quite complicated [RD36], though with careful filter design it can probably be ameliorated [RD37]. In the ngVLA LO architecture, we have the advantage of needing a very narrow range of output frequencies (+/- 2.08 MHz) centered around the nominal LO frequency.

Other factors affecting DDS noise are reference clock noise, DAC resolution, and sample rate. Reference clock noise is directly scaled up or down according to 20*log(Fout/Fclock), but cannot overcome the residual phase noise of the DDS or exceed thermal limits. Quantization noise resulting from the discrete steps the DDS output DAC must make in order to reproduce the sine wave is strongly related to DAC resolution and sample rate.

From [RD35] we can show the effect of oversampling (Clock>>Fout) on SQR (Signal power to Quantization Noise Ratio as Figure 37.

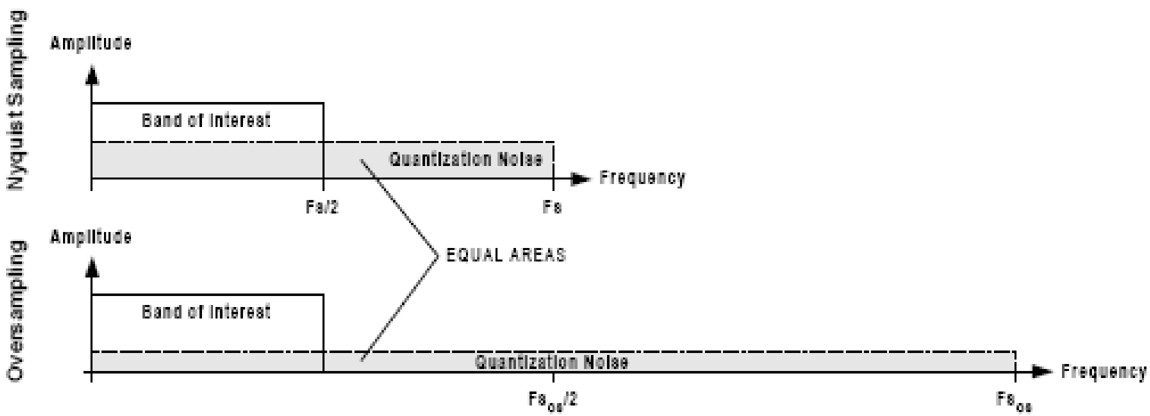


Figure 37 - Effects of Over-Sampling

A figure of merit relating signal power to quantization noise power quantization noise power can be represented as:

$$SQR(\text{in dB, per Hz}) = 1.76 + 6.02B + 20{*}\log(F_{sa}) - 10\log{*}(2F_{out}) \quad [RD35]$$

Where B is the number of DAC bits resolution, $F_{sa}$ is the sample rate, and $F_{out}$ is the DDS output frequency. This does not as such predict spur amplitudes but represents an average power level and should in general be about 10 dB less than the phase noise floor in the band of interest. Note that there is another term in the equation "+20log(FFS)" where FFS=fraction of full scale, however we are assuming that FFS=1 and this term = 0 dB.

As an example, for a 12 bit DAC with a 2.9 GHz sample clock outputting 40 MHz:

$$SQR(dB/Hz) = 1.76 + 6.02(12) + 20{*}\log(2.9E9) - 10\log{*}(8.0E7) = 184 \text{ dBc/Hz}$$

The AD9914 from Analog Devices which we are using for demo evaluations contains a 12 bit DAC, and was chosen mainly based on its maximum clock speed, which accommodates 2.9 GHz. In the sample design shown in Figure 34, the DDS has 2.9 GHz clocking and utilizes oversampling for low spurious.

The choice of DDS will be a tradeoff between clock speed, which correlates to heat generation, and DAC width, which contributes to SFDR and thus spur levels. In general, higher speed and greater resolution also translate into higher cost.

### *5.5.11.3 Multipliers and Band Plan*

Bands 2 and 3A can be reached with DROs operating at fundamental frequencies. All other bands will require multiplication. It is assumed the basic building block of all LOs will be similar in architecture (see Figure 34 as one possible example). Multipliers will be "outside the loop" and thus must be considered carefully. This is the case with ALMA local oscillators and with good thermal environments has not posed any issues. For ALMA, the antenna cabin temperature is tightly controlled to 1 degree Celsius drift per hour. Similarly, for ngVLA the LO assemblies will be co-located with IRD modules in LRUs SA501 and SA502 (see Figure 24), which will have tight temperature control.

As mentioned in section 5.5.6, several architectures will be investigated, though we have chosen the one shown in Figure 34 for illustrative purpose. We can continue that by sketching out the nominal DDS frequency for each band with this approach. This is shown in Table 15 which also includes the output frequency of the primary LO oscillator and the multiplier ratio needed to reach the final LO frequency.

**Table 15 - LO Plan with Fundamental oscillator frequency, multiplier requirements, and DDS frequency**

| | | RF | | LO | | oscillator | internal | external | LO Offset | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RF Band | Module | start (GHz) | stop (GHz) | harmonic | (GHz) | frequency | multiplier | multiplier | n=1 | n=+/-131 | DDS Frequency |
| 1 | a | 1.2 | 3.5 | | | | | | kHz | MHz | nominal (MHz) |
| 2 | a | 3.5 | 12.3 | 2 | 5.8 | 5.8 | 1 | 1 | 15.68 | 2.054E+00 | 20.000 |
| | b | | | 4 | 11.6 | 11.6 | 1 | 1 | 15.68 | 2.054E+00 | 40.000 |
| 3 | a | 12.3 | 20.5 | 5 | 14.5 | 14.5 | 1 | 1 | 15.68 | 2.054E+00 | 50.000 |
| | b | | | 7 | 20.3 | 20.3 | 1 | 1 | 15.68 | 2.054E+00 | 70.000 |
| 4 | a | 20.5 | 34 | 8 | 23.2 | 11.6 | 2 | 1 | 15.68 | 2.054E+00 | 80.000 |
| | b | | | 10 | 29 | 14.5 | 2 | 1 | 15.68 | 2.054E+00 | 100.000 |
| | c | | | 12 | 34.8 | 17.4 | 2 | 1 | 15.68 | 2.054E+00 | 120.000 |
| 5 | a | 30.5 | 50.5 | 11 | 31.9 | 15.95 | 2 | 1 | 15.68 | 2.054E+00 | 110.000 |
| | b | | | 13 | 37.7 | 18.85 | 2 | 1 | 15.68 | 2.054E+00 | 130.000 |
| | c | | | 15 | 43.5 | 10.875 | 2 | 2 | 7.84 | 1.027E+00 | 37.500 |
| | d | | | 17 | 49.3 | 12.325 | 2 | 2 | 7.84 | 1.027E+00 | 42.500 |
| 6 | a | 70 | 116 | 25 | 72.5 | 18.125 | 1 | 4 | 3.92 | 5.135E-01 | 15.625 |
| | b | | | 27 | 78.3 | 19.575 | 1 | 4 | 3.92 | 5.135E-01 | 16.875 |
| | c | | | 29 | 84.1 | 10.5125 | 2 | 4 | 3.92 | 5.135E-01 | 18.125 |
| | d | | | 31 | 89.9 | 11.2375 | 2 | 4 | 3.92 | 5.135E-01 | 19.375 |
| | e | | | 33 | 95.7 | 11.9625 | 2 | 4 | 3.92 | 5.135E-01 | 20.625 |
| | f | | | 35 | 101.5 | 12.6875 | 2 | 4 | 3.92 | 5.135E-01 | 21.875 |
| | g | | | 37 | 107.3 | 13.4125 | 2 | 4 | 3.92 | 5.135E-01 | 23.125 |
| | h | | | 39 | 113.1 | 14.1375 | 2 | 4 | 3.92 | 5.135E-01 | 24.375 |

The seventh column shows the fundamental oscillator frequency. This is limited by DRO technology to less than 20 GHz. For oscillators between 20 and 40 GHz an internal doubler can be used with the output of the doubler within the phase lock loop. Above 40 GHz an external doubler or x4 multiplier is required with the multiplier outside the phase lock loop. The frequency and power levels required of the multipliers can be achieved with COTs devices. Note that because the DDS is applied to the PLL, for the external multipliers the tuning range of the DDS is compressed by the same factor as the external multiplication.

### *5.5.11.4 Band 6 Option: Integrated LO*

As detailed above the Band 6 LOs require eight channels each with external multiplication. The size, weight, and power of these assemblies may be a concern, as well as the possibility of undesired LO-to-RF coupling between LO harmonics and adjacent channels. In this special case of Band 6, we have tested a new type of LO device. This is an integrated circuit W-band local oscillator with the divider and phase-lock-loop included in the chip, as shown below.

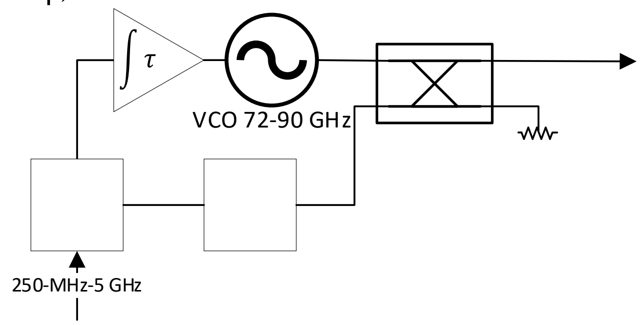


**Figure 38 - W-band integrated circuit oscillator**

The published work on this device is in [RD38] and more engineering detail of a similar device is in [RD39]. The device has considerable advantage in size, weight, and power. Preliminary measurements in [RD38] have been confirmed at NRAO demonstrating less than 50 fsec integrated phase noise at 84.1 GHz, easily meeting the ngVLA requirement of 76 fsec.

