TFC-1

Applications of Microwave Photonics in Radio Astronomy and Space Communication

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Outline

- Introduction and general concepts
  - narrow band vs. wide band signals
- Signal transmission
- Reference distribution
- Photonic antenna metrology

All topics illustrated with current examples:

- VLA, ALMA, ATA, DSN arrays

Radio Astronomy

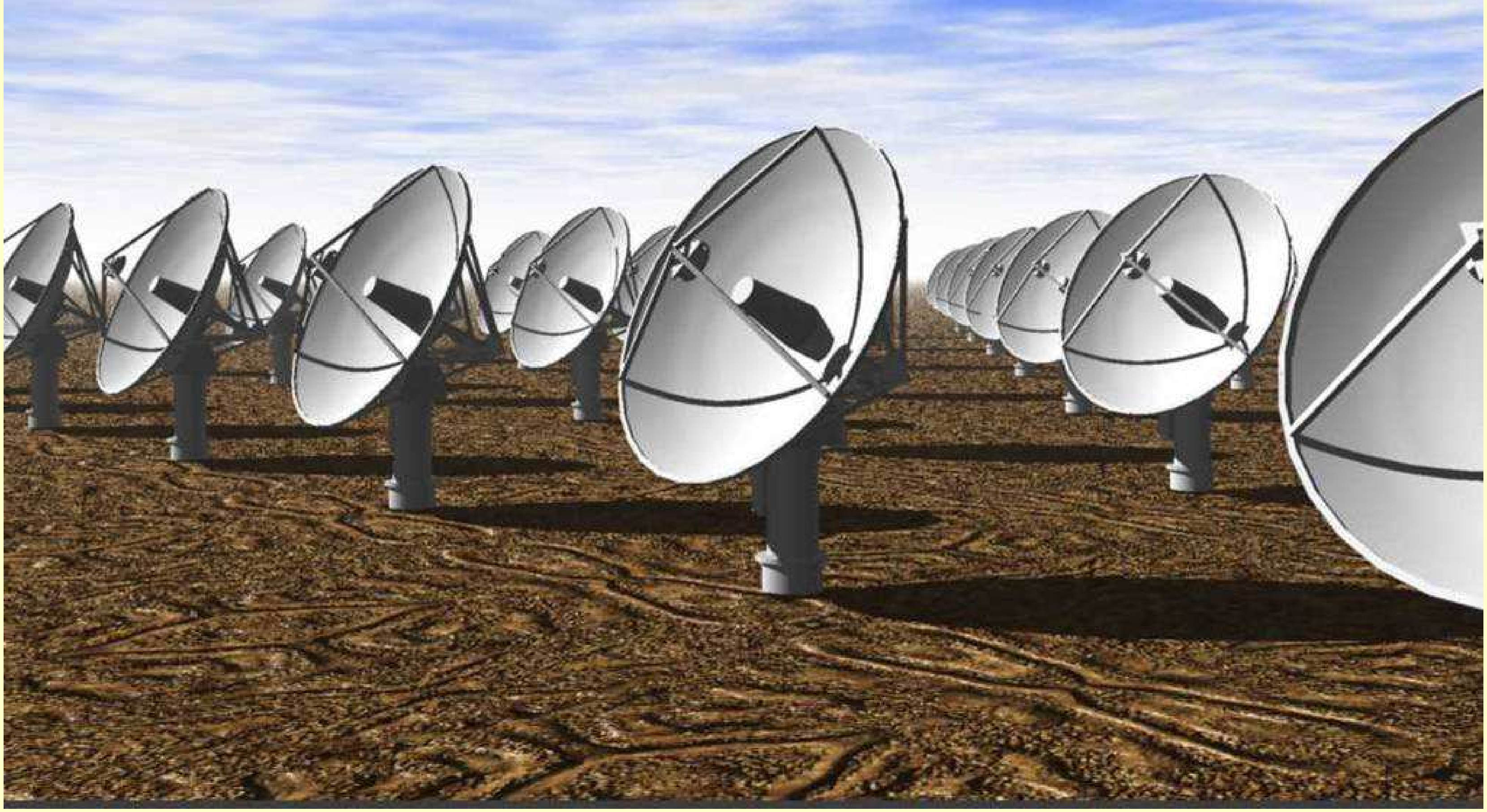
Image courtesy of NRAO/AUI

Space Communications

The 70m deep space communication antenna at Goldstone, California.

The Future

Arrays of many small antennas have become more cost-effective than large antennas for achieving large total aperture or gain, both for astronomy and for communication.



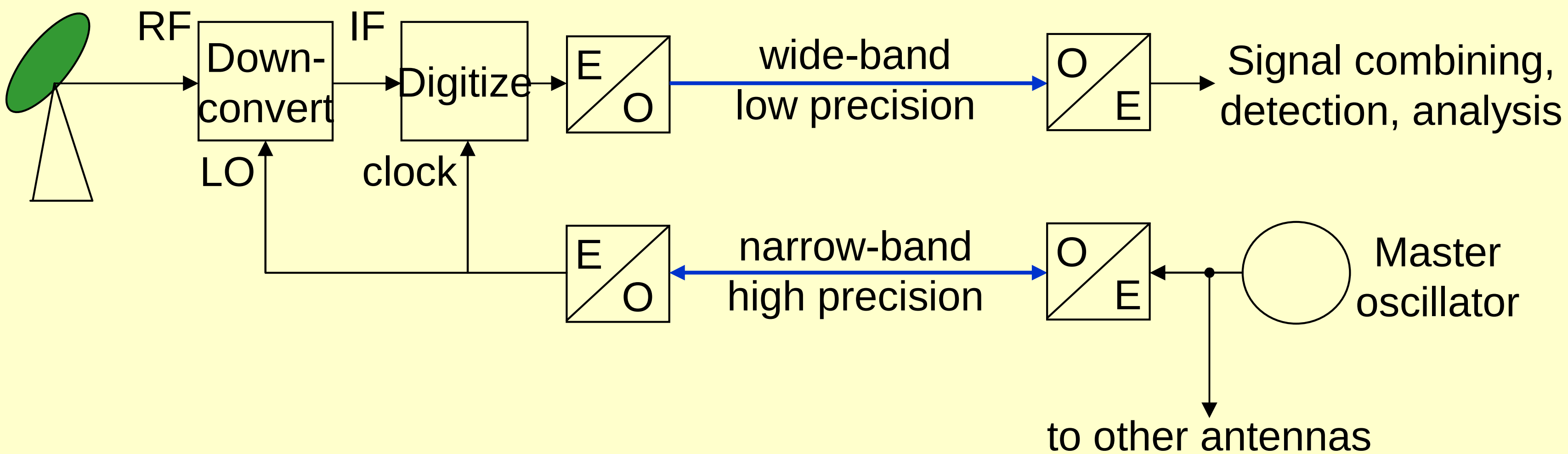
Examples of Systems

Name	*No. of antennas*	*Extent, km*	*Freq. range, GHz*	*Operational*	*Notes*
VLA	27	35	.075-43	1980	upgrade in progress
VLBA	10	8000	1-88	1993	currently no photonics
ATA	350	1.0	0.5-11	2008?	under construction
ALMA	50-80	15	31-950	2012?	under construction
DSAN(R)	400	1.6	8-38	2015?	proposed
DSAN(T)	200	0.4	7.2	2015?	proposed
SKA	4500	3000	0.1-25	2020?	preliminary studies

