An Interferometer to measure Atmospheric Phase Stability

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May 10 1993.

This is a proposal for a simple interferometer which would be put at potential mmA sites, to gather statistics on interferometric phase stability. The interferometer would operate at a frequency of approximately 12 GHz, but would enable reliable predictions of the atmospheric phase instability to be expected at, say, 345 GHz. This document is offered as a "straw-man" proposal, to act as a basis for discussion. We have borrowed freely from reference (2).

Introduction

In order to choose the "best" site for the NRAO mmA, data on likely interferometric phase fluctuations at wavelengths to be used by the mmA are required. A study has already been made using the short-term total power fluctuations of the NRAO 220 GHz tipping radiometers, reported by Mark Holdaway (4,5). Although the tipping radiometers were not originally designed for this type of measurement, which requires extreme stability of calibration, interesting results have been obtained. Elsewhere, simple interferometers, using geo-stationary satellite signals, have been built to measure the interferometric phase fluctuations directly (1,2). Such interferometric measurements should be able to provide more direct data on atmospheric phase fluctuations, and provide access to scale-sizes or timescales not accessible by the tipper fluctuation analysis. The interferometer data do not replace the tipper measurements, but provide complementary information.

Choice of Frequency

To a good approximation, provided atmospheric stop bands are avoided, the atmosphere is non-dispersive. Measurements of phase fluctuations on one frequency (e.g. 12 GHz) can be converted simply to variations of electrical path length and applied directly at another frequency. Ishiguro et al. (1) confirmed this principle between 19 GHz and 98 GHz.

There are many 12 GHz geo-stationary satellites visible from the U.S. These satellites transmit a variety of modulated and unmodulated signals, and may be received at a relatively high signal strength. Small (e.g. 1 m diameter) satellite dishes with low-noise preamps and downconverters are readily available, at relatively low cost. The easy availability of cheap antennas and frontends, combined with the profusion of strong signals in the sky, make 12 GHz the obvious choice of frequency for the proposed interferometer. Because we are interested only in measuring phase stability, we are not concerned if the satellite signal is amplitude modulated.

Electrical and Mechanical Stability

Although the instrumentation operates at this relatively low frequency, the required stability of the electronics, antenna and cables equates to that required for the mmA itself. A phase change of not more than 10 degrees at 345 GHz corresponds to <24 microns. This defines the specification of mechanical and electrical stability of the 12 GHz system. Not surprisingly, this is close to the figure already set for the necessary precision and stability of the individual mmA antennas.

This stability needs to be maintained for a period of approximately 15 minutes. A critical area is the differential change with temperature of the cables carrying the l.o. reference signal to each antenna. Colin Masson did not use any active phase-correction, relying on thermal insulation and long thermal time constants in order to achieve the required phase stability. This may also be possible in the proposed NRAO system, but we will assume initially that for the mmA site tests we *will* need to incorporate some round-trip phase measurement system to allow for changes in relative electrical length of the separate antenna cables. We may be able to copy modules already developed for the VLBA, or for the GBT laser measuring system.

Maximum Baseline

We will have the freedom to change the baseline of the interferometer, but the phase stability must support the largest baseline. Existing data suggest that a maximum baseline of 150 m to 200 m is appropriate.

Number of Antennas

The incremental cost per antenna may be relatively low (see below), so there is the possibility of operating simultaneous interferometers at more than one baseline - e.g. at 50 m as well as 200 m, or with a N-S baseline at the same time as an E-W baseline. Note that the design criteria for this interferometer are somewhat different from the usual radio astronomical interferometer. The system will not be noise limited; for N antennas, it is not necessary to have the usual N(N-1)/2 simultaneous correlations. It may be economic for the "simultaneous" baselines to time-share the same correlation electronics.

For the sake of simplicity, it will be assumed now that a single-baseline 12 GHz interferometer is to be constructed.

Tracking of Antennas

The geostationary satellites typically wander within about 1 degree of their nominal position (there are international regulations that define the maximum permissible wandering.) Assuming the antenna beamwidth is significantly > 1 degree, then the antennas may be aligned manually on the chosen satellite and left fixed. No tracking will be required.

If the beamwidth is to be > 1 degree, then the receiving antenna diameter should be less than ~ 60 wavelengths, or < 1.5m.

Size of Antenna

In order to avoid tracking the satellite, the maximum size (see above) is about 1.5 m. Antennas of approximately 1m diameter are readily available. Does this give adequate signal-to-noise ratio?
For these calculations, factors of order 2 or less (e.g. that the collecting area is doubled in a 2-element interferometer) are ignored.

e.g. GStar A2 transponder 1 has an EIRP of 20 dBW
At a distance of approx. 40,000 km, this gives a flux at the
earth's surface of about 5.E-15 W/m**2.
A single antenna of 1m diameter intercepts K.5E-15.(pi/4) W, where
K is the antenna efficiency, say 0.5
i.e. an antenna intercepts about 2.E-15 W.

