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FOR 2863 Meteracom
Metrology for THz Communications

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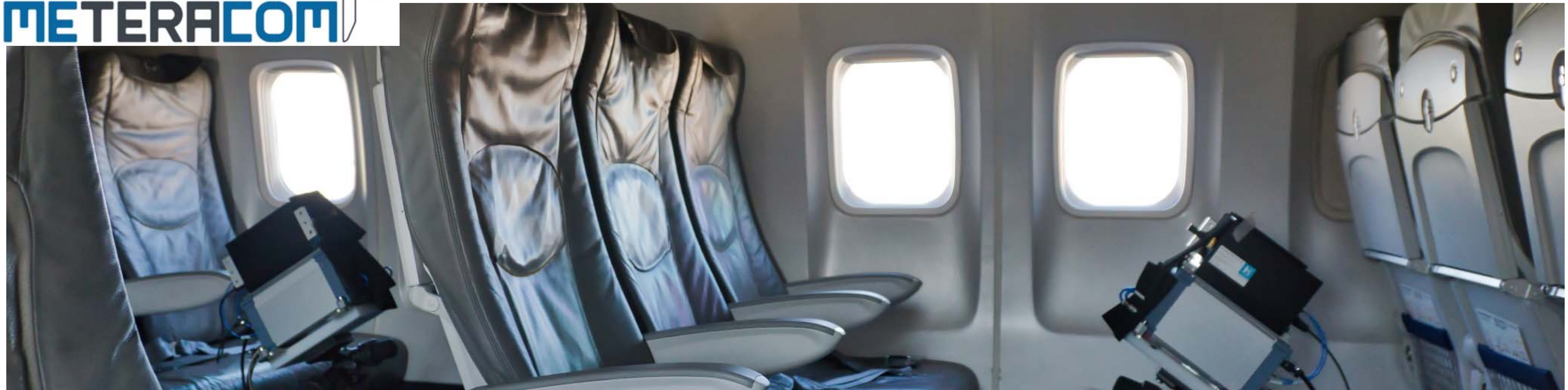

Progress towards traceability for THz communications waveforms and the use of "data-enabled analysis" in testing

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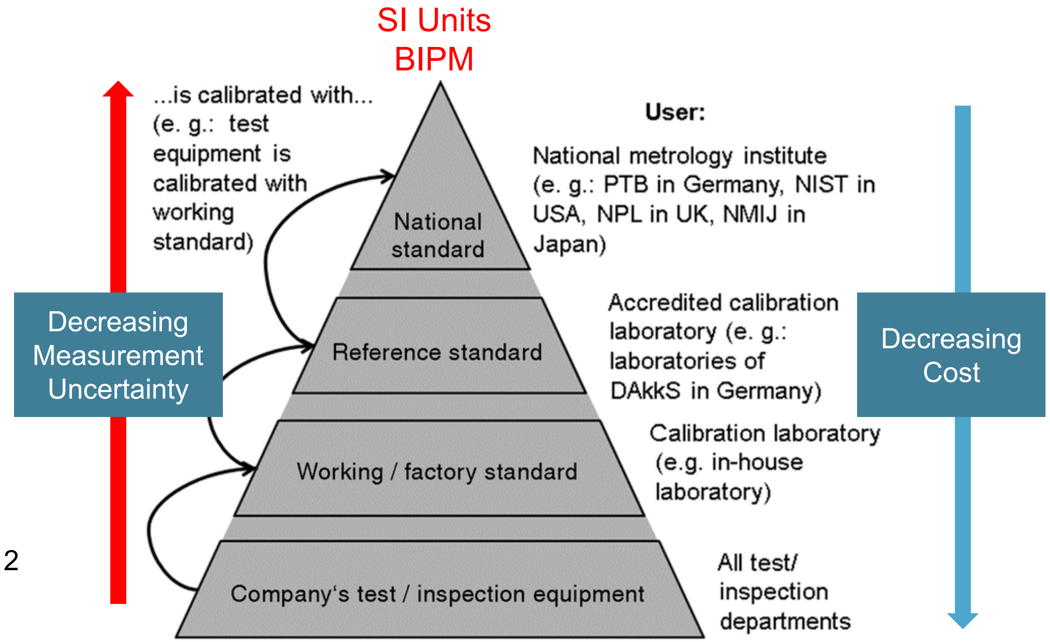
2nd International Workshop on Metrology for THz Communications, Duisburg, 12 March 2024

Traceability

- Metrological Traceability or Measurement Traceability is a " **property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty**." [1]
- Measurement traceability is important because **it gives you confidence and assurance that your measurement results agree with national or international standards within the statement of uncertainty in measurement.** Without traceability, a laboratory can claim anything they want in a test or calibration report.
- How do you know?