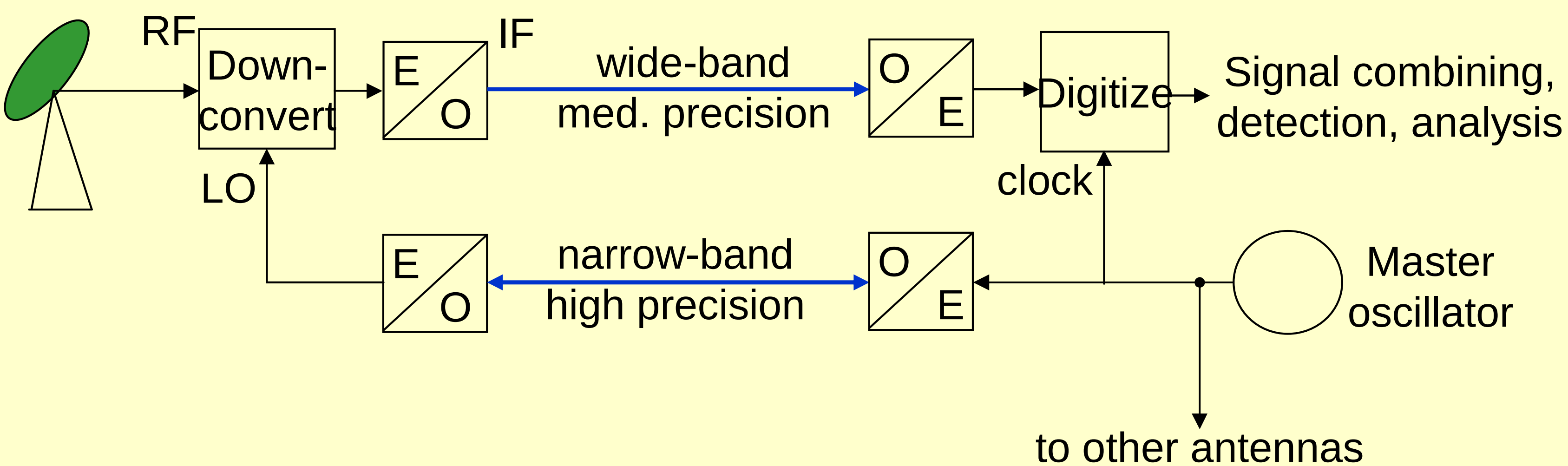
values in red produce challenging requirements