The phase noise measured at University of Ruhr is shown in Figure 39.

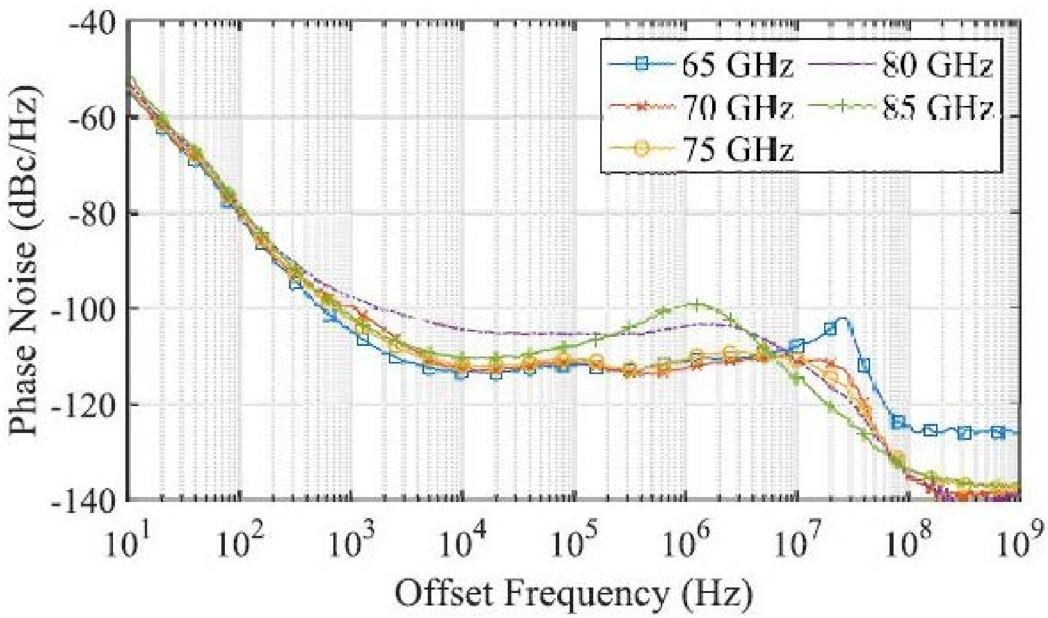


**Figure 39 - Phase Noise of W-band device at various frequencies**

Additionally, below the measurement at NRAO and Univ of Ruhr is compared. At ~ 85 GHz the NRAO measurement was < 50 fsec and the Univ of Ruhr measurement was 57 fsec. This is acceptably close for a W-band phase noise measurement using different test sets and references.

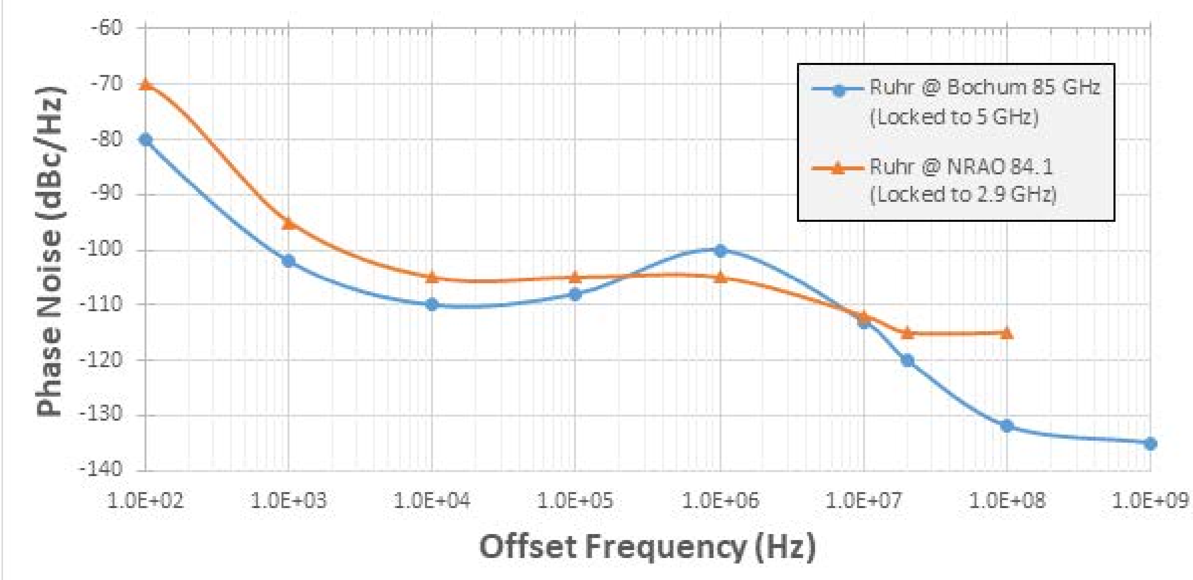


**Figure 40 - Phase noise measurement at NRAO compared to measurement at Univ of Ruhr**

Note that the Band 6 Integrated LO option is low TRL at the moment. This chip was designed for 70-90 GHz which could cover the frequency range of four of the eight Band 6 IRD modules. A second chip covering 90-113.1 GHz would need to be designed as well, which the design team has indicated is feasible for the technology. Additionally, however, it would be desirable to integrate the device with an amplifier to boost the output power to the level required by ngVLA (from < 0 dBm to +13 dBm). Therefore, this Band 6 Integrated LO is for now a secondary option but one that we will try to put further resources toward developing further.

### 5.5.12 LO and Timing Design for Antenna

The LO and Timing arrangement for the antenna is shown in Figure 41**,** including the IRDs, ADCs, and DBE. The "recovered frequency" is the signal coming out of the RTD frequency receiver. Note that the round-trip phase is measured but a real-time correction is not made in such a way as to affect the recovered frequency. ***Thus, this recovered frequency will contain a slow phase drift that represent the changing phase of the link itself.*** Each of the antenna based references is locked to this recovered central frequency reference (as in Figure 35).

The antenna 1 PPS is also derived from the centrally transmitted reference. From Figure 35, the 100 MHz VCXO is locked to the recovered 2.9 GHz, and the 1 PPS is derived ***synchronously*** from this 100 MHz signal – both of these signals are then provided to the ADC clock and timing drivers.

Also detailed in Figure 41 is the 1 PPS timing signal circuitry. There is a round trip measurement of 1 PPS timing from the central building to the antenna that provides a continuous measure of any timing variations between central building and antenna. The timing receiver associated with this subsystem will be located at the secondary focus within L501 in proximity to the LO and IRD modules. This receiver will have a 1 PPS output which is shown in Figure 41 as ***Compensated 1 PPS'***. This ***1 PPS'*** is expected to have a (near) real-time correction applied which represents the one-way delay through the fiber and thus the signal is a servo-adjusted "copy" of the central 1 PPS (this was also shown above in Figure 23). The difference between the 1 PPS (derived from the antenna 100 MHz reference and shown as "Div by 1e8" in Figure 41) and the 1 PPS' derived from the central building 1 PPS will also be continuously monitored via monitor variable 1 PPS'-1 PPS. If this monitor point grows in size beyond a given threshold, then the antenna 1 PPS can be reset to a new (nearest) count on the 100 MHz clock division.

Finally, Figure 41 also shows the physical division between the secondary focus area and the pedestal area where the digital backend (DBE) is located. The data crosses this threshold via commercial high-speed fiber optic transceivers connected by approximately 50m of single mode fiber. In addition, as shown in Figure 41, the 100 MHz clock and 1 PPS also cross this threshold via a transceiver pair. A key question is whether this link requires some form of compensation. Fifty meters of fiber will introduce a fixed latency of 250 nsec and a thermally variable latency of about 2.5 psec per deg C. Over one hour this could amount to 17.5 psec (7$^{0}$C) and over one day 50 psec (20 $^{0}$C). Based on these latencies, no compensation of the reference link will be required.