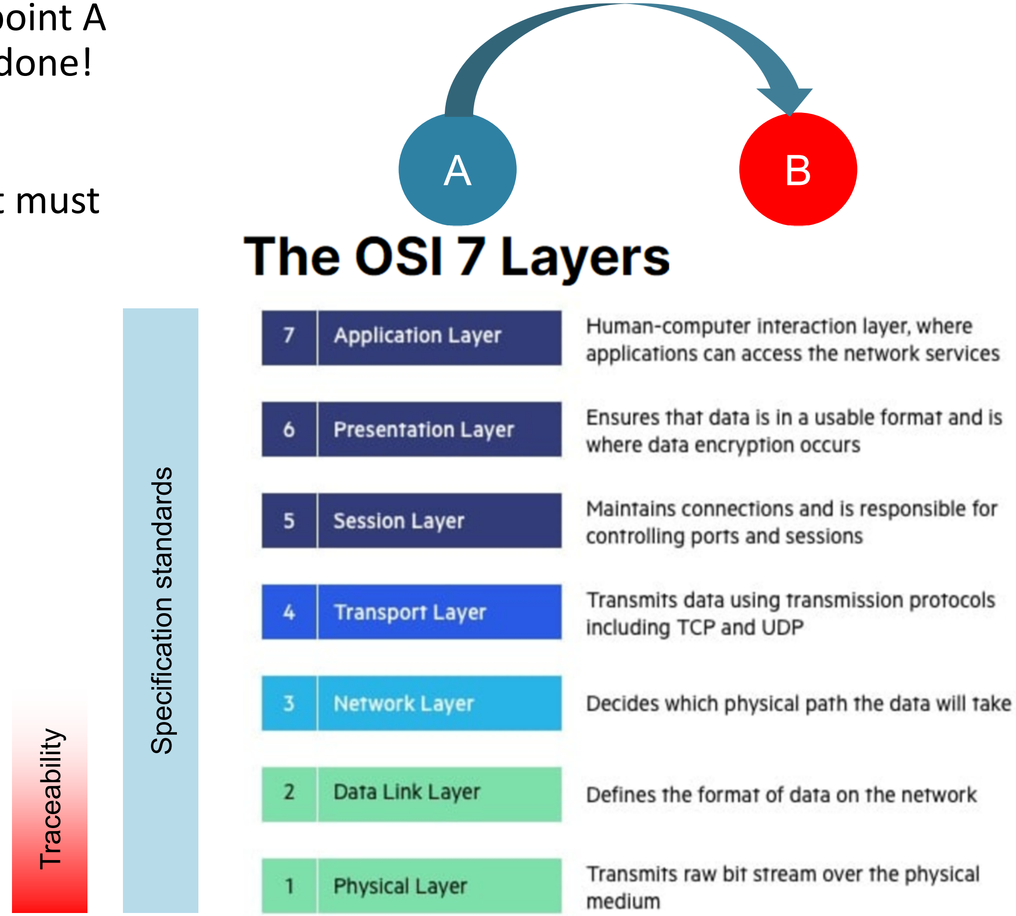


1. BIPM: International Vocabulary of Metrology (VIM), JCGM 200:2012

How does traceability apply to communications?

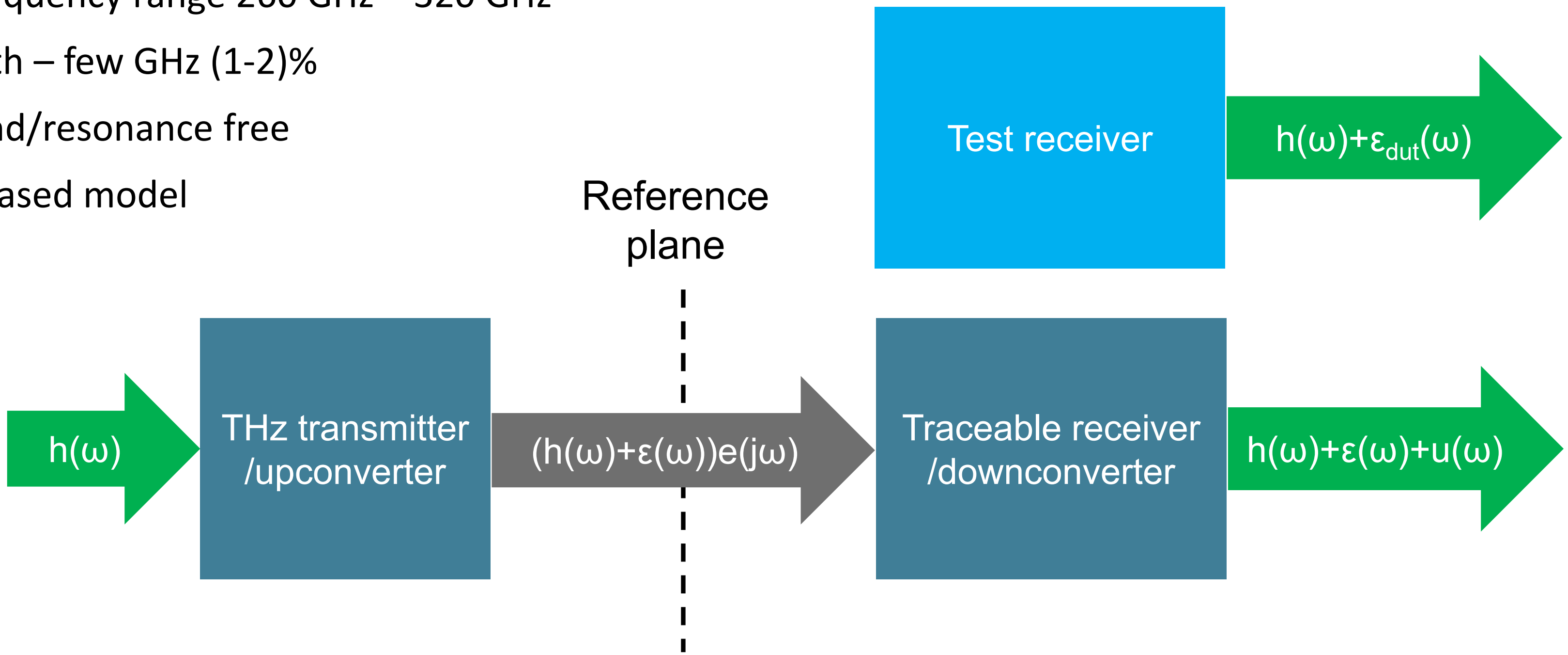
- Communications is just sending a message from point A to point B in a way that it is not corrupted? – job done!
- At the highest level this is true But…
- It is made of real components and equipment that must work together.
- Traceability ensures that the specification can be verified

- Speciation standards are essential for inter-operability
- Measurement traceability is necessary for the physical layer (manufacturing, purchase …)
- There can be interaction between Data Link (coding, headers …) and the physical hardware.