Radio Telescopes, generic

A. Digital transmission: digitize at antenna

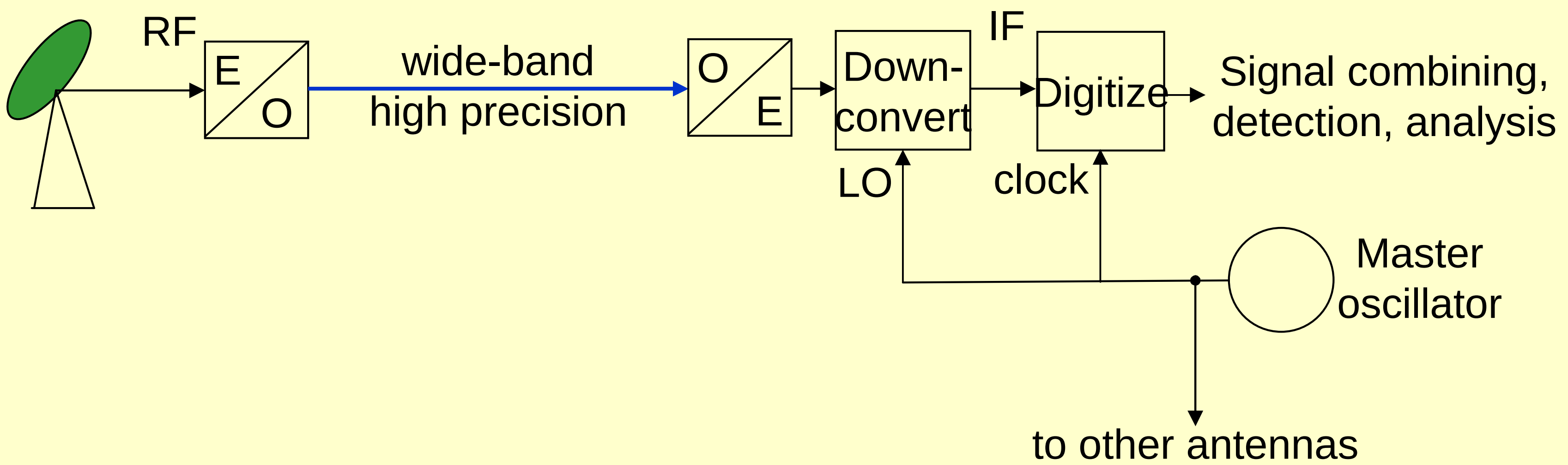


B. Analog transmission: digitize at central building



Radio Telescopes, continued

C. Analog transmission: downconvert and digitize at central building

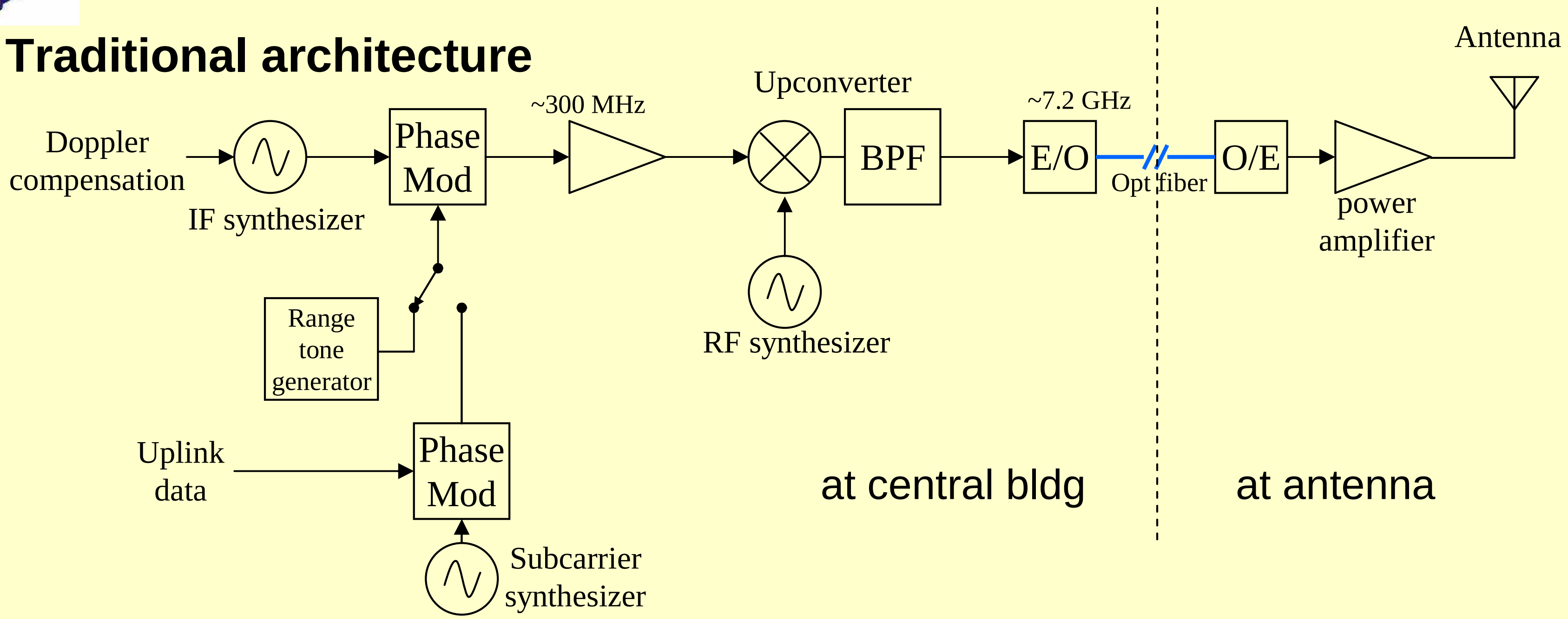


Space Communication

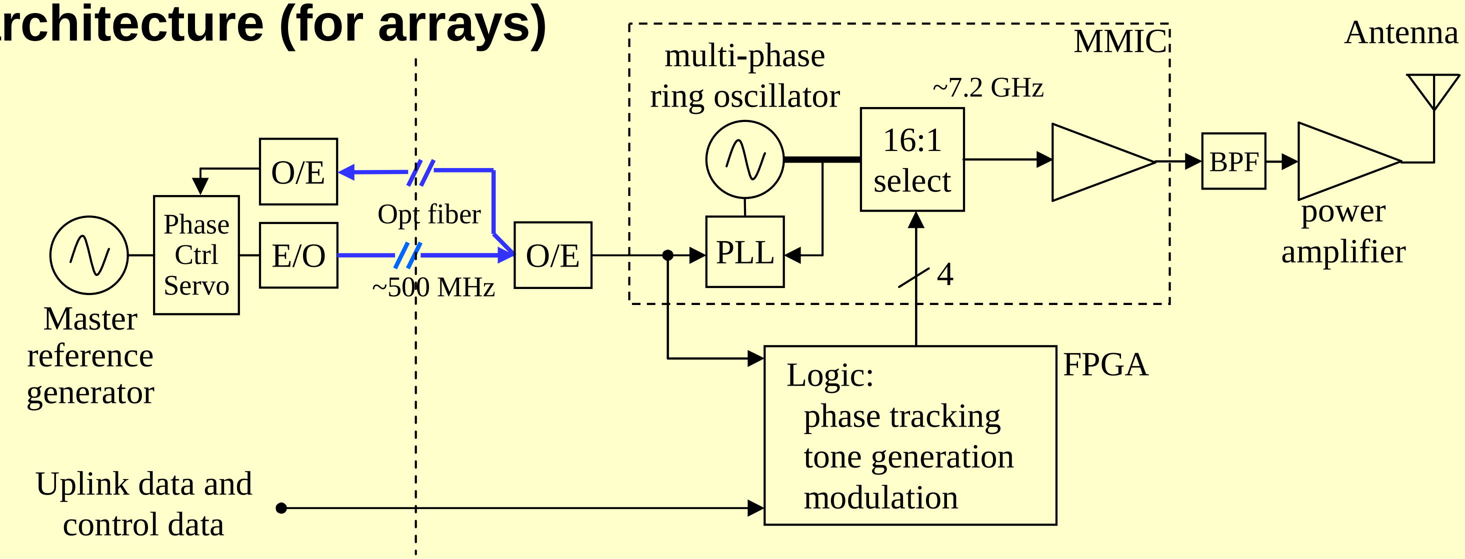
- Both directions needed
  - receive (downlink): similar to radio telescopes
    - narrower bandwidths (restricted to allocated bands)
    - large phased arrays for sensitivity in future
  - transmit (uplink)
    - existing large single antennas, combined with downlink
    - future large phased arrays for EIRP > 100 GW, separate from downlink
- Fiber lengths relatively short: a few km

Uplink Electronics

Traditional architecture



New architecture (for arrays)



Signal Transmission Considerations

- Analog vs. digital
- Long haul vs. short haul
  - VLBI
- Bandwidth
  - Radio astronomy:
    - cm wavelengths: 2x 500 MHz
    - mm/submm wavelengths: 2x 8 GHz
  - Space communication:
    - 10 to 500 MHz now
    - ~1500 MHz future, mainly for near earth
- Allowed distortion or error rate
  - BER up to 10^{-3} is usually acceptable
  - Low harmonic distortion mainly for RFI

Analog vs. Digital

- Similar cost/channel for photonic parts:

  analog bandwidth $B \cong$ digital bit rate R

- R = (bits/sample)*(sampleRate)

  $\geq 2 * 2B = 4B$, so digital costs more

- In addition, digital requires high speed logic for encoding and decoding data packets
- But digital allows large delay variations on link; analog must be stable.

Analog Links: Current SoA

single mode fiber, 1300-1500 nm, up to 20 km

Link Technology`	*Direct/ External Modulation*	*Relative cost (2006)*	*BW (GHz)*	*NF (dB)*	*SFDR (dBHz)*	*Chief Commercial Application*
$LiNbO_3$ Modulator and CW Laser	External	100%	30	40	104	Long Haul Telecom, military, specialty
Electro-absorption modulator-laser	EML	32%	12	35	108	Telecom; 2.5 and 10Gbps
Direct Mod DFB	Direct	19%	5	~40	~105	Telecom, CATV
TOSA/ROSA	Direct	13%	2	> 30	TBD	Telecom; GigE
Direct Mod F-P	Direct	8%	1	~45	~103	CATV, test, telecom
VCSEL	Direct	TBD				None at 1550nm; shorter wavelength devices used in parallel optical interconnects

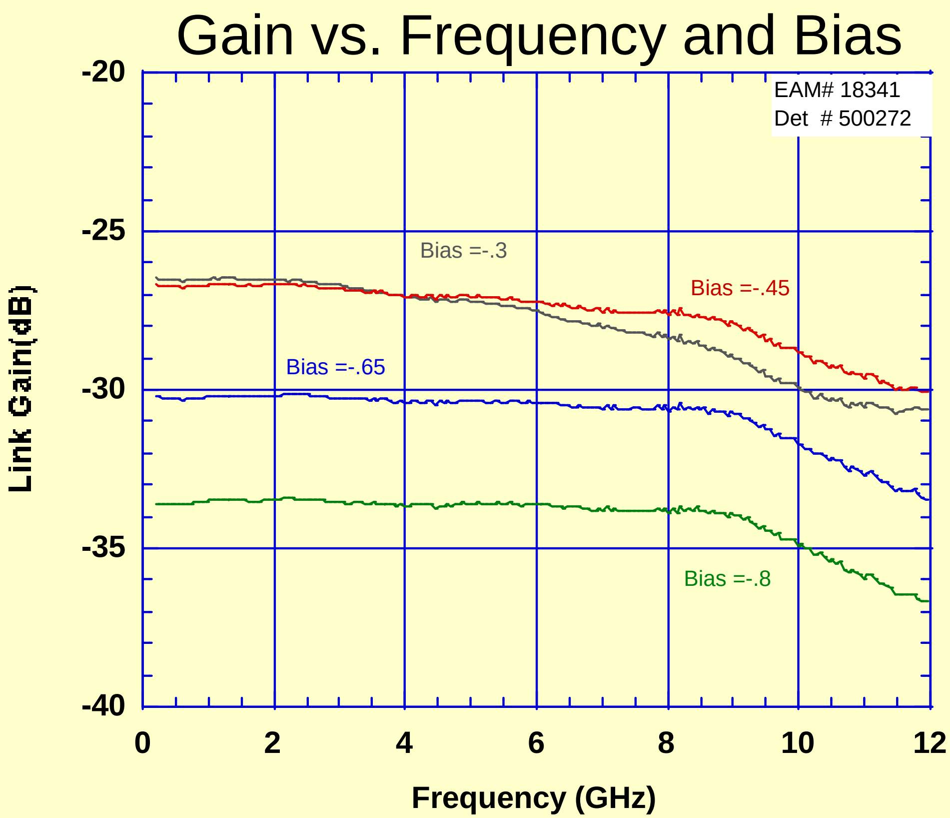
This slide courtesy of
Chris Janson, Photonic Systems