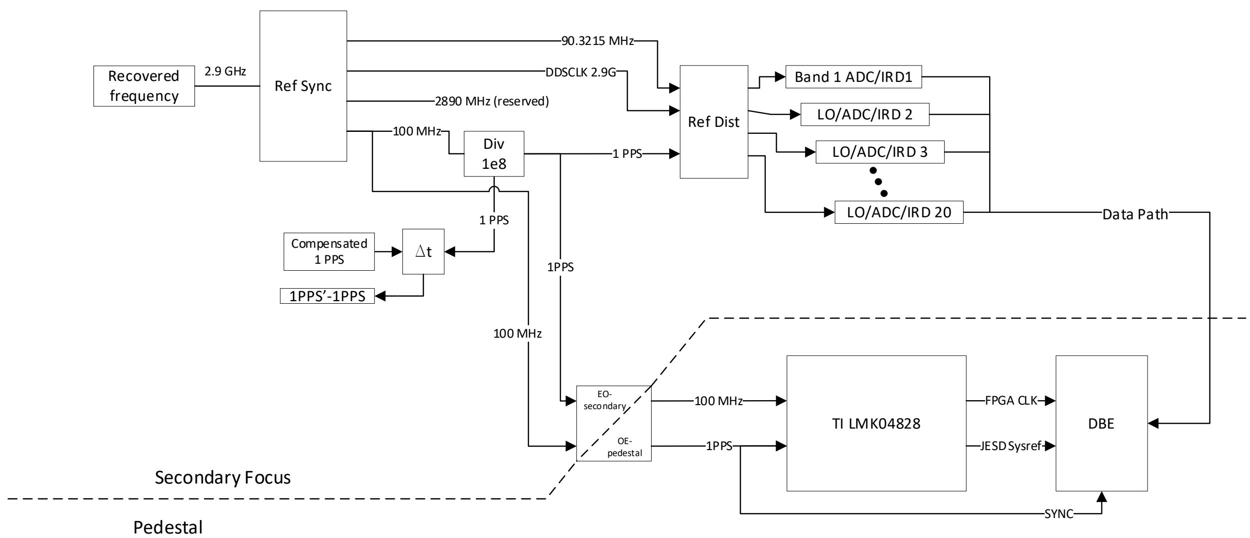


**Figure 41 - LO and Timing Diagram for Antenna including IRDs, ADCs, and DBE**

### 5.5.13 Link Delays

Figure 41 shows three links:

1. **Frequency transfer link:** The box labelled "Recovered Frequency" is the output of the frequency transfer link. This link comprises optical fiber up to ~300km (or more) in some combination of buried and above ground fiber long haul link. However, the design of the frequency transfer subsystem does not include a real-time hardware correction instead implementing a precision record of the round trip phase that can be made available for downstream correction. Thus, the recovered frequency will contain any phase drift that accumulates on the long haul link.

2. **Time transfer link:** The box labelled "Recovered 1 PPS' " is the output of the time transfer link. This link comprises optical fiber up to ~300km (or more) in some combination of buried and above ground fiber long haul link. The design of the time transfer system will allow for a real-time correction to be made to this recovered signal so that the output timing pulse is in principle aligned with the central timing pulse. Note however, that this timing pulse is not used in the signal path. Rather, a separate 1 PPS is generated from the recovered frequency and the difference between these two timing pulses is continuously monitored ( i.e. 1 PPS' – 1 PPS in Figure 41). If

there is significant accumulation of difference between these pulses then the 1 PPS can be reset to the 1 PPS' to within 1 nsec precision.

3. **DBE References link:** This link transfers a frequency reference and timing pulse from the secondary focus to the pedestal. The link is not corrected.

With the description of these three links as a given, we would like to consider the following questions:

(a) What is the typical phase drift of the recovered frequency? We wish to assess whether any phase excursions could somehow impact the signal processing chain and its fidelity.
(b) Given (a), what can we conclude about the likely drift of 1 PPS against 1 PPS' ?
(c) What is the typical uncorrected fiber phase drift of the link between the secondary focus and the pedestal, and how does this impact the DBE signal processing?

Let us assume that the worst case fiber environment is a length of 300km of fiber with 50 km of buried fiber and 250 km of above ground fiber. Further assume that the primary cause of open loop phase shift or delay is due to temperature (of the above ground fiber), and that the optical fiber has a fiber temperature coefficient of k=$10^{-5}$ ppm/°C. Delay change in the fiber goes as

$$\tau = \frac{L}{\frac{c}{n} * k * \Delta T}$$

where L is the fiber length, n is the fiber index (~ 1.5), and T is temperature in °C. Normalizing by distance this comes to 50 $\frac{psec}{km^0\text{C}}$, or 12.5 nsec per $^0C$ for the 250 km of above ground fiber.

We can estimate typical daily (24h) temperature variations of 20 $^0C$, and hourly variations of about one third of the maximum 24h change, or 7$^0C$ in 3600s (measured in May [RD40]). Thus, we can expect a maxim temperature related delay change of about 87.5 nsec/hr for the 300km link. If this corresponds to sunrise or sunset and the rate of change is fairly linear then this is equivalent to 24 psec/s, which is a fractional frequency change of 2.4e-11.

Note that an early study of aerial fiber links [RD41] found the following:

- Theoretical temperature induced delay normalized by length: 49 $\frac{psec}{km^0\text{C}}$
- Typical peak delay variation measured in overhead 127 km link: 200 nsec per day

This study theorized that additional pressure induced delay changes from wind, solar radiation, and precipitation add approximately 60% additional delay compared to what might be expected from temperature change alone. Thus for the ngVLA 300km link with 250 km buried fiber, we might expect:

**Table 16 - Delay versus time for ngVLA long haul link with 300 km total fiber: 50 km buried and 250 km aerial**

| Delay due to temperature | Delay due to all causes |
|---|---|
| 50 $\frac{psec}{km^0\text{C}}$ | 80 $\frac{psec}{km^0\text{C}}$ |
| 87.5 nsec/hr | 140 nsec/hr |
| 24 psec/s | 36 psec/s |

Using the second column of Table 16, we can calculate the phase change versus frequency:

Table 17 - Expected maximum rate of change of RF phase versus time for various ngVLA reference frequencies

| Frequency | | cycles/s | radians/s | deltaF/F |
|---|---|---|---|---|
| 10 | MHz | 0.00036 | 0.0023 | 3.60E-11 |
| 100 | MHz | 0.0036 | 0.0226 | 3.60E-11 |
| 1 | GHz | 0.036 | 0.2262 | 3.60E-11 |
| 2.9 | GHz | 0.1044 | 0.6560 | 3.60E-11 |
| 30 | GHz | 1.08 | 6.7858 | 3.60E-11 |
| 113 | GHz | 4.068 | 25.5600 | 3.60E-11 |

Two additional studies were found to provide relevant data points. In Krehlik et al [RD42], 300km of aerial fiber had delay variation of 200 nsec in a day, 80 nsec in an hour, and 2 nsec in a minute. These are of the same magnitude as what we estimated above. Finally, in Gozzard et al [RD43], on one-second timescales a fractional frequency variation above $10^{-11}$ (at one second) was measured for three aerial links between 30 km and 150 km. This implies delay variation changing at a rate of between 10 and 100 psec per second, which is also similar to what we estimated above.

With regard to the DBE reference link between the secondary focus and the pedestal, if we assume that this fiber is 50-m, then the scale of changes will be on the order of 17.5 psec maximum in any one hour period or 50 psec in a day. Since the ADC samples at 7 Gs/s = 143 psec, these variations should be benign.

### 5.5.14 LO and Digitizer Phase Performance Budget

Every attempt has been made to set forth a design concept that can meet the stringent ATF subsystem requirements [AD12], especially the key performance requirements detailed in Section 5.5.1. A plan for testing early demo LO modules is set to take place soon as a means to get early returns on our assessment of the performance risks.

In the following table the phase drift and phase noise performance budgets are set forth, consistent with [AD11].

Table 18 - Phase noise and drift performance budgets

| Parameter | System Req. # | | |
|---|---|---|---|
| Allocation of Phase Noise & Drift | SYS5001 | | |
| Component | Noise (fsec, rms) | Drift Residual 300 sec fsec, rms | Absolute Drift 300 sec psec |
| **System** | **132** | **95** | **4.3** |
| **Sub-System Allocations:** | | | |
| ANT | 76 | 42 | 2 |
| ATF (LO) | 76 | 42 | 0.25 |
| ATF (DTS Clock) | 76 | 42 | 0.25 |
| ATF (RTP) | 0 | 42 | 0.25 |
| RTD | 0 | 42 | 1.25 |

For each column (noise, drift, absolute drift) the table shows the allowable system level, and listed below are allocation to the various subsystems. This table is interpreted as follows for the LO Reference and Timing subsystem:

- In [AD03] and Table 18 the phase noise is not allocated for upstream oscillators, just the final oscillators used for LO or digitizer. Thus, the RTD phase noise allocation is zero. However, in [AD12] and [AD13] 44 fsec is allocated for RTD phase noise which is 1/3 RSS of the allowable 76 fsec for the 1st LO.
- Phase noise is assumed to vary linearly in radians with frequency and remain fixed in terms of delay with frequency
- Digitizer clock phase noise is allowed to exceed 76 fsec by the ratio of sky frequency to digitizer frequency in this coherence derivation. However, it is anticipated that the digitizer clock interface (JESD204D requirement) will require aperture jitter less than 100 fsec
- For phase drift measured between two end-to-end LO systems, verification testing allows $\sqrt{2}$ increase above what appears in the table.