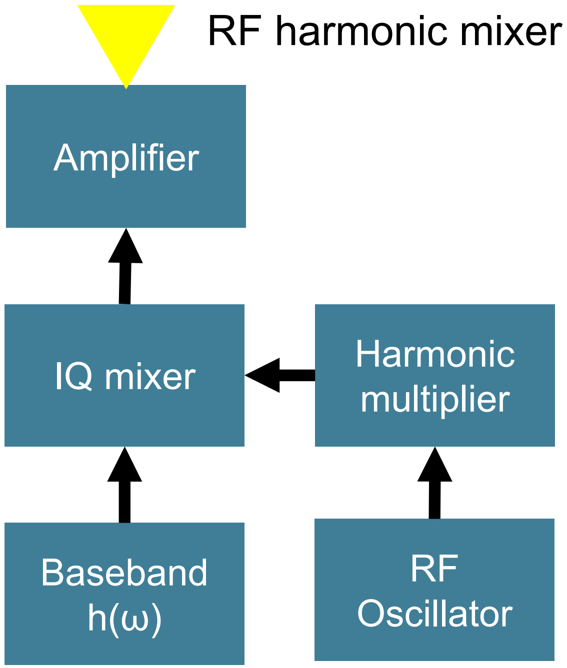
Traceability objective

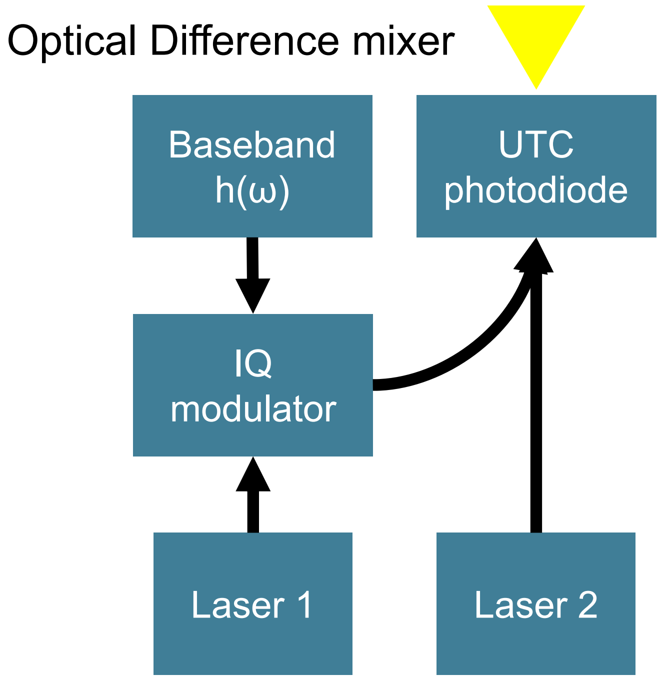
- The aim is to provide traceability of THz modulated frequencies for a complex waveform stimulus
- Target frequency range 260 GHz – 320 GHz
- Bandwidth – few GHz (1-2)%
- Broadband/resonance free
- Physics-based model