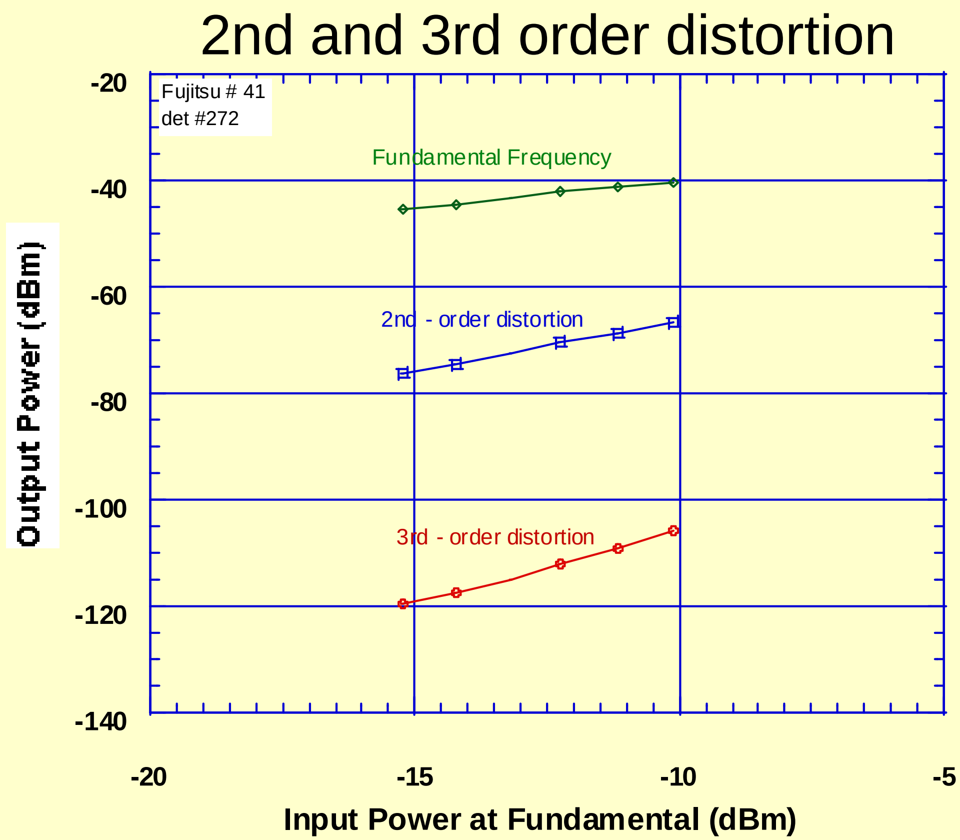
Key:
Measured
Modeled
Estimated

PHOTONICSystems, Inc.®
www.photonicsinc.com

Inexpensive 12 GHz Link (ATA)

Allen Telescope Array, typical RF link performance
(data courtesy of the ATA Project)





$NF \leq 41$ dB

$SFDR_3 \geq 100$ dB·Hz$^{2/3}$

$SFDR_2 \geq 73$ dB·Hz$^{1/2}$

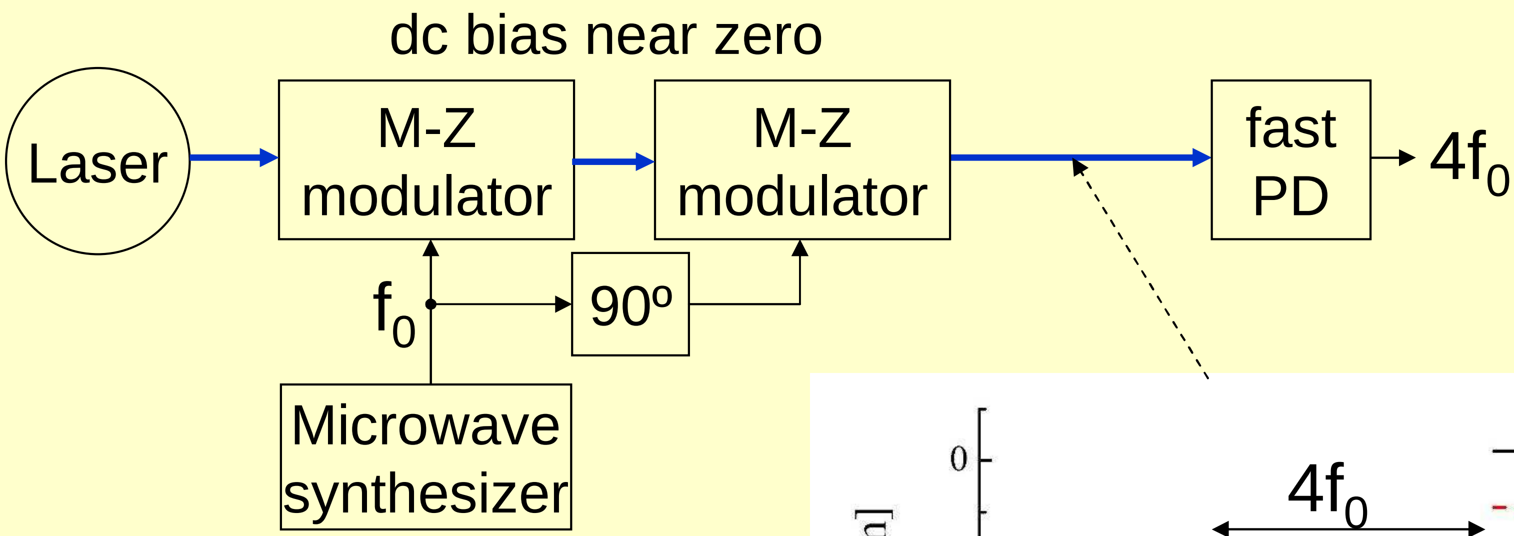
Very Long-Haul Links

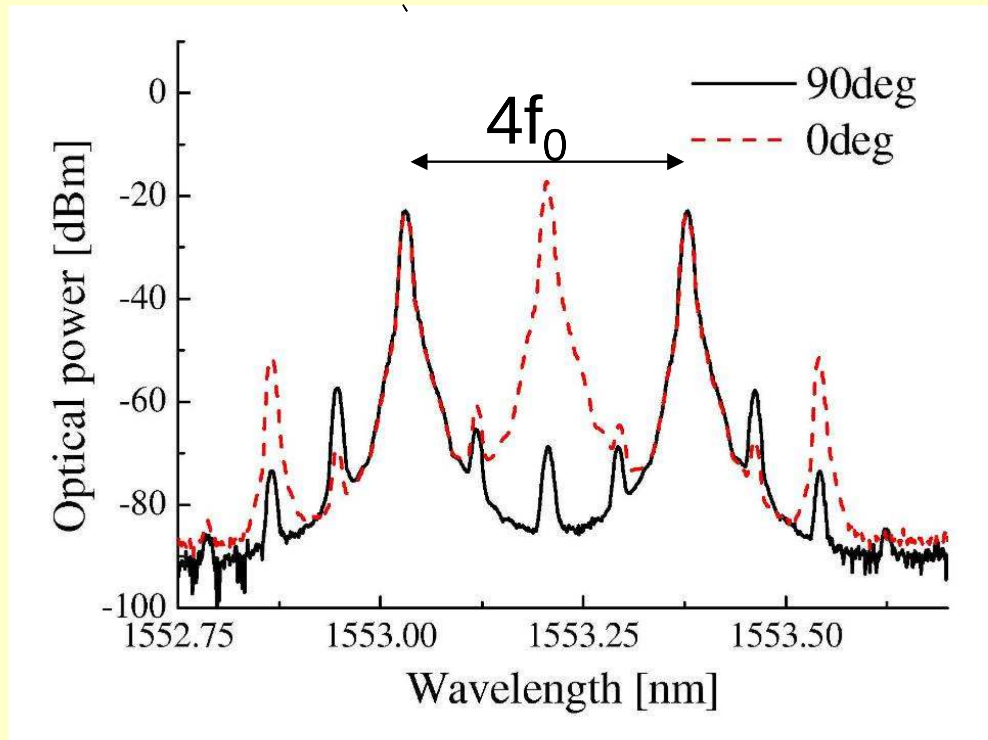
- VLBI radio astronomy
  - antennas separated by intercontinental distance
  - current practice is to record signals and ship media; logistically messy, small *N* only.
  - future large arrays (SKA) may have hundreds of antennas 100 to 3000 km from center
  - bandwidths ~1 GHz (~4 Gb/s) per antenna
- Spacecraft navigation
  - also uses intercontinental baselines
  - desire for rapid determination of spacecraft position precludes shipping media
  - usually requires only small bandwidth, ~10 MHz

Optical Reference Generation

- Single laser, intensity modulated by reference
  – Simplest, least expensive
  – Usable up to ~40 GHz in current SoA
  – Dispersion penalty
- Single laser, suppressed carrier modulated by 1/2 or 1/4 reference
  – Extends above to higher frequency
  – Avoids dispersion penalty
- Two lasers, difference phase locked to reference (“laser synthesizer”)
  – necessary for highest frequencies
  – allows precise phase control

