Enhanced local oscillator for the Event Horizon Imager

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Abstract—Due to a well-known empirical correlation in their properties, black holes are a "convenient lab" to compare concurring gravity theories. Available angular size (50 uas max) establishes a requirement to angular resolution of an imaging interferometer (5 uas). Both scattering broadening and atmospheric turbulence call for space-space interferometry on a 0.5 THz band. Having noticed that space-qualified oscillators are not so much optimal for this interferometry, we explore a concept for syntonization utilizing a two-way frequency transfer between telescope-satellites. We aim to relax the interferometer correlator by equalizing radiofrequencies (of core oscillators) exchanged over optical inter-satellite links for the syntonization purpose. We recognize that the syntonization concept is promising for operation at the same frequencies of core oscillators. We built a breadboard to evaluate that. We show the measured performance. We prove the capability to deliver the target performance (in fractional frequency stability) at the same frequencies of core oscillators. We demonstrate the syntonization at the same radio frequencies over optical inter-satellite link thus alleviating a need to correct for "communication Doppler" difference at the interferometer correlator. A syntonization progress is available for further assessment in support of the Event Horizon Imager.

Keywords—syntonization, two-way frequency transfer, radio interferometry, astronomy and astrophysics, Event Horizon Imager, M87, Sgr A*

I. INTRODUCTION

Imaging black holes from space requires a 0.5 mm observation band [1] challenging the "clocks" driving the imaging interferometer [2]. A topical ESA-patent [3] offers a concept being a prominent candidate solution.

We proved the concept in [4] by breadboarding the simplest architecture. The demonstrated frequency stability satisfies the interferometer requirement with an order of magnitude margin, the stability is compliant with both a temperature difference (±3°C between branches for 4.5 hours, the orbit period) and an Inter-Satellite Link (ISL) delay (0.2 s in the worst case over the mission).

Operation at rather small frequency offsets (up to 2.7 kHz) between core (not disciplined to each other) oscillators would allow to equalize the Doppler frequency shifts over the ISLs, alleviating the need to correct for these shifts at the interferometer correlator. This mode, being useful at mission-level, is not possible with the above-mentioned breadboard.

This conference paper is to report a progress in development of a new breadboard dedicated to operate at a very small (virtually 0) frequency offsets between core oscillators and a performance achieved.

II. THE CONCEPT

The considered two-way frequency transfer concept consists in a symmetric exchange of core/ceed frequency components between two (or more) satellites and in a follow-on mixing (adding) of these components. Sums of these components are very similar on a different satellites, namely:

$$A+B' = B+A', \quad (1)$$

where A and B are the core frequencies on-boards satellites and superscript symbol $'$ denotes delay and Doppler frequency shift.

At the particular case of A=B being useful for Doppler equalizing, the simplest implementation (1) is prone to frequency doubling. Because higher-order harmonics are less powerful than the second harmonic (therefore their presence at the proximity to the mixing product is less harmful), another implementation may be of interest for this particular case of A=B. Following the concept, these sums may be formed utilizing a higher-order harmonics of core frequencies

$$2A+B'+B' = 2B+A'+A', \quad (2)$$
$$3A+B'+2B' = 3B+A'+2A', \quad (3)$$
$$4A+B'+3B' = 4B+A'+3A', \text{ etc.} \quad (4)$$

Level of harmonics shall be considered in two mixers instead of one (1) though. This paper reports performance achievable at the simplest of the high-order implementations (2).

III. BREADBOARDING

A. Block diagram

Block diagram of the breadboard Fig. 1 follows the (2). The breadboard is integrated by two satellites and an optical ISL. Each satellite has the code oscillator at "F", denoted A and B. Each satellite has two mixers (frequency up-converters), while a single mixer suffices (1) at A≠B. This is a difference between architectures suitable for Earth Observation (A≠B) and Radio Astronomy (A=B is aimed) applications.