Baseband to RF

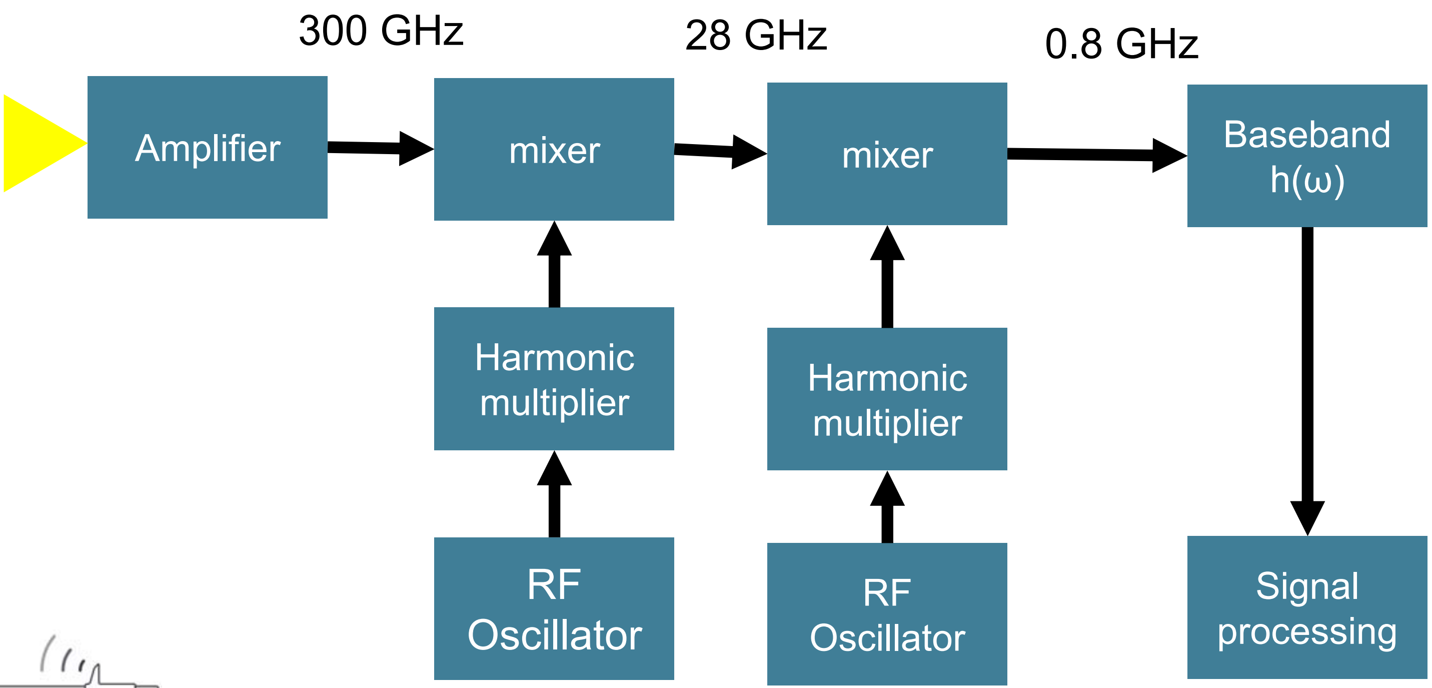
- RF Harmonic generation. RF signal is modulated (and may be further multiplied) to reach THz frequency
- Mixer phase/group delay measurements
- Optical (difference mixing on a UTC photodiode) – what is the O to E group delay with frequency?





RF to Baseband

- Receiver may contain multiple Local oscillator frequencies
- The mixer phase response is difficult to measure



Characterising mixers

- DSO approach
  - DSO specification typically 50-80 GHz but measurements show response to >100 GHz
  - limited by co-axial connectors (1 mm 110 GHz).
  - Timebase errors require correction
  - Technique shown (NIST) cannot be applied to all DSO types to remove timing jitter
- VNA Mixer method
  - Phase reference provides phase information for the LO, baseband and RF
  - VNA also corrects for the impedance match of all the components
  - Frequency range is bounded by the phase-standard

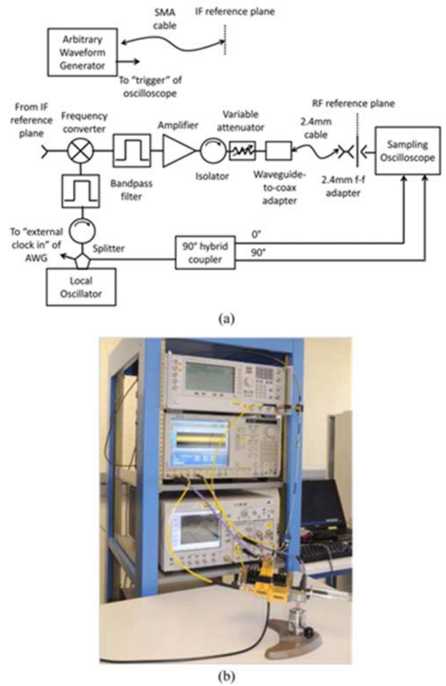


Fig. 1. (a) Block diagram of the millimeter-wave modulated-signal source and equivalent-time sampling oscilloscope. (b) Photograph of the source: the 10-GHz LO is at the top, the AWG is in the middle, and the sampling oscilloscope is on the bottom of the rack. The frequency converter and associated electronics are on the table at front. Depiction of various products does not imply endorsement by NIST. Other products may work as well or better.

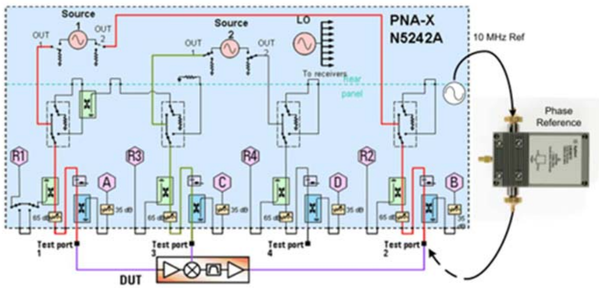


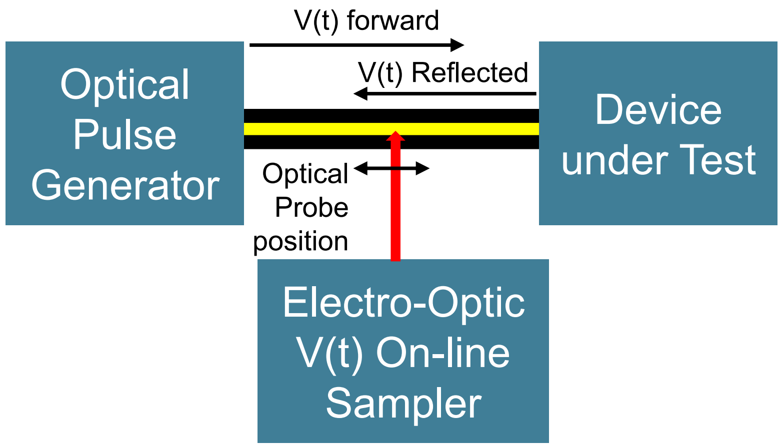
Figure 1: Mixer Measurement System Block Diagram