Low noise uncooled amplifiers are available with noise factor 1.3 dB. (101 K).
Allowing 50 K for spillover gives Tsys of 150 K, or per kHz of bandwidth
Pn=kTB = 2.E-18
i.e. assuming no post-detection integration

S/N in 1 kHz bandwidth = 30 dB

With detection of coherent signals, the power S/N goes linearly with bandwidth, not as SQRT(B) as with the usual radio astronomy signals. If we narrow the bandwidth to 1 Hz (e.g. using coherent post-integration):

S/N in 1 Hz bandwidth = 60 dB

If we require to measure 25 microns, at 12 Ghz this is approx. 0.001 wavelengths, or 0.36 degrees of phase. In order to measure to this precision, the required (Voltage) S/N is approximately

1/sin(0.36degs) = 159, or 44 dB.

i.e. **Required S/N = 44 dB**

Conclusion: Using this satellite transmitter,

WITH A 1-METER DISH, THE SYSTEM WILL NOT BE NOISE LIMITED.

Alternative satellite transmitters:

Transmitted powers for many 12 GHz satellites are in excess of 40 dBW ERP. However, Colin Masson and Marty Levine (CFA) have suggested using an INTELSAT beacon at 11.198 or 11.452 GHz, which has an ERP of only a few dBW. Use of one of these beacons is still possible with the proposed system, but without such a large margin of S/N ratio.

In practice, it may be a good idea to assemble fairly soon a simple single dish monitoring system to decide exactly which satellite transmission is the most suitable for our proposed 12 GHz interferometer.

Frequency Control:

Due to the wandering of the satellite, Doppler shift at 12 GHz on a given satellite varies from +/- a few tens of Hz to +/-2 kHz. The i.f. bandwidth of the system should be wide enough to accommodate this and any l.o. frequency drifts. Provided that free space and cable electrical paths to the two antennas are fairly well equalized, the l.o. frequency stability only needs to be good to a few (e.g. 10) kHz. This can be provided by a good quality fixed frequency crystal oscillator. In practice we may lock the l.o. chain to the satellite signal.

Block Design:

Figure 1 shows a possible block diagram for one two-element interferometer system. The design is simplified by using direct conversion down to baseband; this sacrifices 3 dB of S/N ratio, but gives a worthwhile simplification. The round-trip cable delay correction is not shown.

The apparent received signal frequency will drift a few kHz, due to Doppler shifts, drifts in the satellite's own oscillator, and the stability of our own l.o. crystal. The final baseband signal is arranged to be a constant 5 kHz, which may be synchronous with the clock in the A/D board.

Power Budget:

The power required to run the system is less than 50 W. Conversations with Gerry Petencin indicate that there is a very large solar cell/battery supply at Springerville. The system is designed to provide 10 amps at 12 volts for five days with no input from the solar cells, giving a power capability that is more than adequate for our needs.

POWER BUDGET

This does not include extra power which may be required for thermal stabilization circuitry, or for the round-trip delay measuring electronics.

		WATTS
<u>Per Antenna</u>		
FRONT END		5.0
DRO		5.0
AMPLIFIERS		3.0
XTAL OSCILLATOR		1.5
VCXO		2.5
DC AMPS		1.5
A/D		2.0
<u>Per System</u>		
PC		5.0
	TOTAL	46.0

Cost Estimates

These are approximate.

	Number Required	Price	Total
ANTENNA & FRONT END	2	$1,000	$2,000
PHASE-LOCKED DRO	2	1,200	2,400
AMPLIFIERS	4	200	800
FILTERS	2	300	600
MIXERS	2	100	200
VCXO	1	1,400	1,400
VIDEO AMPS	2	100	200
A/D	2	500	1,000
PC	1	2,500	2,500
MISCELLANEOUS	1	1,000	1,000
MECHANICAL & HARDWARE	1	500	500
ROUND-TRIP CORRECTION	2	2,500	5,000
CABLE	1 (1.5 $/FT)	1,500	1,500
		TOTAL	19.1 K

Although this is very approximate, it seems that about $20,000 would enable a 2-antenna interferometer system to be built.