The core oscillator signal (at frequency F=A) gets splitted by two paths. For the local path, it gets doubled (block ×2) so to form a local oscillator (LO) for the 1st of the two mixers. For the remote path, it gets modulated over a colour (block E/O), transmitted to the counter-satellite (an optical link), demodulated (O/E), and fed to the 1st mixer of the counter-satellite B. Inputs to this 1st mixer are a delayed and

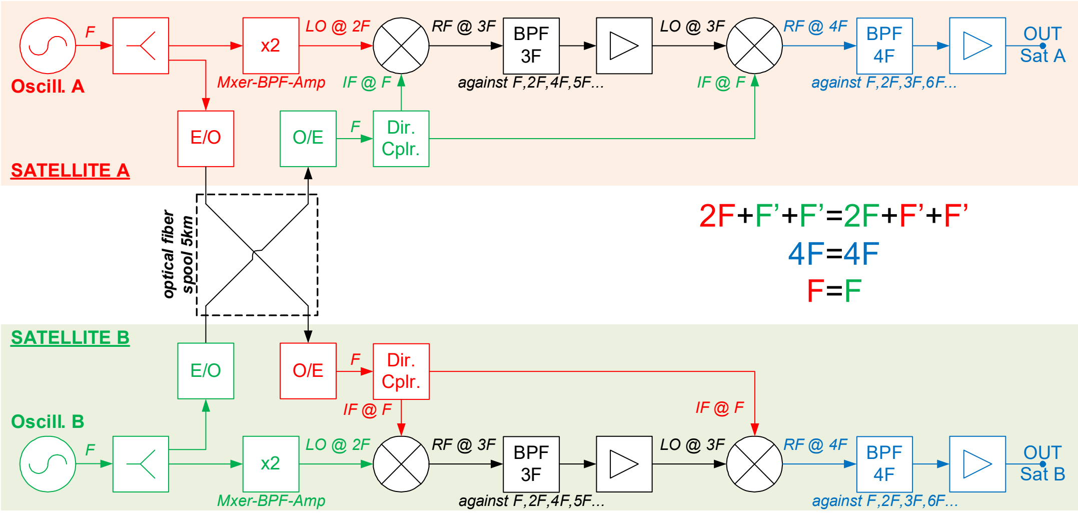

Fig. 1. Breadboard block diagram.

Doppler-shifted A, denoted as A′ in (1, 2), and the frequency-doubled B. The 1st mixers produce "3F" signals at

$$RF=LO+IF=2A+B' \quad (5)$$

at satellite A, and at "3F" frequency of 2B+A′ at satellite B.

Each of "3F" signals gets amplified and filtered to act at LO at the 2nd mixer. IF inputs of a both mixers are the same, it is the "F" received from the counter-satellite.

Each of the 2nd mixers produces the desired signal at "4F" as

$$2A+B'+B' \text{ and } 2B+A'+A'. \quad (6)$$

Following the concept (2), these two sums of (6) are very similar. The manuscript is to publish Allan Deviation measured between them.

B. Building bloks

1) Inter-satellite link

The ISL breadboard (DAS-Photonics) is integrated by a 5 km fiber spool (bidirectional / circulators), 2 lasers, 2 EDFAs, 2 MZMs (MXER-LN-20), 2 PhDs (U2T XPDV2150R) and a control circuitry.

2) Generators of core frequencies

Two free-running (not interlocked) lab generators are used, at F=11.575 GHz. Generators are Agilent PSG E8257D featuring UNX Enhanced Phase Noise, table 1. Generators permit to fine-tune core frequencies to assure |A-B|<<1 Hz.

At the case of Event Horizon Imaging, because the inter-satellite communication delay is constrained by flight-time over 30 m – 25,000 km, a meaningful offset frequencies are within [f_{Min}, f_{Max}] of

$$f_{Min}=1/\tau_{ISL}=1/(25{,}000 \text{ km} / 300{,}000 \text{ m/s})=12 \text{ Hz}, \quad (7a)$$
$$f_{Max}=1/(30 \text{ m} / 300{,}000 \text{ m/s})=10 \text{ MHz}, \quad (7b)$$

In which the main science case operates on inter-satellite distances of 20 km – 25,000 km refining the offset frequency band to [f_{Min}, f_{Max}'], where

$$f_{Max}'=1/(20 \text{ km} / 300{,}000 \text{ m/s})=15 \text{ kHz}. \quad (7c)$$

All in all, the frequency band of the most interest of EHI is 12Hz-15kHz (10 MHz).