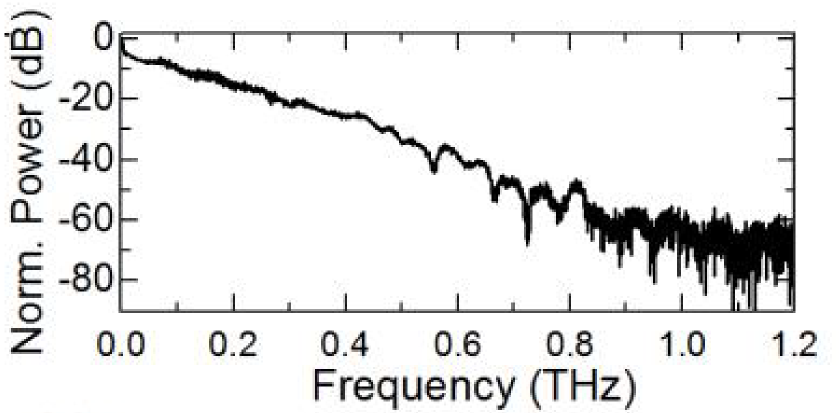
Joel Dunsmore, "A New Calibration Method for Mixer Delay Measurements that Requires No Calibration Mixer", Proc. 41st European Microwave Conference, 11 Oct 2011 Also see Application note PNA-X 1408-23.

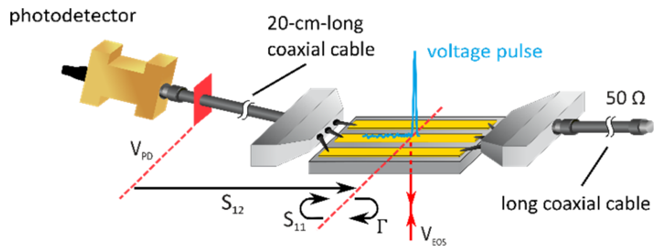
K. A. Remley et al., "Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement With Uncertainty", IEEE Trans. MTT Vol.63, No. 5, pp.1710-1719, May 2015

Traceability for dynamic voltage measurement V(t)

- Broadband: Provides traceability for instruments such as Oscilloscopes, fast Analogue to Digital converters
- Based on ultra-fast physics phenomena (Electro-optic effect)
- Two parts required: Pulse source, EO voltage sampler V(t)
- Combined response >500 GHz bandwidth