Manpower

This is much more difficult to estimate. The largest fraction of time will probably be spent in assuring adequate phase stability of the system. These are guesses:

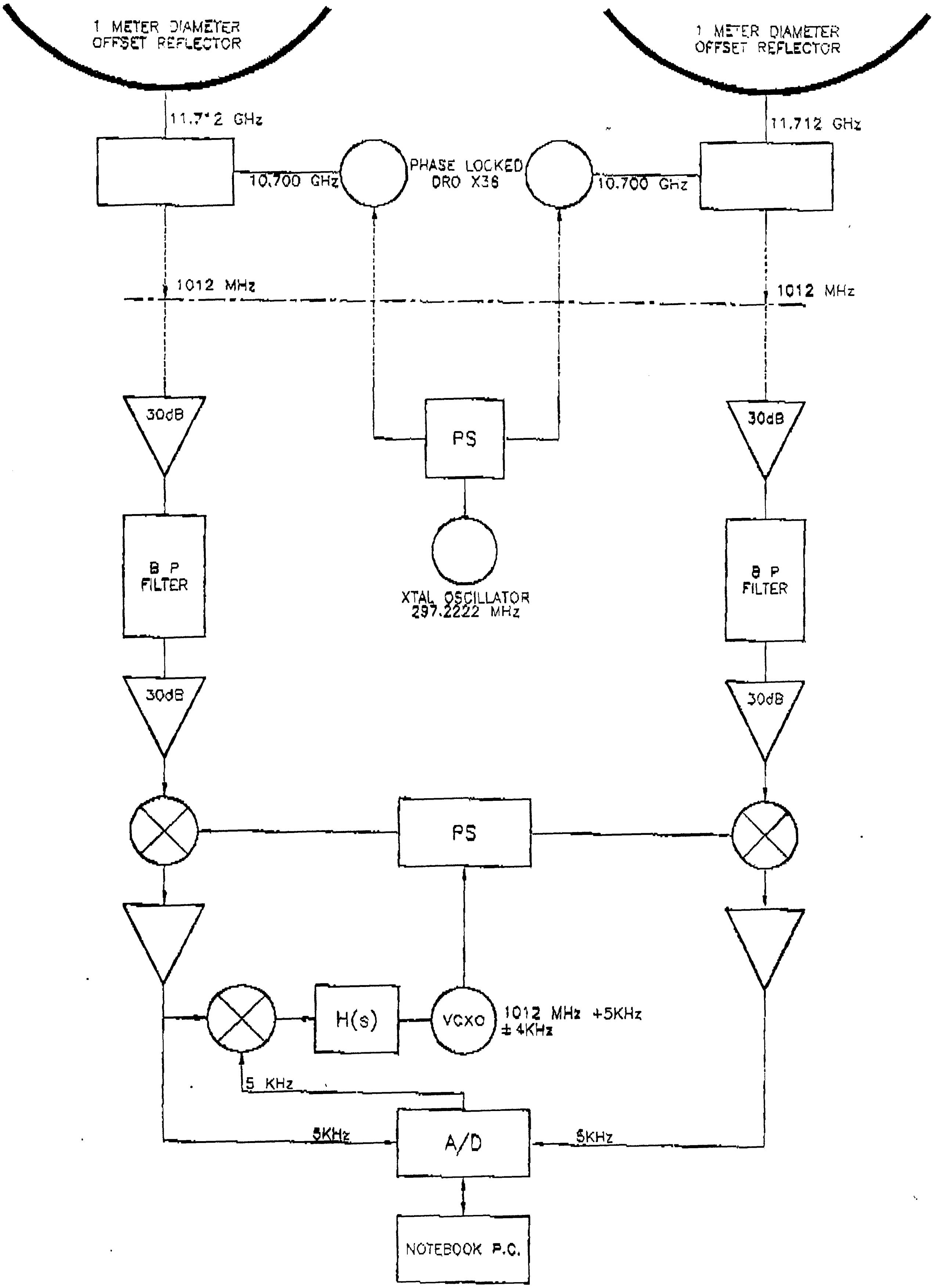
Round-trip or other phase calibration scheme:	0.5 Engineer-years 0.5 Technician-year
General set up and testing:	0.5 Scientist-years
Data analysis	???

Acknowledgements:

This draft has benefitted from correspondence and discussions with Colin Masson, Marty Levine, Mark Holdaway, Frazer Owen, Gerry Petencin and others.

References:

(1) Ishiguro, M., Kanzawa, T., Kasuga, T., 1989. *Monitoring of atmospheric Phase Fluctuations using Geostationary Satellite Signals.* NRO Technical Report No. 21.
(2) Colin Masson, J.D. Williams, Dan Oberlander & Jim Herrnstein, 1990. *The SAO Phase Monitor.* Submillimeter Array Technical Memorandum No. 30.
(3) A.R. Thompson, *"Some Thoughts on a Site-Testing Interferometer"*, NRAO internal memo, April 1993.
(4) M.A. Holdaway, 1991. *A Millimeter wavelength Phase Stability Analysis of the South Baldy and Springerville Sites.* Millimeter Array Memo No. 68.
(5) M.A. Holdaway, 1993. *Site Test INT stability requirements.* NRAO internal memo, April 16 1993.



BLOCK DIAGRAM