The breadboard performance would depend on the core frequency phase noise at offset frequency defined by the ISL length (5 km) as

$$f = 1/\tau_{Fiber,\ 5km} \approx 1/(5{,}000 \text{ m} / 200{,}000 \text{ m/s}) = 40{,}000 \text{ Hz}. \quad (8)$$

3) Mixers, frequncy doublers, amplifiers

TABLE I. PHASE NOISE OF AGILENT PSG E8257D MEASURED USING R&S FSWP 50

Offset frequency, Hz	**L(f) dBc/Hz, at 11.575 GHz**
1	-47
10	-79
100	-94
1,000	-106
10,000	-115
40,000	-115
100,000	-115
1,000,000	-142
10,000,000	-153
100,000,000	-154

Mixers used at 1st and 2nd stage are Marki M2-0250L (triple balanced) and MM1-2567L (double balanced), respectively.

Frequency doublers are modelled utilizing available building blocks (a mixer, a band-pass filter at “2F”, an amplifier at “2F”). Use of 2nd harmonic out of photodetectors (-7.9 dBc) is practical though, is not aligned with the concept under demonstration.

Amplifiers by Eravant have been used as an economic solution.

4) RF-passive components

Band-pass filters at “2F”, “3F” and “4F” are to reject unwanted multiples of the “F”. Waveguide filters A1 Microwave PB2320WL (23,070 – 23,230 MHz), PB1674WB (35 GHz), PB2319WL (46,140 – 46,460 MHz) are used.

Splitters (Mini-circuits) and directional couplers (Marki) have been selected to maximize inter-channel isolation across multiples of the “F”.

Coaxial cables, transitions and adaptors are selected to minimize reflections.

IV. Measurements

A. Spectra out of mixers

A mixer produces not only the desired RF=LO+IF but also unwanted mixing products. Introducing a small |A-B| allows estimating these unwanted interferences (otherwise incorporated to the RF at A=B). The “3F” mixers produce such main interfering tones

- -28…-30 dBc, offset 2×(A-B) from RF at “3F” (5),
- -41…-42 dBc, offset 4×(A-B) from “3F” and dubbed 2×LO-IF,
- *3×IF* at -56…-52 dBc, offset 2×(A-B) from “3F” , etc.

The “4F” mixers produce such interfering tones in addition to the RF

- -25…-31 dBc, offset 2×(A-B) from RF at “4F” (6),
- *4×IF* at -31…-35 dBc, offset 2×(A-B) from “4F” ,
- -35…-36 dBc and -31…-50 dBc, offset 4×(A-B) from “4F”,
- -57…-60 dBc and -50…-54 dBc, offset 6×(A-B) from “4F”, etc

At A=B, the simplest implementation (1) is constrained by a second harmonic (A+B=2A=2B) level of -20…-25 dBc to the RF. These 2nd harmonics of both LO and IF inputs modulate the RF. These modulations compromise an achievable stability between RF tones derived on two counter-satellites at A=B (these modulations are alleviated at A≠B as both 2×LO and 2×IF get filtered-out by a BPF out of the mixer). At A=B, the implementation (2) allows to enhance the level of interfering tones (of individual oscillators) from -20…-25dBc to -31…-35 dBc.

Fig. 2. Performance measurement approach.

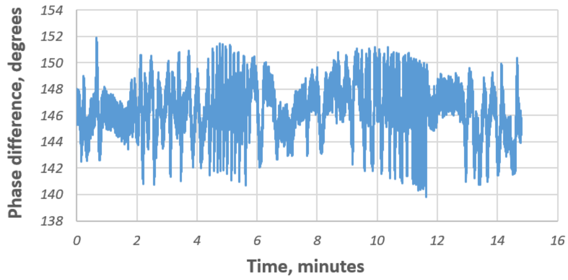

Fig. 3. Phase difference between derived LOs (6) with respect to time, at 46.3 GHz during 15 min. “1-sigma” = (151-141)/6=~1.7°. Analyzer used is PNA Agilent N5227B.