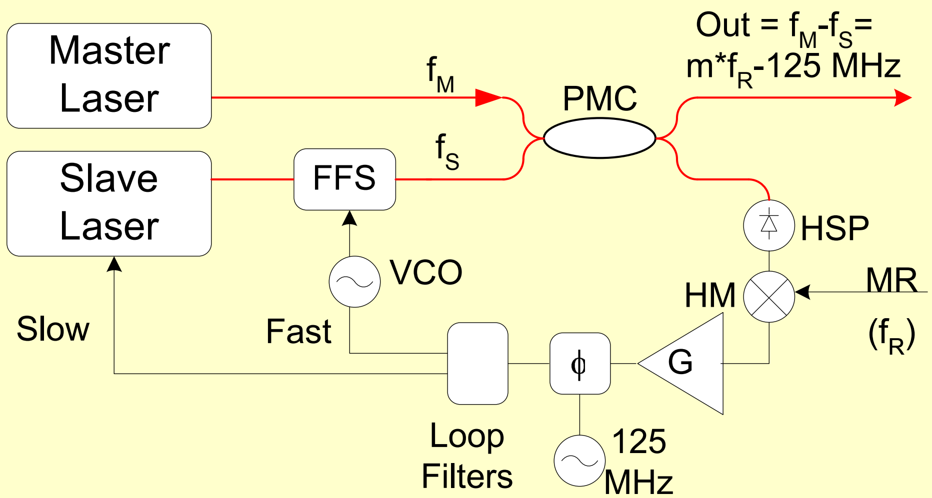
Optical Frequency Quadrupler



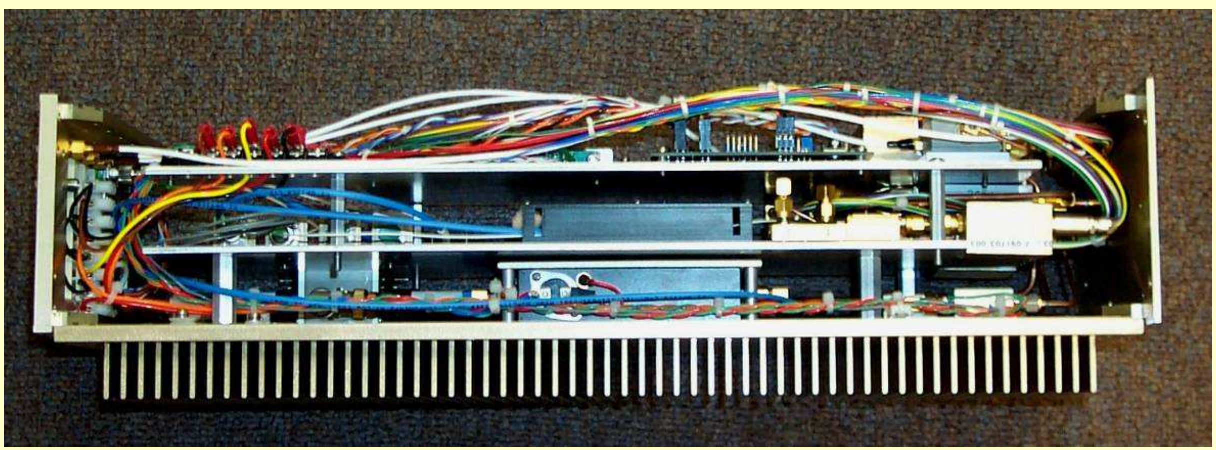


From: T. Kawanishi *et al.,* Intl. Topical Meeting on Microwave Photonics, 2005.

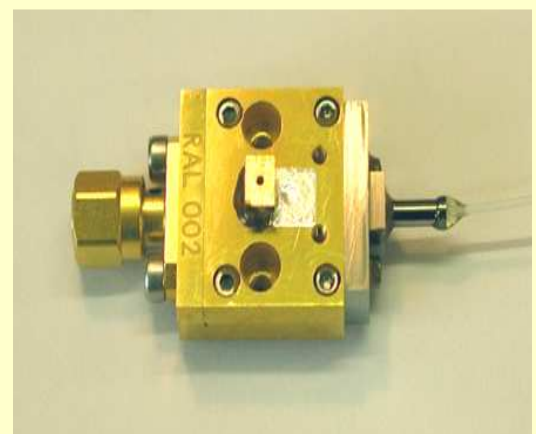
Laser Synthesizer (1)



FFS: Fiber Frequency Shifter
PMC: Polarization Maint. Coupler
HSP: High-Speed Photomixer
MR: Microwave Reference
HM: Electronic Harmonic Mixer
VCO: Voltage Controlled Oscillator
ϕ : Phase Detector



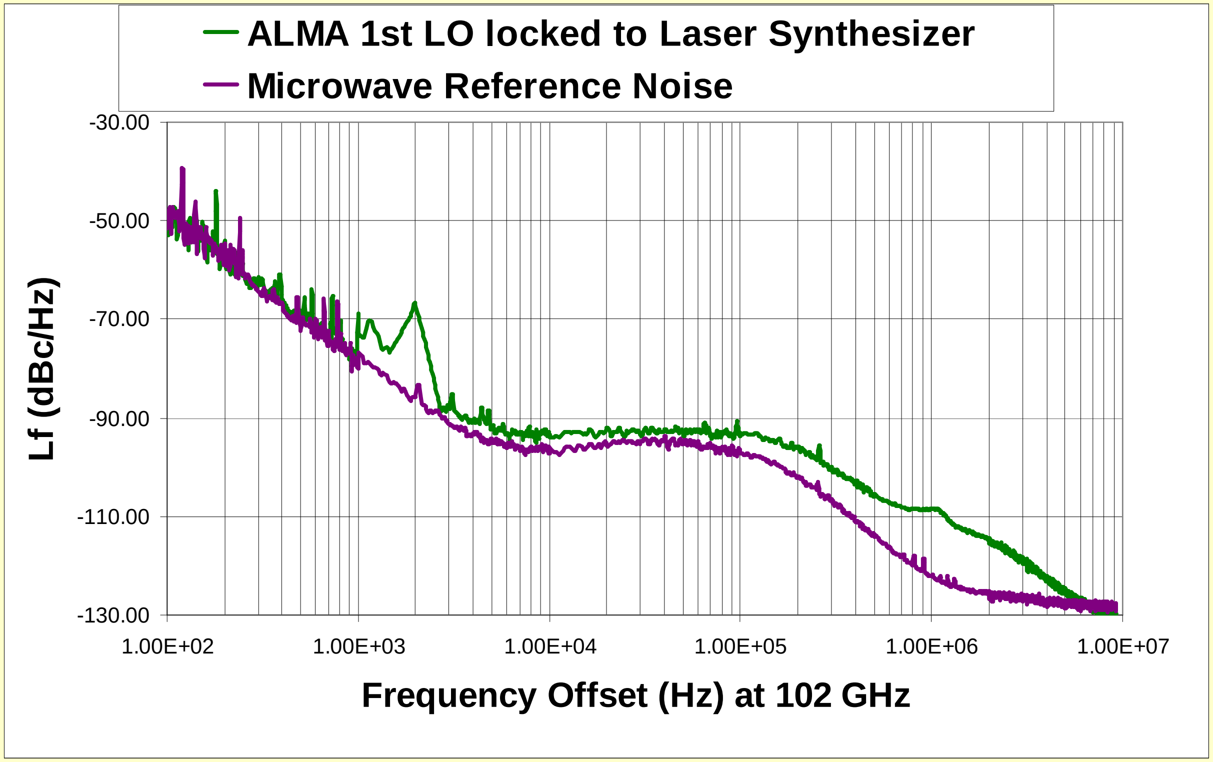
Laser Synthesizer Module



High-Speed Photodetector

Laser Synthesizer (2)

- Two-Laser Heterodyne Phase-Lock
- Requires PLL Bandwidth >> Laser Linewidth/Jitter
- Two Approaches:
  - Narrow-Linewidth (Fiber) Laser ~1 MHz Loop BW
  - Semiconductor Laser, 20-100 MHz Loop BW