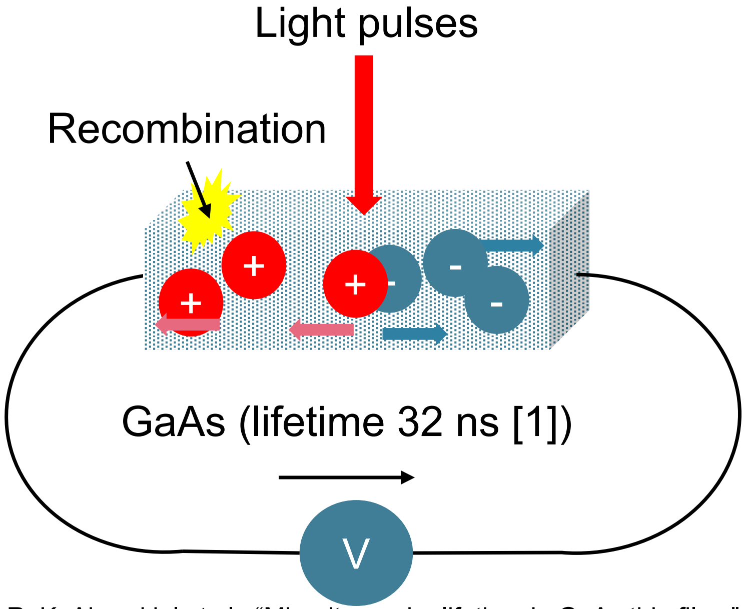


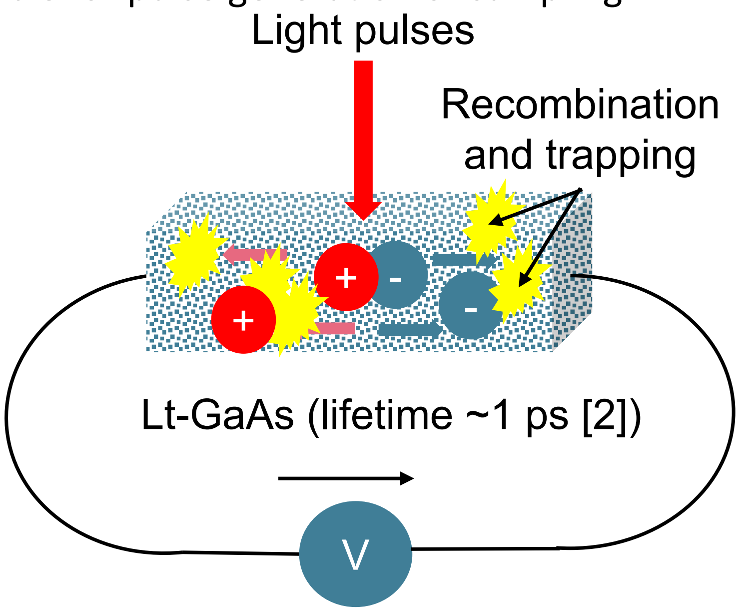


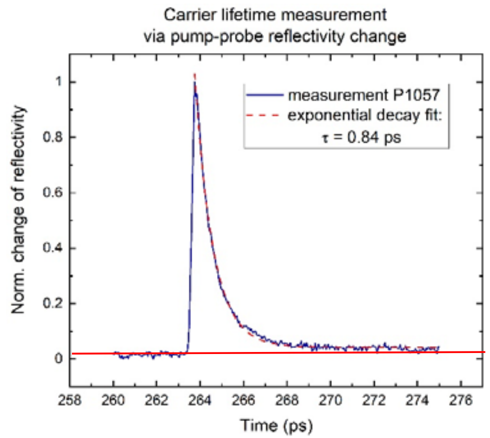
Mark Bieler, et al., “Time-Domain Optoelectronic Vector Network Analysis on Coplanar Waveguides”, .63,No..11,pp.3775-3784, Nov. 2015

Photoconductive Optical Pulse Generator

- Sub-picosecond light pulse generates electron-hole pairs
- The drift of the electrons and holes generates current proportional to electric field and illumination
- Normal GaAs has a long lifetime, so a photoconductor will not generate a short pulse
- LT-GaAs has a much shorter lifetime and is suitable for pulse generation or sampling



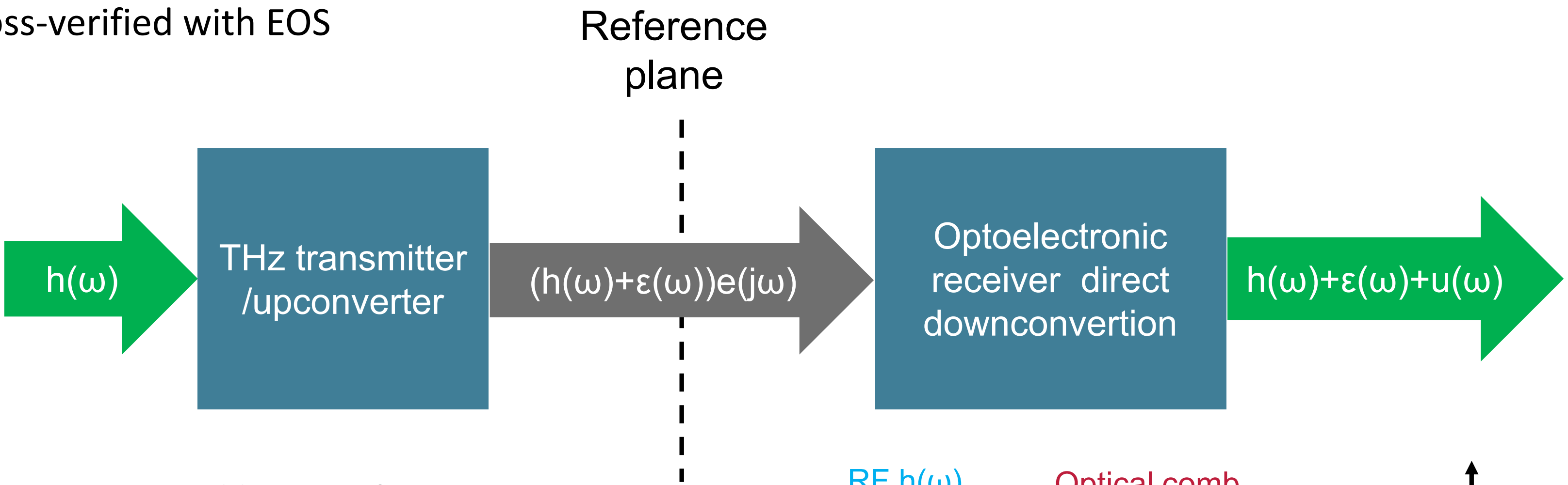




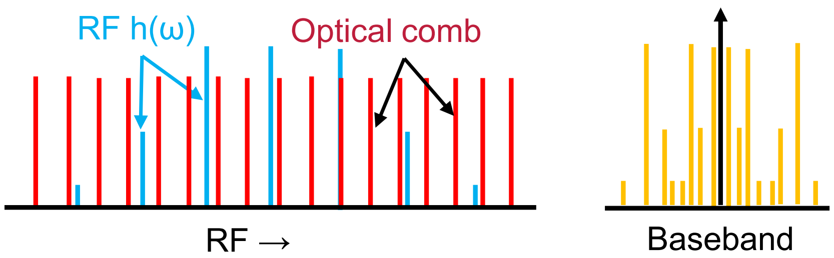
1. R. K. Ahrenkiel et al., “Minority-carrier lifetime in GaAs thin films”, Appl. Phys. Lett. 53, 598–599 (1988)
2. Mark Bieler, et al., “Time-Domain Optoelectronic Vector Network Analysis on Coplanar Waveguides”, .63,No..11,pp.3775-3784, Nov. 2015

Proposed approach

- Physics-based approach
- Similar to the V(t) system
- Simple antenna design Broadband/resonance free
- Can be cross-verified with EOS