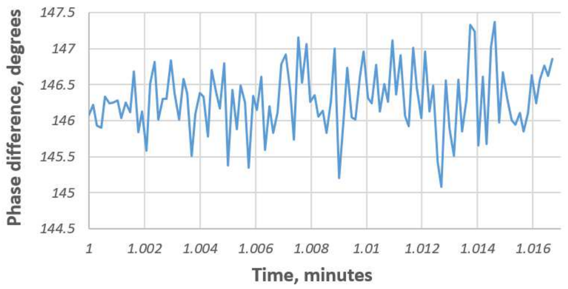

Fig. 4. Zoom-in Fig. 2 starting at 1 minute, duration 1 s.

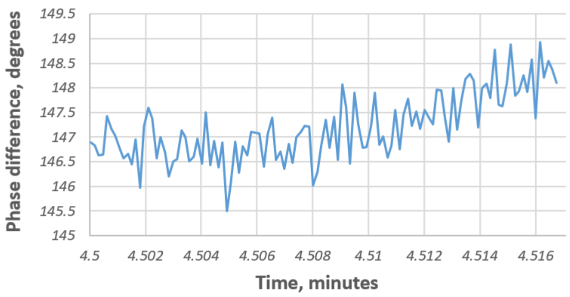

Fig. 5. Zoom-in Fig. 2 starting at 4.5 minute, duration 1 s.

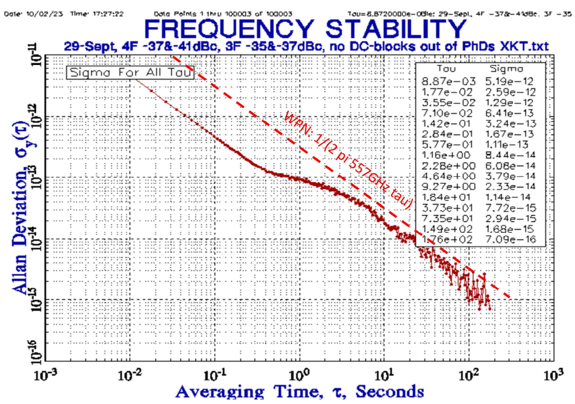

Fig. 6. Allan Deviation of the breadboard (2), at A=B.

B. Performance measurement approach

The phase difference between two derived oscillators has been measured utilizing a measurement approach [4].

Derived oscillators (6) are fed into a Network Analyzer, Fig. 2. The analyzer is set-up to operate a CW (continuous waveform) sweep at frequency of "4F". The max buffer length is selected to maximize a recording duration. Analyzer filter passband is selected to keep "4F" frequency change well withing its passband. We compute xk(t) at selected Analyzer sampling time *dt* of $1/BW_{IF}$ as:

$$\delta\varphi(\tau)=[\varphi_1(\tau)-\varphi_{VNA}(\tau)]-[\varphi_2(\tau)-\varphi_{VNA}(\tau)]=\varphi_1(\tau)-\varphi_2(\tau), \quad (9a)$$

$$x_k t = [\varphi_1(t)-\varphi_2(t)] / (f_0\ 360°), \quad (9b)$$

where f_0="4F" is the CW sweep frequency, $\varphi_{1,2}(t)$ are phases of derived oscillators (6), $\varphi_{VNA}(t)$ is a phase of frequency down converters at the Analyzer. The derived $x_k(t)$ is input to Stable32 to compute the Allan Deviation (Fig. 2).

As a sanity check, the fractional frequency stability between two oscillators (at 30 MHz) has been measured utilizing Miles-design TimePod driven by TimeLab software (as a measurement reference) and this approach [4].

C. Performance at A=B

At A=B, the phase difference with respect to the time (Fig 3) is within 6° of the carrier frequency 46.3 GHz. This plot has "good" parts with a white-like phase noise (e.g. Fig. 4) and "bad" parts with a phase ramp (e.g. Fig. 5). This performance has been achieved by minimizing the wave reflections in several coaxial adaptors used.

Allan deviation corresponding to Fig. 3 data is on Fig. 6. The level of harmonics out of mixers is not worser than -35 dBc at this measurement Fig. 2-5.