From [AD12] and [AD13] we have sub-allocations as follows:

**Table 19 - Phase noise allocation breakdown for 1st LO**

| Phase Noise source | Frequency offset limits | Phase noise allocation rms | RSS contribution |
|---|---|---|---|
| RTD output integrated from 1 Hz to 1 kHz | 1 Hz to 1 kHz | 44 fsec | 33 % |
| Contribution of Cleanup loop 2.9 GHz oscillator | 1 Hz to 2.9 GHz | 31 fsec | 16.6 % |
| Output of Cleanup Loop Oscillator | 1 Hz to 2.9 GHz | 54 fsec | 50 % |
| Higher frequency multiplication and synthesis | 1 Hz to 2.9 GHz | 53.7 fsec | 50 % |
| LO Output | 1 Hz to 2.9 GHz | 76 fsec | 100 % |

Or, represented schematically:

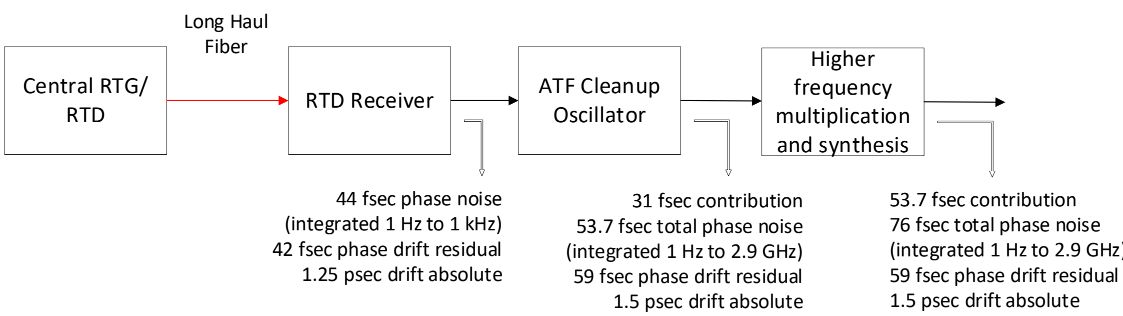


**Figure 42 - Phase Noise requirement vs position in the LO chain**

To consider an example oscillator as a candidate for the cleanup oscillator at 2.9 GHz, the phase noise of a Rakon oven controlled SAW oscillator has been plotted below (scaled from manufacturer data at 3.2 GHz - additionally, performance has been extrapolated in the 1 Hz to 10 Hz offset regime to correspond with an ultra low-noise crystal reference scaled up in frequency). This spectrum yields:

- 40.9 fsec integrated from 1 Hz to 1 kHz
- 41.5 fsec integrated from 1 Hz to 100 MHz

which meets the output requirement of 54 fsec for the cleanup oscillator. If the LO synthesis and multiplication is tightly locked to a reference like this, then the overall LO phase noise of 76 fsec can be be met. Nevertheless, the various elements in the LO chain each need to be optimally designed.

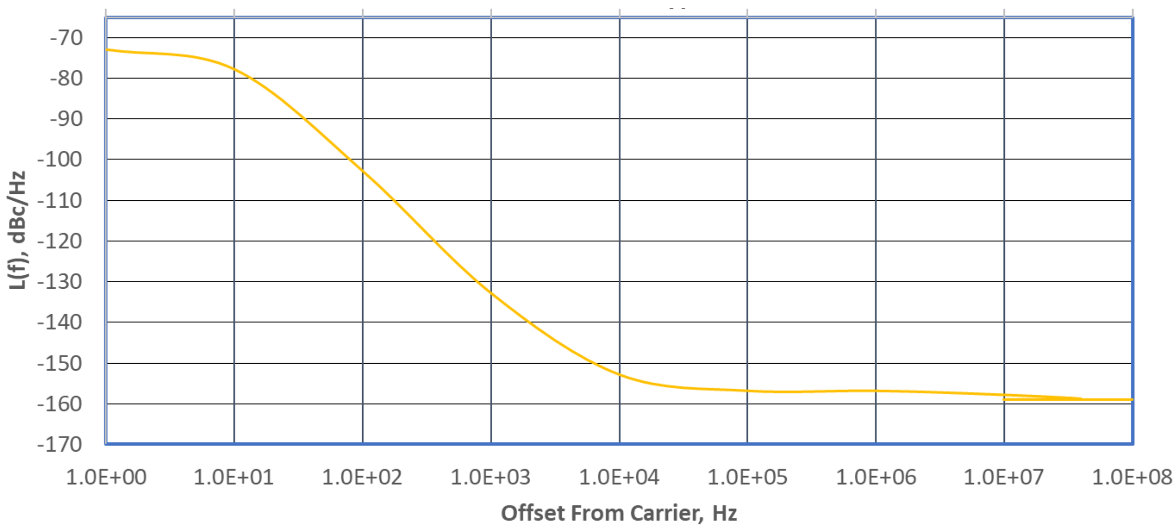


**Figure 43 - Phase noise of ultra-low noise microwave oscillator**

### 5.5.15 Risk

ngVLA risk is managed through the ngVLA Risk Register [AD14]. Currently documented risks for the ATF subsystem include:

**Table 20 - ATF subsystem risks**

| Risk | Description | Scale |
|---|---|---|
| LO Frequency Plan | The LO Frequency plan is an interface requirement that comes from the front end receiver and Antenna Electronics IPT and will be strongly determined by the use/choice of IRD-based digitizers or commercial digitizers. Any change from the current plan could impact the LO design, schedule, and budget forecast. | Med |
| LO Spurious Requirement | The LO spurious requirement set by interface with the IRD downconverter is -103 dBc for offsets from the LO frequency falling in the RF passband. The risk is that this requirement proves difficult or impossible to meet in all cases. | Med |

An additional risk that is related to the ATF subsystem but catalogued as a front end risk is the size, weight, and power (SWaP) requirement of the secondary focus-located electronics. This is a shared risk between all groups contributing deliverables that add to the SWaP budget.

### 5.5.16 Interfaces

Major interfaces of the ATF subsystem include:

- Reception of time and frequency references from the RTD subsystem
- Interface to Antenna Fiber optic distribution
- Monitor and Control interface via the Front End Hardware Interface Layer
- Interfaces with mechanical, thermal, and power supply interfaces with Antenna Electronics
- Signal interfaces with Front End receiver local oscillators and digitizers
- Signal Interface with Digitial Backend: JESD204 timing

### 5.5.17 Functional Requirement for ATF

A functional overview of the RTD subsystem is shown in Figure 44.

The frequency reference and timing reference are the primary inputs. These are conditioned and distributed to the IRD module first LO and digitizer inputs, and to the DBE. An antenna specific frequency offset is added to LO and digitizer clock.

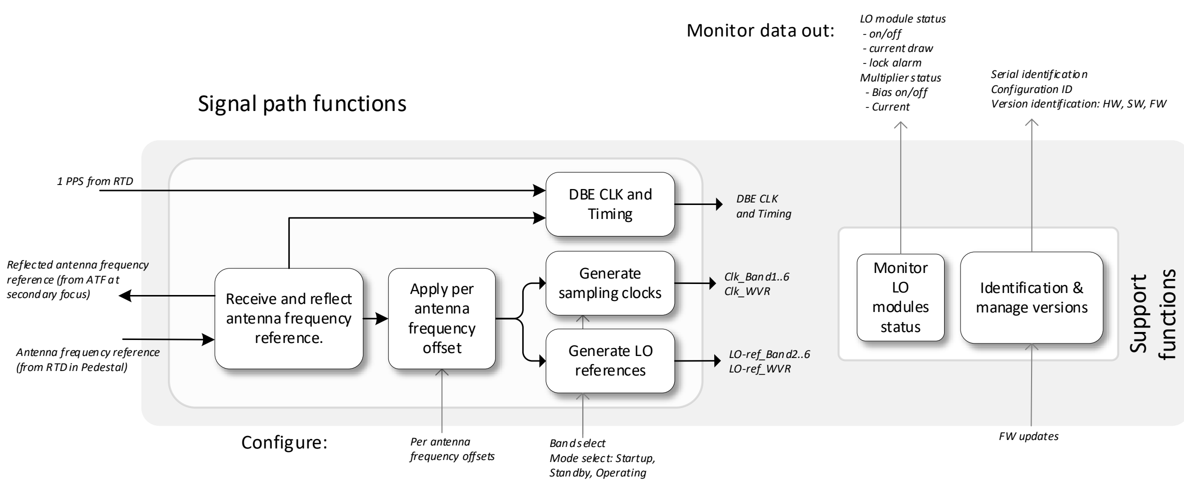


**Figure 44 - Functional Requirements for the ATF Subsystem**

- **A. Receive and Reflect Frequency Reference:** this function is part of the round trip phase measurement of the RTD subsystem but included here because the interface between RTD and ATF occurs at this mirror/frequency shifter.
- **B. Apply per Antenna Frequency Offset**: An offset will be applied by direct digital synthesizer (DDS) in the LO modules and by a JESD compliant frequency synthesizer in the digitizer clock circuit.
- **C. Generate sampling clocks and LO references:** for 20 digitizers and 19 LO modules.
- **D. DBE Clock and Timing:** With a 1 PPS timing reference and a frequency reference input, the clock and timing signals needed by DBE will be sent by optical fiber to the DBE which is located in the antenna pedestal.
- **E. Monitor LO Module Status:** Monitor and Control of LO and Digitizer clock modules.
- **F. Identification and Version Management:** Configuration ID, Version ID, Firmware version …etc.

## *5.6 Long Baseline and Distant Mid-Stations*

The ngVLA configuration (i.e. – geographical location of antennas) has been updated several times with most recent published version D [RD01]. Mainly the significance of the iterations of the configuration involve subtle performance improvements to the imaging model, or in some cases in response to land access issues. In any case, for the time and frequency distribution of ngVLA the following has been true for each iterated configuration:

A. The majority (70%) of the antennas are located within 30 km of the central building at the existing EVLA site. (217 antennas: 114 Core, 54 Spiral Arm, 19 Small Baseline Array (SBA))
B. About 17% (46 of 263 in Rev D) are between 30 and 800 km, this is called the MID-Array
C. Thirty antennas in ten groups of three are at continental span distances

Further, we can say that any future changes to configuration are not expected to impact the link design substantially, in the sense that the use of amplifiers and/or repeaters allows flexibility in antenna location and link distances. The goal for the central time and frequency design is to provided connected-fiber support for all of group (A) and as many of group (B) as possible. The long baseline antennas of Group (C) and the most distant MID stations of group (B) will be supported by a dedicated hydrogen maser for short term timing and GPS for long term timing. This is shown schematically in Figure 45.