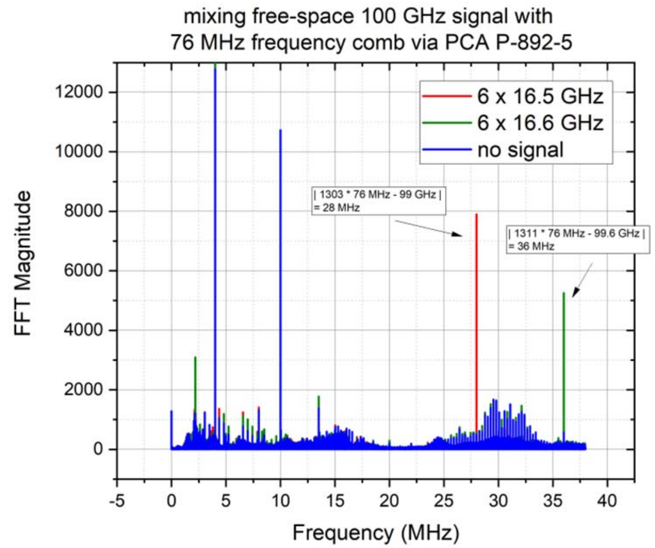


- h(ω) communications-like waveform
- Designed to operate with traceable receiver
- Fine tuning of frequencies to avoid degeneracy



Traceability via photoconductive switch – initial test

- Uses PTB V(t) EOS system
- Verified with existing bow-tie antenna/photoconductive switch CW at 100 GHz
- Direct optical downconversion (mixing) in photoconductor
- Complex signals mapped onto 76 MHz frequency space
- Frequencies will have to be carefully selected to avoid degeneracy
- Modulated waveform (e.g. PRBS) will have lower RF power
- EOS Verification of photoconductor is possible
- RF reflections must be considered



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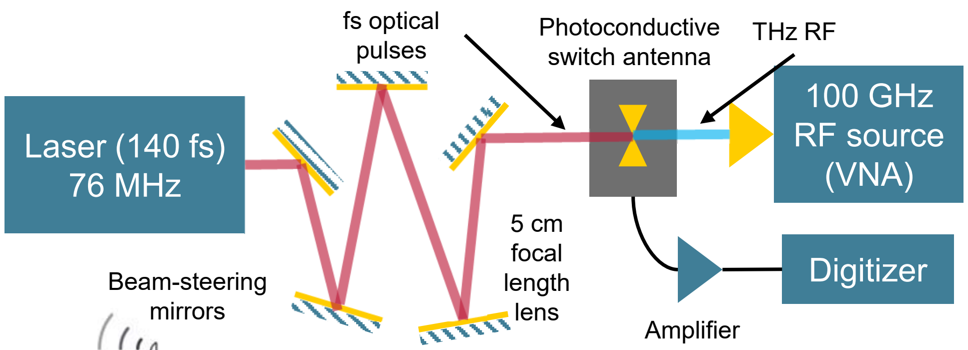
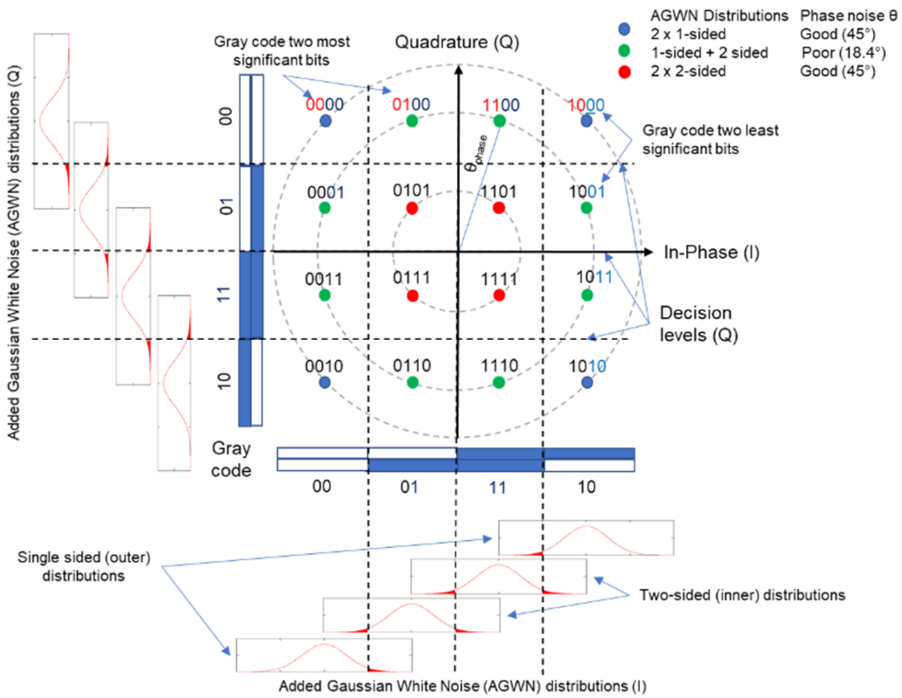
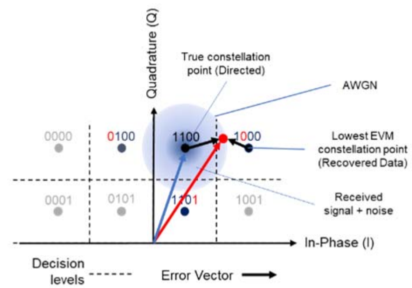