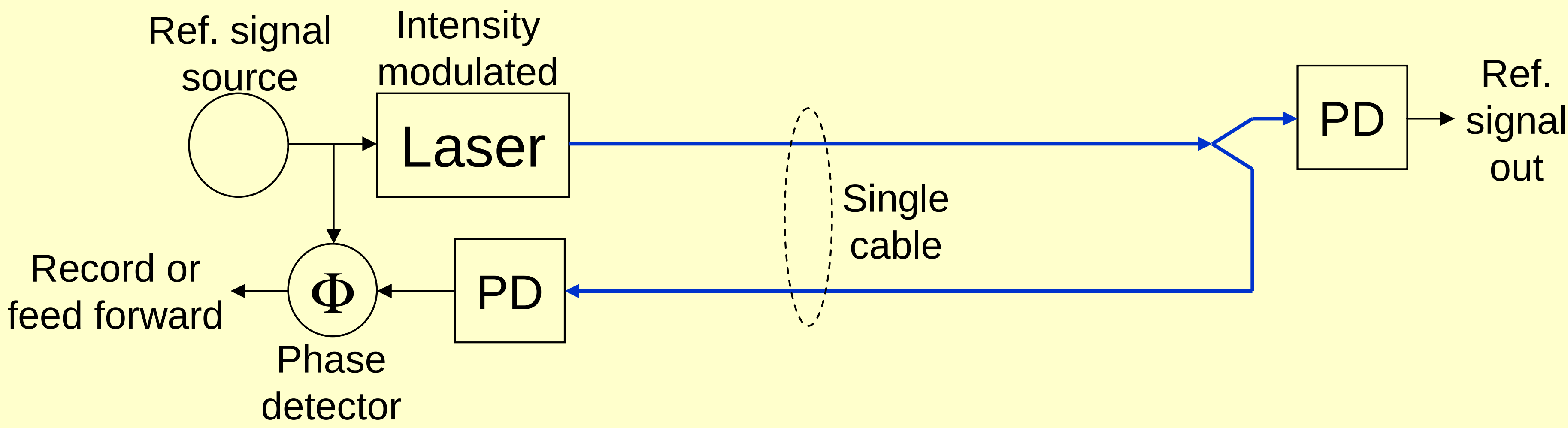


Stabilization of Fiber

- Return received signal to transmitter over an identical path; measure phase difference, attribute half to outgoing path

Returned signal → Adjustment ↓	*None*	*Separate fiber*	*Same fiber, separate laser*	*Same fiber, reflected*
None	SMA	VLA DSAN(R)		
Fiber spool temperature			DSN	
Fiber stretcher, piezo driven				ALMA
Electronic PLL		DSAN(T)		

Simplest Fiber Stabilization

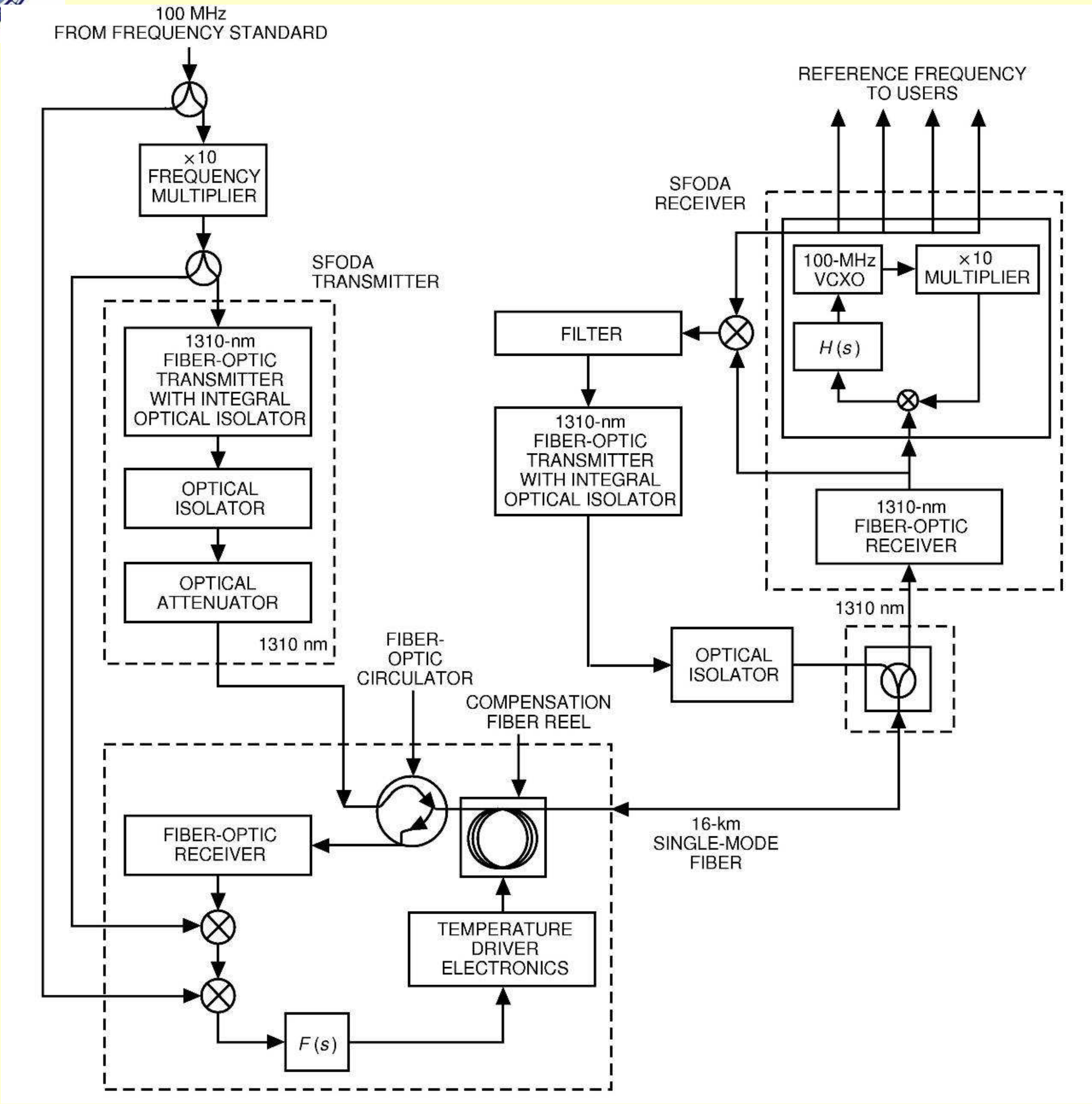


Open loop (no feedback), single laser, separate fiber for return signal

Measured phase change is used to compute corrections, applied in signal processing

Used by VLA, eVLA, DSAN(R)