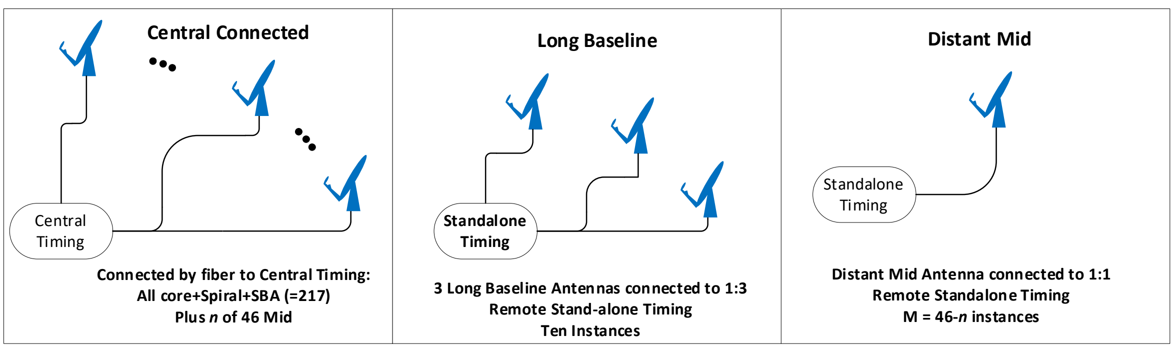


**Figure 45 - Configuration of Distribution of Frequency and Timing for Long Baseline and Distant Mid Antennas**

Note that for the 3x10 = 30 long baseline antennas and the distant MID stations, the ATF subsystem is the same as in the Main array, i.e. – nothing changes at the antenna. The instantiation of the standalone timing and the distribution of the timing to three (LBS) or one (distant MID) antenna will differ somewhat from the Central Timing, but mainly this difference will be just one of scale (i.e. – the distribution of frequency and timing involves different arrangements of splitter networks).

### 5.6.1 Long Haul Link Design

For the main array, the frequency and timing distribution (RTD subsystem) consists of central transmitter and antenna-based receiver. The fiber link distances are <= 30 km and the links are point-to-point. The time and frequency transfer is implemented for each antenna on a single fiber (see Figure 27), but a dedicated fiber is required for each antenna.

For the MID array antennas that are connected to the central timing, the fiber distances will in general entail losses that require compensation by periodic amplification. Any such amplification will need to be bidirectional to accommodate the round-trip nature of the frequency and timing links. Bidirectionality is not typically possible over commercial fiber links, so in cases where ngVLA leases fiber from commercial entities a special arrangement will need to be made to accommodate bidirectionality. A bidirectional optical amplifier with 20 dB gain placed approximately every 80 km is assumed. This has been demonstrated to work well in prior timing and frequency distribution systems [RD44].

### 5.6.2 Rev D Configuration

The MID array consists of 46 antennas. The configuration has been repeatedly updated and optimized, with revision D being the most recently fully released configuration [RD01]. The geographic configuration for rev D is shown in Figure 46.

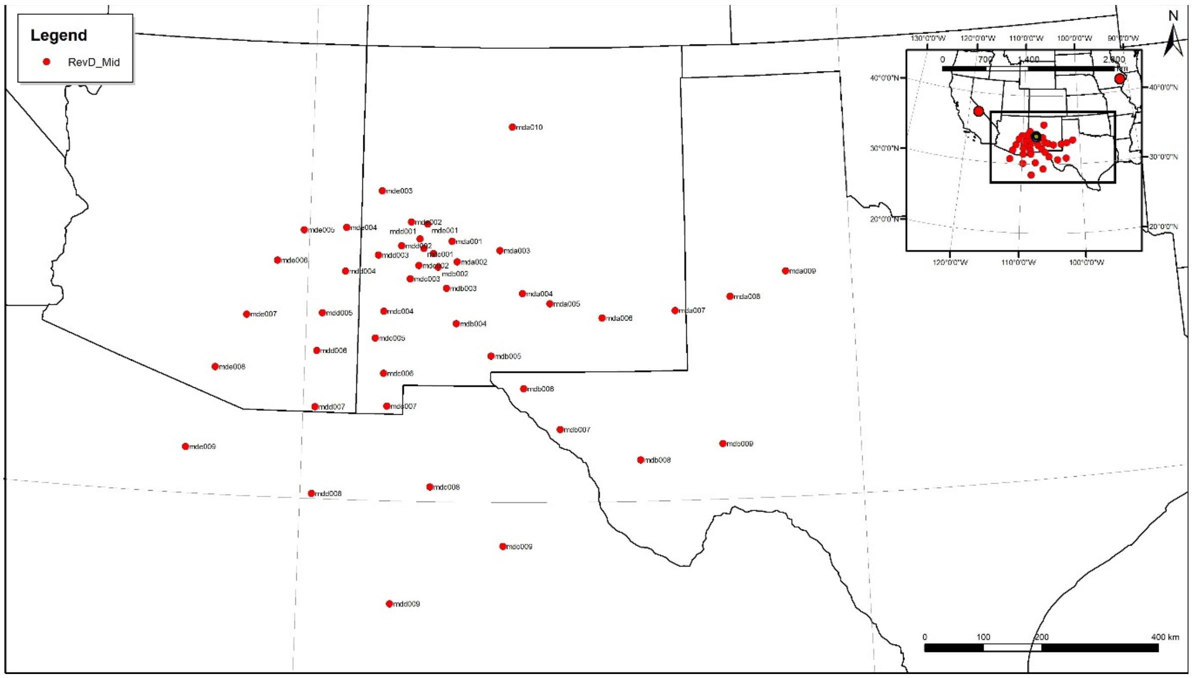


**Figure 46 - Rev D Mid-Baseline Antennas: geography**

In Table 21 the distance data are included for the rev D configuration which are arrange in loose and mostly southerly directed spirals. For each antenna the second column is the distance between stations and the third column is the accumulated distance from the array center. The distances are line-of-sight so the actual fiber distances would be somewhat greater.

**Table 21 - Distances to Mid-Stations. Note that the distances are line-of-flight. Thus, the distances will inevitably exceed these once the roads and rights-of-way are accurately factored in.**

| Mid Antennas | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a spiral | | | b spiral | | | c spiral | | | d spiral | | | e spiral | | |
| | inter-station distance | distance from center | | inter-station distance | distance from center | | inter-station distance | distance from center | | inter-station distance | distance from center | | inter-station distance | distance from center |
| mda001 | 27 | 27 | mdb001 | 30 | 30 | mdc001 | 30 | 30 | mdd001 | 29 | 29 | mde001 | 26 | 26 |
| mda002 | 36 | 63 | mdb002 | 24 | 54 | mdc002 | 30 | 60 | mdd002 | 33 | 63 | mde002 | 28 | 55 |
| mda003 | 76 | 139 | mdb003 | 39 | 94 | mdc003 | 28 | 88 | mdd003 | 42 | 105 | mde003 | 73 | 127 |
| mda004 | 83 | 222 | mdb004 | 63 | 156 | mdc004 | 72 | 159 | mdd004 | 63 | 168 | mde004 | 87 | 215 |
| mda005 | 50 | 272 | mdb005 | 81 | 237 | mdc005 | 48 | 207 | mdd005 | 81 | 249 | mde005 | 73 | 287 |
| mda006 | 93 | 365 | mdb006 | 79 | 316 | mdc006 | 62 | 270 | mdd006 | 65 | 314 | mde006 | 70 | 357 |
| mda007 | 126 | 491 | mdb007 | 94 | 410 | mdc007 | 56 | 326 | mdd007 | 96 | 411 | mde007 | 106 | 463 |
| mda008 | 97 | 588 | mdb008 | 147 | 557 | mdc008 | 157 | 482 | mdd008 | 155 | 566 | mde008 | 105 | 568 |
| mda009 | 105 | 692 | mdb009 | 144 | 701 | mdc009 | 161 | 643 | mdd009 | 231 | 797 | mde009 | 146 | 713 |
| mda010* | 275 | 409 | | | | | | | | | | | | |

### 5.6.3 Example Mid-Array Link Design

The fiber link design for the MID-array will ultimately depend on how many antennas can be linked by fiber and what are the final configuration and distances. However, as an exercise and as a demonstration of the approach that the design will entail, an example is included here. For this example, the D-arm of the MID array is chosen. An additional assumption is that the entire arm is connected to the central station, despite that this may very well be too expensive or impractical. Thus, the design needs to contend with a most distant antenna station at 797 km line-of-flight. For this example design we have assumed that the fiber distances are 10% greater than the line-of-sight distances. A further assumption is that there is just ***one fiber*** for the entire spiral arm. Thus, in addition to multiplexing the time and frequency onto a single fiber, it is also necessary to have nine separate transmission wavelengths for each of the time and frequency links. This is a significant additional expense but is included in this example in case the provision of a dedicate fiber to each antenna is prohibitively costly.