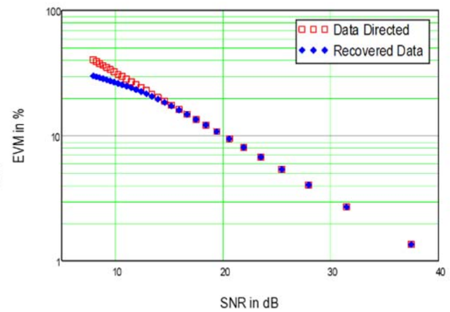
Data directed testing: Rationale and Objective



- “Nearest neighbour” data recovery under-reports the results
- Provide correct assessment of Error-Vectors
- THz communication at higher risk of phase-noise
- Determine impairments from constellation points symbol errors
- Testing with non-PRBS traffic



(a) Upper half of 16-QAM constellation diagram

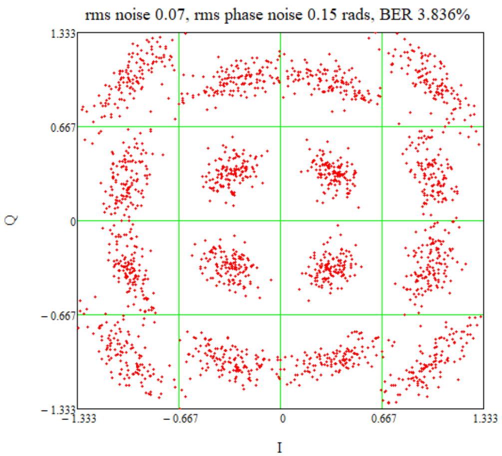


(b) EVM roll-off due to incorrect symbol identification (1-bit error)

David A. Humphreys “Chapter 29: THz Communications, Paving the way towards wireless Tbps”, Springer series in optical sciences 234, 2022

Directed data results

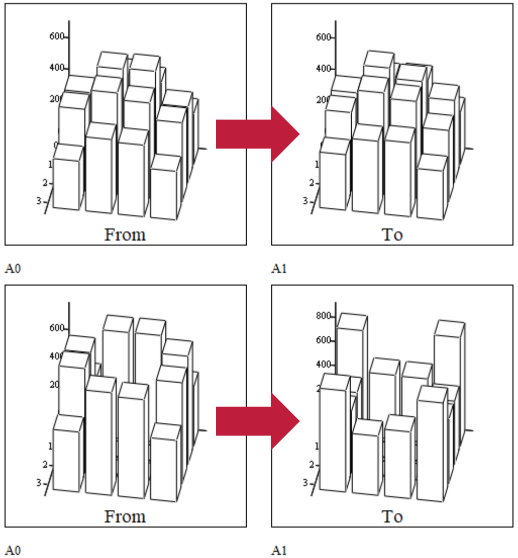
- Results for 16QAM PRBS with added complex amplitude (I+Q) and phase noise
- Data for PRBS (or other repeated dataset) sequence should be recoverable from multiple repetitions of the sequence, provided that the errors are not dominant. Results showed no errors for PRBS
- Data directed values can be recovered without errors
- At high BER values the estimated EVM is reduced as expected

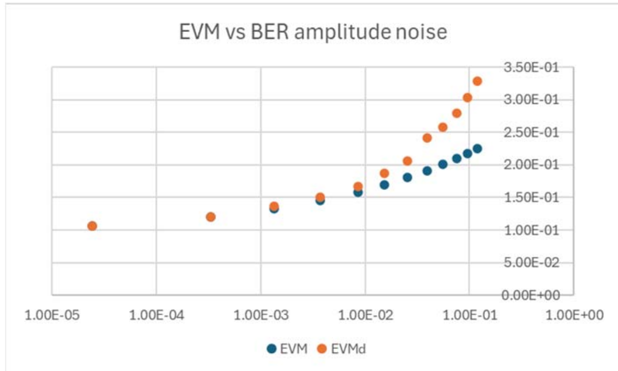


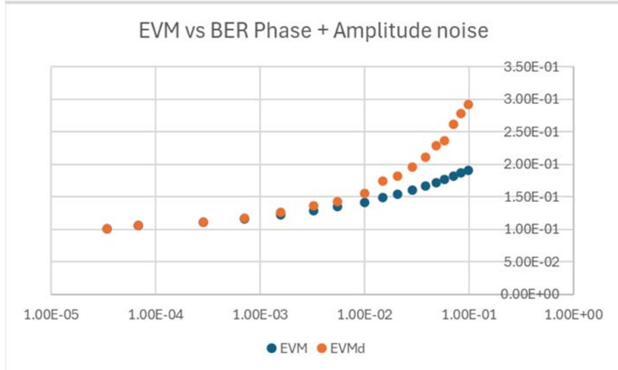
Incorrectly assigned data bits due to noise (100 repeats)

Amplitude noise
BER 3.9×10^{-2}

Amplitude and
phase noise
BER 3.8×10^{-2}







Summary and Next steps

1. Traceability
   a) Verification of antenna/photoconductor over a wider range of frequencies
   b) Power estimates for modulated vs CW signals
   c) Simulation of the low-frequency circuitry and performance of new design
   d) Test waveform design and evaluation
   e) System uncertainties
   f) Assess whether this artefact can be verified by EOS (future work)

1. Data Directed measurements
   a) A good estimate of the data can be made from repeated measurements where the errors are randomly distributed
   b) Improved estimate of error vectors will help identify design issues
   c) Validate this work by experimental evaluation with test devices
   d) Add improved data recovery methods for non PRBS/repetitive data
   e) EVM and BER are blunt metrics

Thank you very much for your Attention

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