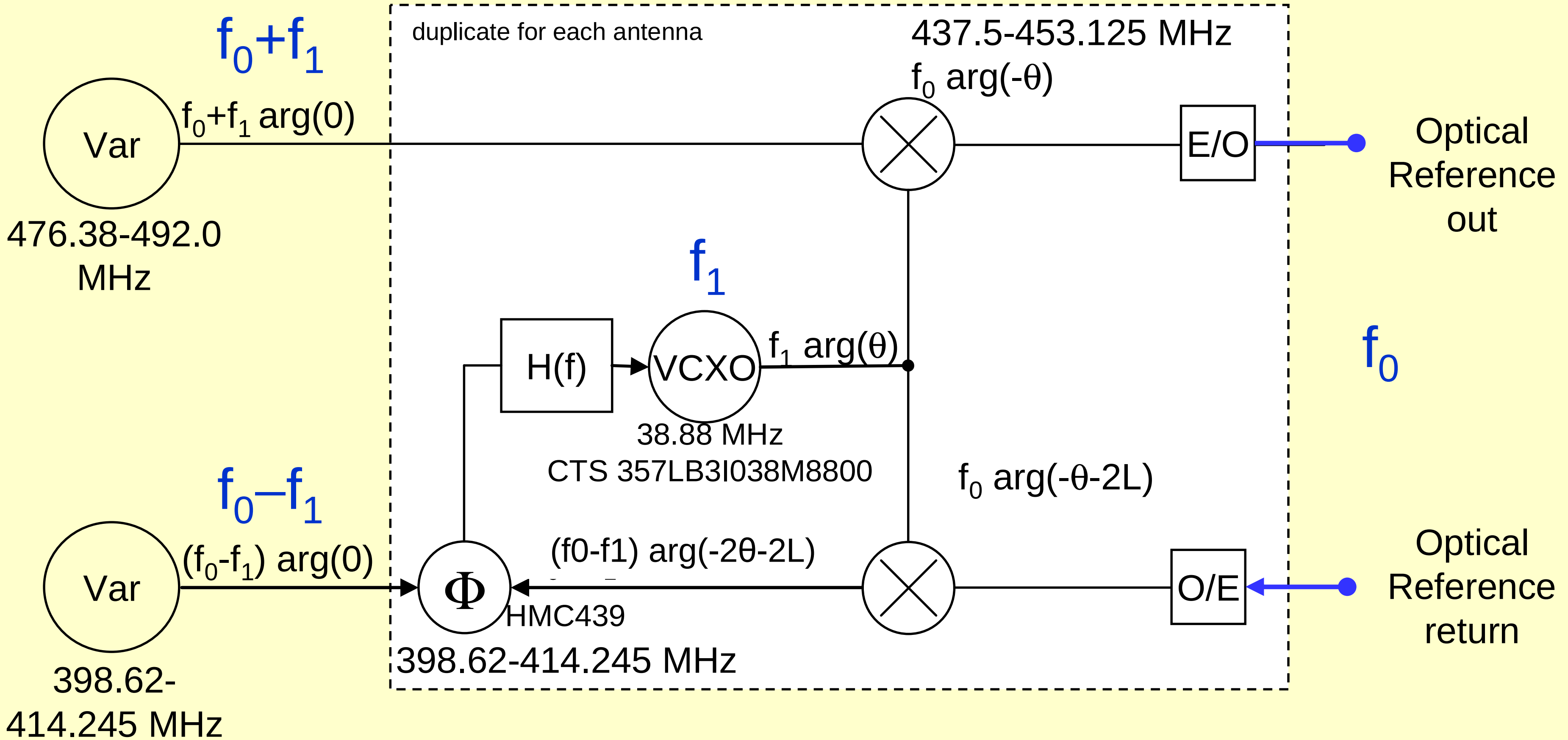
Heated Fiber Spool (DSN)



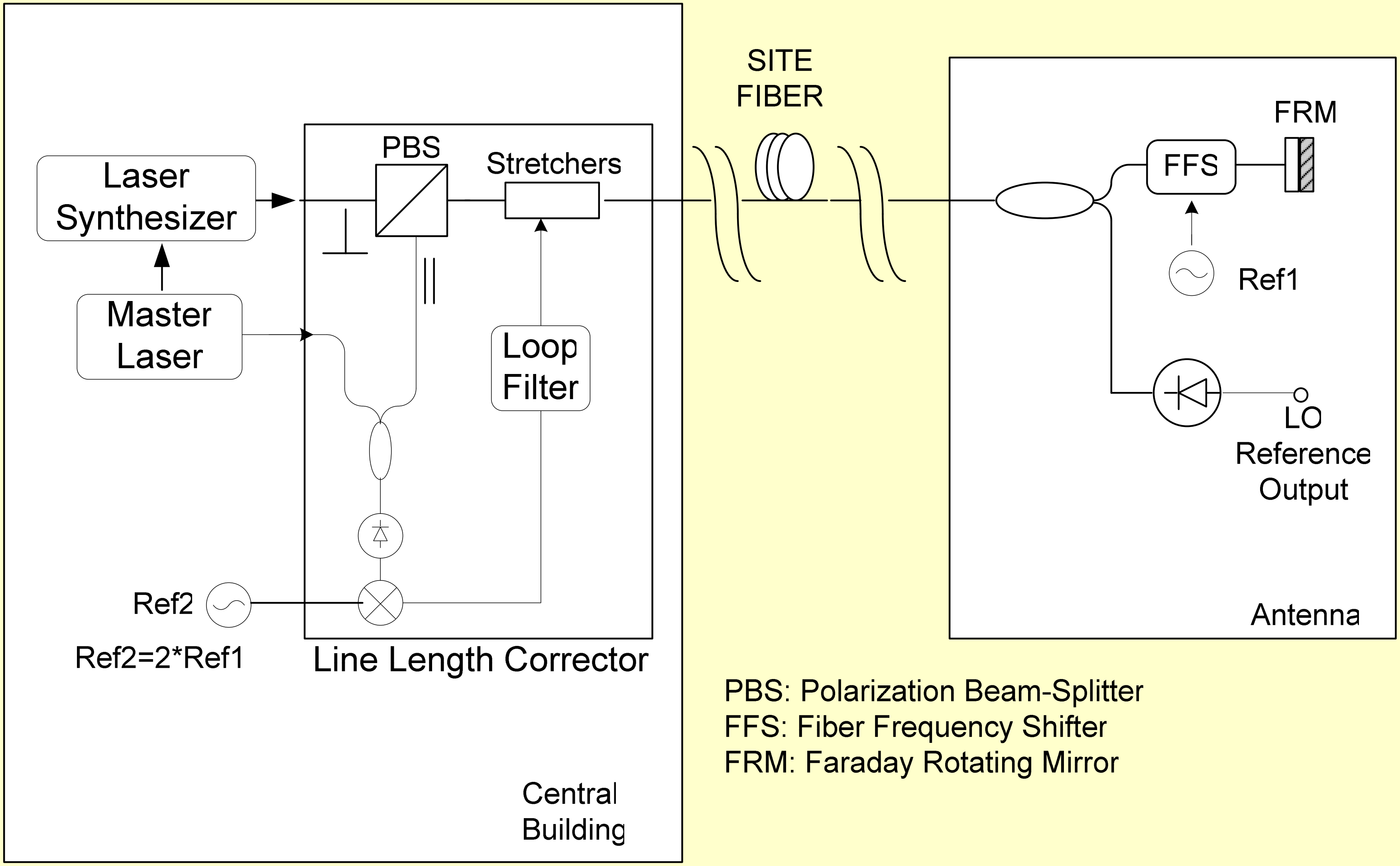
Round-trip correction method used by NASA's Deep Space Network, developed at JPL.

From: M. Calhoun *et al*., *IPN Prog. Rpt.* 42-148, 2002.

Electronic PLL (DSAN-T)



Fiber Stretcher and Faraday Mirror (ALMA)



PBS: Polarization Beam-Splitter
FFS: Fiber Frequency Shifter
FRM: Faraday Rotating Mirror

Note: Requires master laser with high stability and coherence.