In Figure 47, each station that is shaded gray has a bidirectional fiber amplifier (***bidi-edfa***) at the station. A very rough rule is that these should be spaced no more than 80km. In the case of the first two stations, mdd001 and mdd002, strictly speaking there might not need to be a bidi-edfa at the first stations. However, for distances between 30-80 km, it makes sense to include them to allow for a little design margin and also for keeping the station designs more uniform. For each of the first four stations, in addition to the bidi-edfa, there would be a WDM filter to “pick-off” the wavelength that is assigned to carry the LO and timing for that particular station. At some distance, which in this example is 240 km, it may be necessary to have a “repeater station” (shaded green). At the repeater station, there is a more substantial and expensive equipment footprint that will perform an optical-to-electrical, and electrical-to-optical conversion (O-E-O) to regenerate the LO and Timing signal with the original signal-to-noise. Then, between stations mdd006 and mdd007, the distance is 106 km. Thus a bidi-edfa could be needed ***between*** the antenna stations. This represents an important requirement that would have to be satisfied by ngVLA as new infrastructure or by leasing from existing commercial (telecom) infrastructure. This process is repeated to the end of the spiral arm. In total, there are nine stations, six with bidi-edfas and three with repeaters, and an additional four standalone bidi-edfa installations.

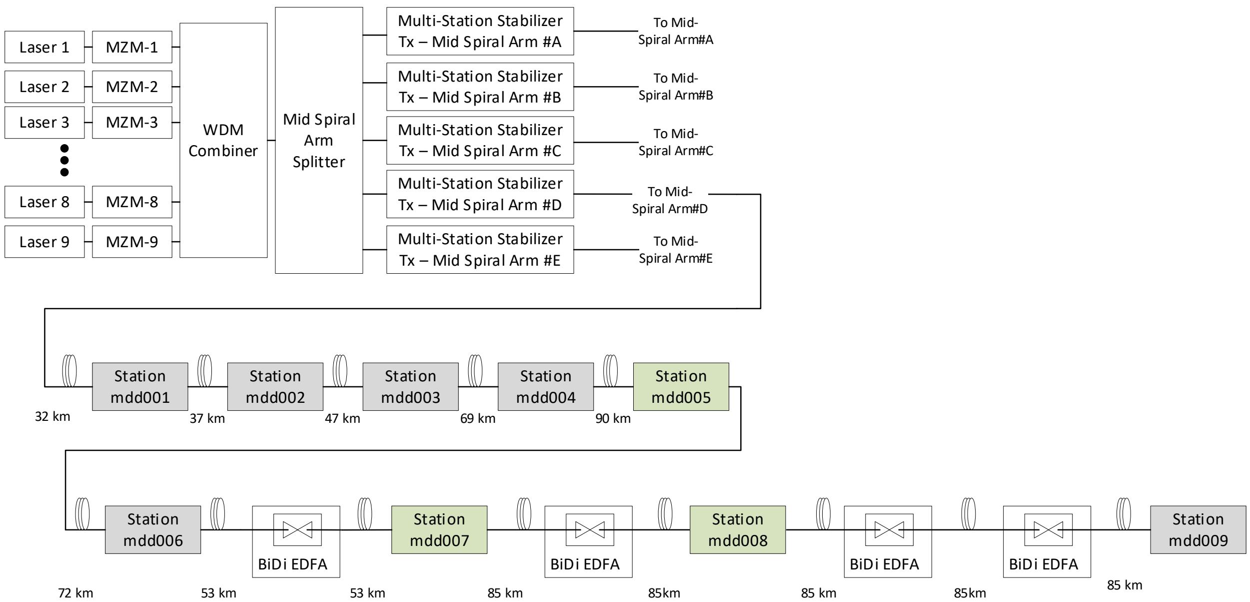


**Figure 47 - Example Mid-Baseline LO Distribution. Stations shaded gray contain a bidi-edfa. Stations shaded green contain a repeater. Additional bidi-edfas are installed between stations as required.**

# 6 Downselect Decisions

## 6.1 Frequency Transfer Downselect

### 6.1.1 Prior Work

A number of the published cases of frequency transfer by fiber have been comparison plotted below. Some effort has been made to select very good demonstrations of the technique over long fiber distances. These are plotted in Figure 48 below, along with a typical Allan variance of a hydrogen maser.

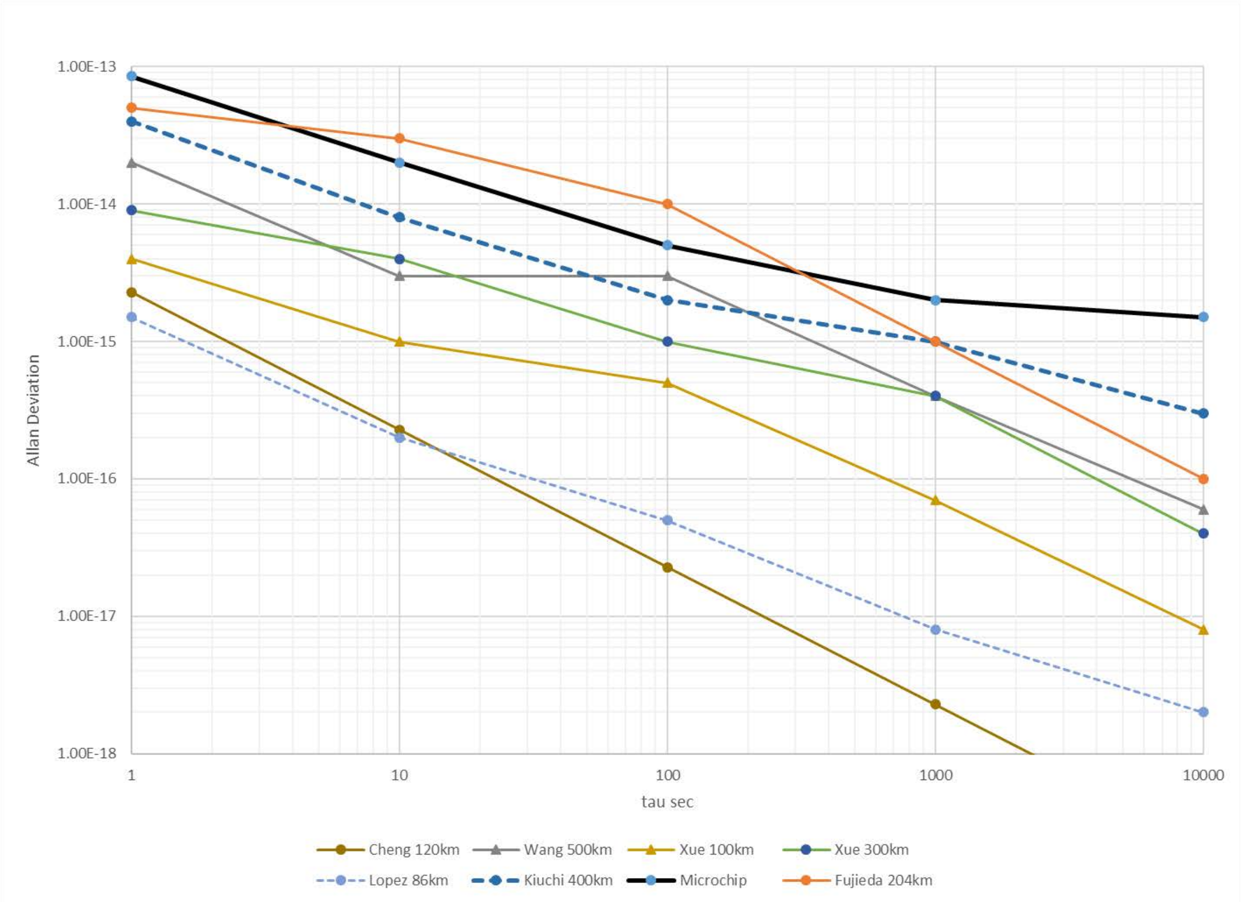


**Figure 48 - Frequency transfer published results (references listed below)**

Each of these examples used a different fiber testbed. The type of fiber link corresponding to these studies as shown in Table 22:

**Table 22 - Fiber link corresponding to the studies shown in Figure 48**

| | | |
|---|---|---|
| Cheng, [RD45] | "Digital output compensation for precise frequency transfer over commercial fiber link" | 120 km commercial link |
| Wang, [RD46] | " Long-Haul High Precision Frequency Dissemination Based on Dispersion Correction" | 500 km consisting of 310 km urban link plus spools |
| Xue, [RD47] | "Cascaded microwave frequency transfer over 300-km fiber link with instability at the $10^{-18}$ level" | 100 km spool |
| | | 300 km spool |
| Fujieda, [RD20] | "Coherent microwave transfer over a 204-km telecom fiber link by a cascaded system." | 204-km JGN2+ link Tokyo Subway |
| Lopez, [RD48] | "Fiber frequency dissemination with resolution in the $10^{-18}$ range" | 86km urban link |
| Kiuchi, [RD12] | "Frequency transfer subsystem Design description" | 400 km spool |
| Microchip | www.microchip.com | H-maser ADEV for reference |

A further step can be made to compare the results by relying on derivations from [RD49], [RD50] that projects that the link noise behavior with distance will vary as $L^{1.5}$ where L is the length of the link. Thus, the following figure shows again the very same published results but with the results scaled according to this $L^{1.5}$ relation to a normalized link length of 100 km.