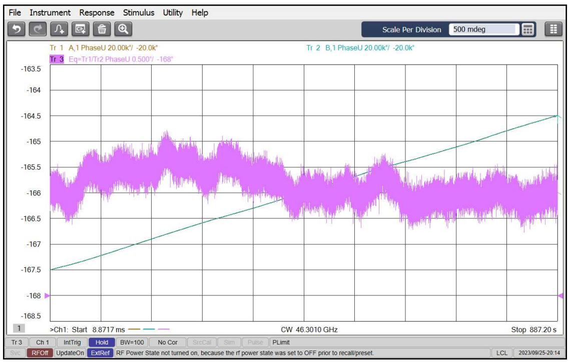

Fig. 7. Phase difference between derived LOs (6) with respect to time, at 46.3 GHz during 15 min. "1-sigma" = (166.5-165)/6=~0.25°.The main differrence to Fig. 2 (A=B) consists in the |A-B|=1 MHz.

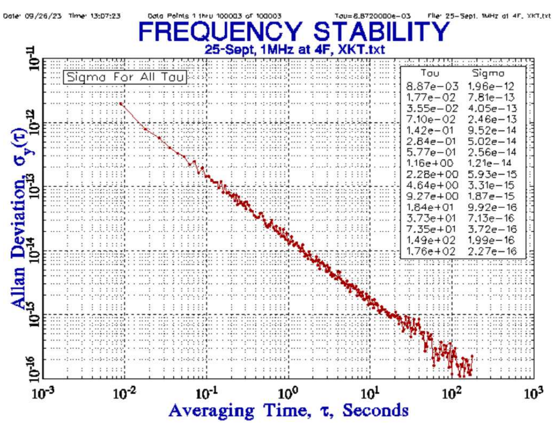

Fig. 8. Allan Deviation of the breadboard (2), at |A-B|=1 MHz.

D. Performance at A≠B

De-tuning from A=B allows that the phase difference between two derived LOs at 46.3 GHz is more white phase noise like, Fig. 7.

Corresponding Allan deviation is on Fig. 8. This Allan Deviation is better than the Allan Deviation on Fig. 6 because the interfering harmonics are outside the derived fundamentals, these harmonics are far from the filter passband.

Following [4], a performance with respect to |A-B| has been checked. A performance measure is

$$F_{max}=1/[2\pi\ \tau\ ADev(\tau)], \quad (10)$$

where F_{max} is a maximum frequency of a coherent integration (in a radio interferometer) at White Phase Noise mode of the core-oscillators A,B; ADev(τ) is the Allan Deviation between derived (6) oscillators driving the interferometer.

For this comparison, each recording duration is 15min, Analyzer sampling time is 8.87 ms (inverse to Analyzer IF filter), at 46.3GHz. In result, we observed that increasing the |A-B| permits improving the ADev towards 1e-14/τ in a way similar to implementation (2) at [4].

V. Conclusions

The reported breadboard confirms a possibility of syntonization utilising the same frequencies of free-running core/ceed oscillators driving radio interferometer embarked on separate satellites. This is useful for a candidate future science mission into imaging black holes form space dubbed Event Horizon Imager (EHI). Namely, operation at the same frequencies of core/ceed oscillators allows the same RF Doppler frequency shifts over inter-satellite links so alleviating a need to compensate their difference at the interferometer correlator. All in all, a capability to deliver the required frequency stability at very small (virtually 0) frequency offsets between core oscillators has been demonstrated.

References

[1] F. Roelofs et. al., "Simulations of imaging the event horizon of Sagittarius A* from space", Astron. and Astroph., vol. 625, 2019, pp. A124

[2] V. Kudriashov et. al., "An Event Horizon Imager (EHI) mission concept utilizing medium Earth orbit sub-mm interferometry", Chin. J. Space Sci., vol. 41, no. 2, 2021, pp. 211-233

[3] M. Martin-Neira et. al., "Syntonisation of signals between satellites", WO patent number WO/2023/147885, 2023

[4] V. Kudriashov et. al., "Laboratory demonstration of the local oscillator concept for the Event Horizon Imager", Journal of Astronom. Instrumentation, vol. 10, no. 03, 2021, pp. 2150010