Fiber Stabilization Performance

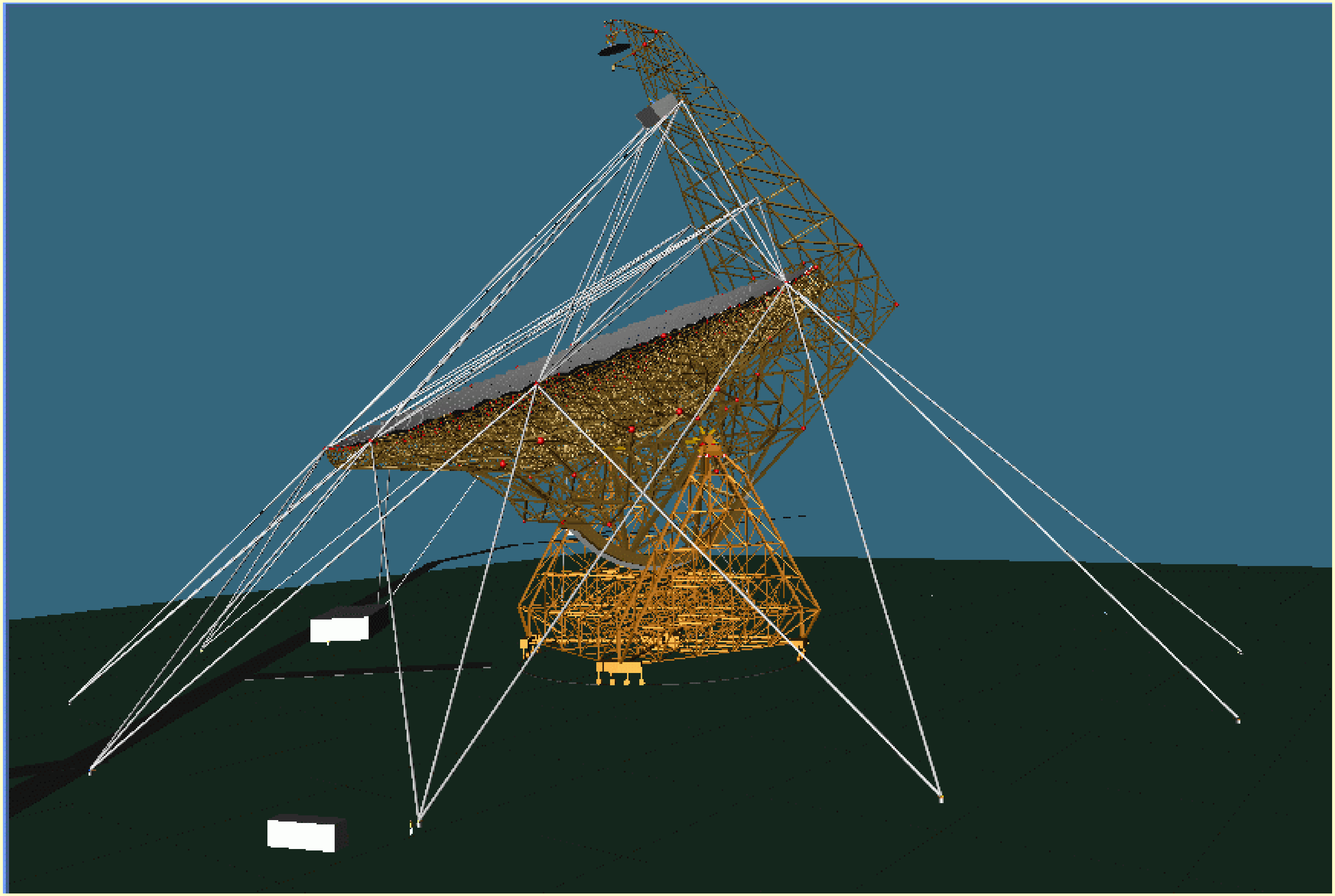
Method	*Signal, GHz*	*Distance, maximum*	*Error, psec*	*Used on*
Separate fibers Open loop	0.512	22 km	~2	eVLA
Separate fibers Open loop	7 to 8	3 km	TBD (~1)	DSAN (R)
Separate fibers Electronic PLL	0.45	1 km	TBD (~1)	DSAN (T)
Separate lasers Thermal spool	1.0	16 km	0.2	DSN
Split light, F. mirror Fiber stretcher	27 to 142	15 km	.025	ALMA

Limitations of Fiber Stabilization

- All techniques rely on reciprocity assumption:

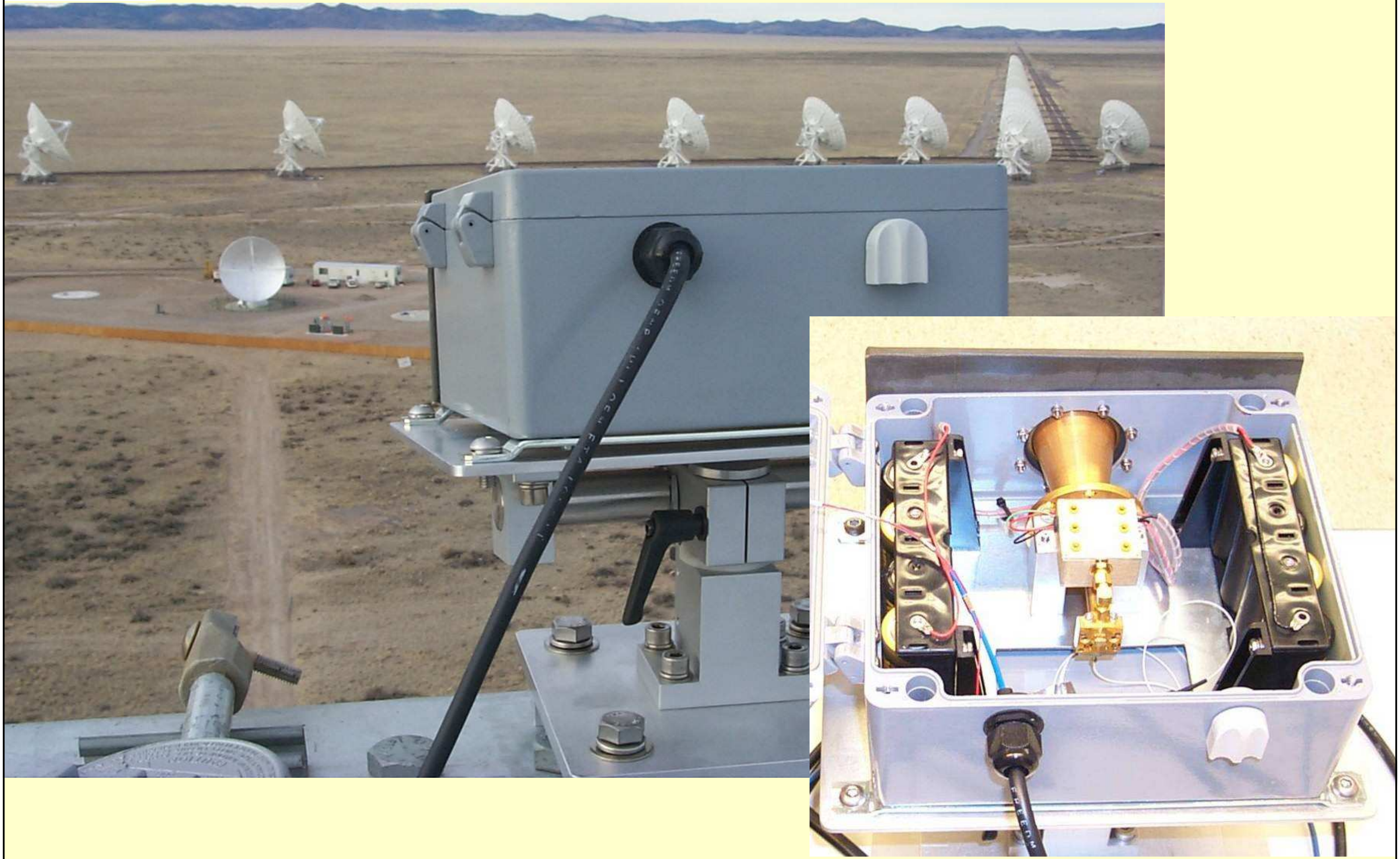
  round-trip phase = 2*(one-way phase.)
- Round-trip delay $\tau = 2nL/c$ limits correction servo bandwidth to ~1/τ or ~12.5 kHz/km
- Fiber Sensitivity: Acoustic and vibration environment must not exceed correction range or bandwidth
- Signal-to-noise and loop bandwidth considerations might require “cleanup” oscillators at remote site
- Dispersion: Applies differently to each technique, often important.
- Phase detector errors: minimized at high signaling frequency
- Polarization-Phase Conversion: Shen *et al*., MWP 2005
- Amplitude-Phase Conversion: J.Ye *et al.*, *Opt. Lett.*, 2004

Structural Metrology
based on 1.5 GHz modulated laser range meters



Green Bank Telescope, WV

104 GHz Photonic Transmitter
(supporting holographic antenna measurement)



Summary

- Emerging applications involving arrays of many antennas require low-cost optical communication of two types:
  - wide bandwidth, low timing precision (analog or digital)
  - narrow bandwidth, high timing precision
- Development of round-trip correction schemes enables timing precision ~50 fsec over 10s of km
- Free-space laser beams with microwave modulation allow structural metrology with ~100 μm precision over distances ~200 m (<1 ppm).