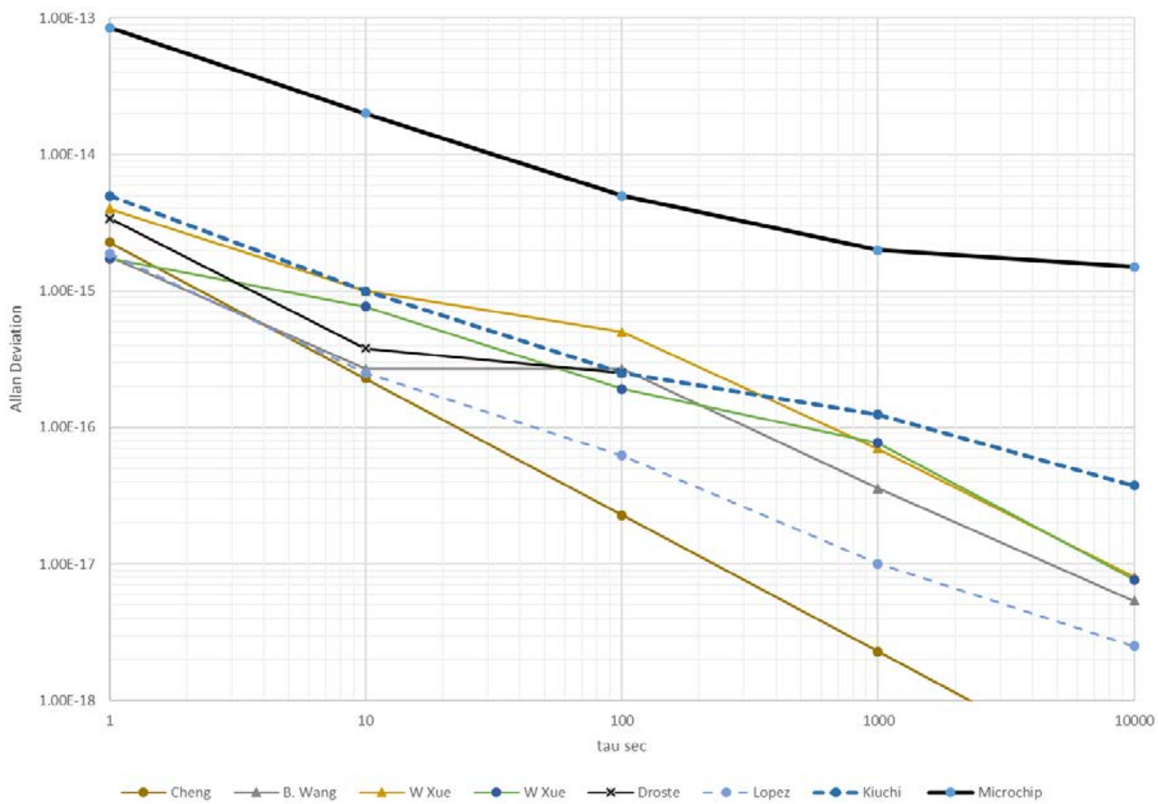


**Figure 49 - Frequency transfer: published results with results scaled to 100km**

Note again that per section 5.3.1 the ngVLA requirement is 42 fsec at 300s. We may expect Allan deviation corresponding to this level of drift to be ~42e-15/300 ~ 1.4e-16. This may depend on the type of noise and drift but the techniques are all showing a slope approaching 1e-16 at 300 seconds. Thus, all of these examples could be candidates for meeting the ngVLA requirement – at least at 100 km.

Thus:

- Out to about 100 km the ngVLA requirement may be considered low risk technically.
- Between 100 and ~400km, the ngVLA requirement may be considered medium risk technically with likely underperformance against the requirement but still better than use of independent masers
- Beyond ~400km, the issue may be moot due to the high incremental cost of fiber links and the likely use of independent masers instead of a direct fiber link.

### 6.1.2 Downselect Decision

A number of different approaches have been used in prior work to accomplish accurate frequency transfer by fiber (see section 6.1). Results of published measurements differ by length of fiber, condition of the fiber (buried, metro, and aerial), transfer frequency, link distance, and method of actuation, or measurement of the phase.

The NAOJ method introduced by H. Kiuchi [RD12] is the recommended design for the conceptual design phase. The technique has been proven conceptually and as a lab prototype and has the backing of willing and capable partner institute.

Features of the proposed technique include:

- State of the art phase stability performance (see [RD12])
- Flexibility: Designed for offline compensation but can accommodate real-time compensation
- Flexibility: Can accommodate any reference transmission frequency: 100 MHz to 100 GHz
- Flexibility: Double difference technique with digital averaging phase detectors with variable time constant

## *6.2 Timing Transfer Downselect*

### 6.2.1 Prior Work

Time transfer by optical fiber has advanced steadily in accuracy. Where fiber links are available it is more accurate to transfer time by optical fiber than by other means such as satellite. For ngVLA we are particularly interested in being able to transfer timing accurately over long haul (> 100 km) links. Thus, a review of scientific literature on long distance time transfer was conducted filtering by the last ten years and link distances >= 80 km. Published results are usually presented in the form of a quantity called $T_{dev}$, Time deviation, which is an analog of the modified Allan Standard Deviation [RD51, RD52]. In the plot below, the published $T_{dev}$ accuracy is shown versus the averaging period, for each of the selected examples of prior work [RD44, RD53-RD64].

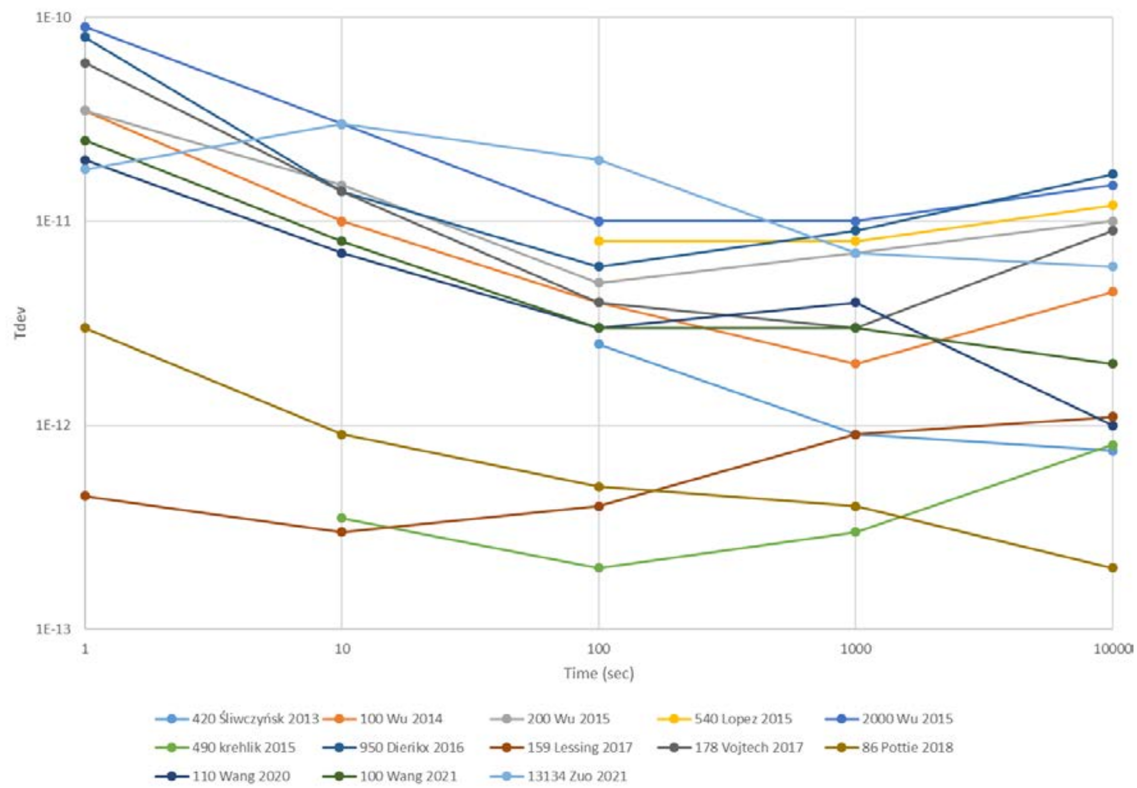


**Figure 50 - $T_{dev}$ plotted versus averaging time for each of thirteen timing experiments. In the legend, the first number refers to the number of kilometers of fiber, followed by the lead author's name, and the year of the study.**

Note that the results are not noticeably weighted by fiber distance. This suggests that systematic effects (equipment type, time measurement accuracy, how corrections are applied, …etc) are more important than the fiber length or impact of the signal-to-noise.

### 6.2.2 Time Transfer: NAOJ technique

See section 5.46 and [RD21,RD22].

### 6.2.3 Time Transfer: White Rabbit

#### *6.2.3.1 Concept*

White Rabbit is an improved version of pre-existing network time protocols (NTP, IEEE-1588) designed for sub-nanosecond synchronization of a large number of timing nodes (> 1000) over links of up to 10 km [RD65, RD66]. The White Rabbit approach to timing systems has some built-in features that make it an attractive approach:

- Scalability: based on a tree and node design
- Open source development concept
- Network compatibility
- Hardware supported by COTs equipment

Initially WR was implemented in Gigabit-Ethernet but has now been extended and demonstrated in 10 GbE networks [RD67]. The aim of WR (which has been realized) was to improve upon network time accuracy from NTP (1 msec) and IEEE-1588v2 (50 nsec) to reach sub-nsec accuracy. The primary feature that enables this improved accuracy is the use of a phase detector that measures the phase within a clock cycle, whereas IEEE-1588 implementations are limited in accuracy by the delay length of the clock cycle.

#### *6.2.3.2 Mechanism*

The WR system is implemented over synchronous ethernet with timing protocol via commands sent between nodes by packets. The clock, data, and timing embedded in the ethernet packets is decoded at the remote node receiver and a clock is locked at the remote node to the central clock. By using bidirectional SFP transceivers, a round-trip measurement of the clock signal is made and this phase is used to make adjustment to the recovered clock and timing at the remote node. The technique has secondary corrections for both link delay asymmetry in the forward/reverse direction, and fixed hardware delays.

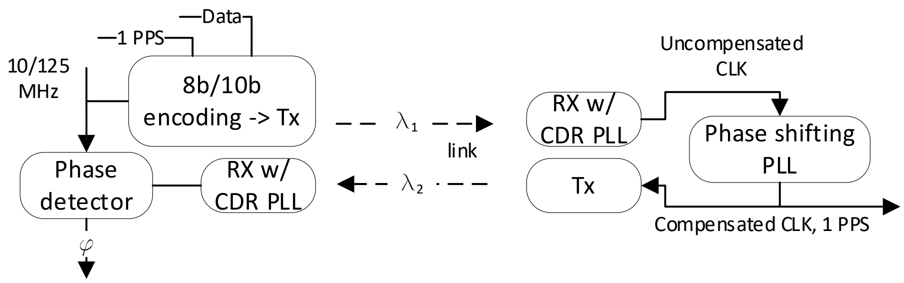


**Figure 51 - White Rabbit signal path diagram**

#### *6.2.3.3 Frequency Transfer and Phase Noise*

In an ngVLA study, Koelemeij reported transfer of 10 MHz with frequency stability of 7e-13 at 1 sec and 3e-16 at 7000 sec, and phase noise jitter of 180 fsec integrated from 1 Hz to 100 kHz [RD68]. Another report measures 10 MHz recovered phase noise from 1 Hz to 100 kHz as 1.4 psec (using a WR system with 'low jitter daughterboard') [RD69]. These are good results but not good enough for consideration of WR as a source for the frequency transfer for ngVLA.

#### *6.2.3.4 Systems in Use*

White Rabbit systems are in use in many places such as: at CERN (where it was developed), many European physics and timing labs, and a few labs in USA and China. In the USA there are installations at NIST and FermiLab. In addition, the SKA will use White Rabbit for timing distribution. These installed networks have in some cases thousands of nodes, and there are a many examples of link lengths exceeding the 10 km specification [RD70].

#### *6.2.3.5 Accuracy Versus Distance*

Many factors could affect the accuracy of a particular installation, including the type of fiber, the accuracy of the fiber transceiver wavelengths, the temperature stability of the equipment and fiber environment, and the length of the fiber. Generally, sub-nsec accuracy has been achieved for < 50 km links and links > 80 km appear to have a somewhat lower accuracy in the range of 1-10 nsec [RD70]. Boven reported that for long haul links, use of Bidi SFP transceivers is required for good results, and the use of temperature controlled lasers and closely spaced DWDM channels improved the timing error budget for the SKA 173-km links to 1.174 nsec [RD71]. Another study showed that by eliminating the wavelength separation altogether between the light traveling in each direction, 200 psec accuracy at 50 km can be reached with also some simplification of the calibration procedure [RD72]. However, this also required the addition of optical circulators on each end of the link.

#### 6.2.3.6 Available Hardware

At least three companies make White Rabbit equipment: Seven Solutions (now Safran), OPNT, and Creotech.

### 6.2.4 Downselect Decision

As noted in section 5.4.1, the 2 nsec timing requirement to support DBE timestamping is a challenging one, particularly over long baselines. The fiber connected array spanning hundreds of km will have a fixed propagation delay of several msec, so the ~nsec residual after one-way correction requires ~1 ppm accuracy. In addition, the propagation delay will have temporal variability due to the effect of temperature which could approach ~ $1\mu$m. A time transfer system with this accuracy is being developed by NAOJ and appears well-matched to the ngVLA requirements. The White Rabbit system is in use by SKA and could also be a good match. The NAOJ system has potentially better accuracy.

The NAOJ method introduced by H. Kiuchi [RD12] is the recommended design for the conceptual design phase. The technique has been proven conceptually and as a lab prototype and has the backing of willing and capable partner institute.

The downselect selection of the NAOJ approach to timing transfer is discussed in sections 6.2, 5.4.6, 6.2.2, and 6.2.4. The White Rabbit alternative provides a risk mitigating backup option if needed.

## *6.3 Fixed vs Tunable vs Remote Local Oscillators*

The tradeoff between (a) tunable LO synthesizers (b) fixed LO and (c) remote photonic LO synthesizers was investigated in [RD03]. Option B was downselected.

## *6.4 Location of Direct Digital Synthesizers*

There was some consideration given to the idea of having the small offset frequencies needed for the LO to be synthesized centrally, and distributed to the antenna. This has the advantage primarily of separating the frequency synthesis from the low-noise receiver front ends and thereby reducing the likelihood of self-interference and making the EMI/RFI engineering easier to manage. This was the implementation chosen for the SKA, in which a similar frequency offsetting scheme was needed [**]. However, a number of factors weighed in the other direction:

- For ngVLA there is a need for multiple mutually synchronized antenna references: local oscillator, digitizer, and DBE.
- For ngVLA there are not only multiple receiver bands, but multiple downconverter slices (as many as eight for Band 6) within those bands – all requiring uniquely different LO frequencies but the same digitizer frequency
- For ngVLA, small frequency offset capability is planned for both the LO and the digitizer.
- The frequency transfer scheme can easily accommodate a variable frequency but does not easily accommodate multiple frequencies.

For these reasons, a single fixed frequency transfer was chosen, from which multiple tunable references will be synthesized at the antenna.

# 7 Appendix

## 7.1 Abbreviations and Acronyms

| Acronym | Description |
| --- | --- |
| AD | Applicable Document |
| AFD | Antenna Fiber Distribution subsystem |
| AIV | Acceptance, Integration, and Verification |
| ALMA | Atacama Large Millimeter Array |
| ANSI | American National Standards Institute |
| ATF | Antenna Time and Frequency |
| BMR | Bins, Modules, and Racks subsystem |
| CDR/CoDR | Conceptual Design Review |
| CEB | Central Electronics Building |
| CI | Configuration Item |
| CoDR | Conceptual Design Review |
| COTS | Commercial-off-the-Shelf |
| CSP | Central Signal Processing |
| CSPT | CSP and Timing IPT |
| CSW | Computing and Software |
| DBE | Digital Backend |
| DRO | Dielectric Resonator Oscillator |
| DWDM | Dense Wave Division Multiplexing |
| EEC | Antenna Electronics Environmental Control subsystem |
| EMC | Electromagnetic Compatibility |
| ESD | Electrostatic Discharge |
| EVLA | Extended Very Large Array |
| FDR | Final Design Review |
| FED | Front End subsystem |
| FEE | Front End Enclosure |
| FIB | Central Fiber Infrastructure |
| GHz | Gigahertz |
| GNSS | Global Navigation Satellite System |
| HIL | Hardware Interface Layer |
| HVAC | Heating, Ventilation, and Air Conditioning |

| | |
|---|---|
| I/F | Interface |
| ICD | Interface Control Document |
| IEC | International Electrotechnical Commission |
| IPT | Integrated Product Team |
| IRD | Integrated Receiver Digitizer |
| KPP | Key Performance Parameter |
| LBS | Long Baseline Subarray |
| LED | Light Emitting Diode |
| LO | Local Oscillator |
| LOC | Limit Operation Conditions |
| LRT | LO Reference and Timing |
| LRU | Line Replaceable Unit |
| M/C | Monitor and Control |
| MCL | Monitor and Control subsystem |
| MOE | Measure of Effectiveness |
| MOP | Measure of Performance |
| MTBF | Mean Time Between Failure |
| MTTM | Mean Time to Maintenance |
| MTTR | Mean Time to Repair |
| NAOJ | National Astronomical Observatory of Japan |
| ngVLA | Next Generation Very Large Array |
| NLL | Narrow Linewidth Laser |
| NOC | Normal Operation Conditions |
| NRAO | National Radio Astronomy Observatory |
| NRC | National Research Council (Canada) |
| NSB | ngVLA Site buildings |
| OEO | Optical-Electronic-Optical |
| OLED | Organic Light Emitting Diode |
| PBS | Product Breakdown Structure |
| PCB | Printed Circuit Board |
| PDF | Portable Document Format |
| PDU | Power Distribution Unit |
| PE | Project Engineer |

| | |
|---|---|
| PLDRO | Phase Locked Dielectric Resonator Oscillator |
| POC | Precision Operating Conditions |
| PPS | Pulse Per Second |
| PSU | DC Power Supply subsystem |
| RD | Reference Document |
| RFI | Radio Frequency Interference |
| RMS | Root Mean Square |
| RTD | LO Reference and Timing - Distribution |
| RTG | Reference Timing Generation |
| SBA | Small Baseline Array |
| SKA | Square Kilometer Array |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| TPM | Technical Performance Measure |
| TRL | Technology readiness level |
| VCO | Voltage Controlled Oscillator |
| WVR | Water Vapor Radiometer |

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