

and of the substrate echo in the absence of the sample. Then by use of equations that are readily derived from the basic signal time-of-flight equations, the thickness of the sample and the through-the-thickness velocity in the sample are com-

puted from the various echo times.

This work was done by Donald J. Roth, Jeffrey P. Seebo, and William P. Winfree of Glenn Research Center. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the

commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18254-1.

Multiparallel Three-Dimensional Optical Microscopy

Lyndon B. Johnson Space Center, Houston, Texas

Multiparallel three-dimensional optical microscopy is a method of forming an approximate three-dimensional image of a microscope sample as a collection of images from different depths through the sample. The imaging apparatus includes a single microscope plus an assembly of beam splitters and mirrors that divide the output of the microscope into multiple channels. An imaging array of photodetectors in each channel is located at a different distance along the optical path from the microscope, corresponding to a focal plane at a different depth within the sample. The optical path leading to each photodetector array also includes lenses to compen-

sate for the variation of magnification with distance so that the images ultimately formed on all the photodetector arrays are of the same magnification.

The use of optical components common to multiple channels in a simple geometry makes it possible to obtain high light-transmission efficiency with an optically and mechanically simple assembly. In addition, because images can be read out simultaneously from all the photodetector arrays, the apparatus can support three-dimensional imaging at a high scanning rate.

This work was done by Lam K. Nguyen, Jeffrey H. Price, Albert L. Kellner, and Miguel Bravo-Zanoquera of the University of Califor-

nia for Johnson Space Center. For further information, contact the JSC Innovation Partnerships Office at (281) 483-3809.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

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Stabilization of Phase of a Sinusoidal Signal Transmitted Over Optical Fiber

Two-way transmissions allow for rapid correction of common reference tones.

NASA's Jet Propulsion Laboratory, Pasadena, California

In the process of connecting widely distributed antennas into a coherent array, it is necessary to synchronize the timing of signals at the various locations. This can be accomplished by distributing a common reference signal from a central source, usually over optical fiber. A high-frequency (RF or microwave) tone is a good choice for the reference. One difficulty is that the effective length of the optical fiber changes with temperature and mechanical stress, leading to phase instability in the received tone. This innovation provides a new way to stabilize the phase of the received tone, in spite of variations in the electrical length of the fiber.

Stabilization is accomplished by two-way transmission in which part of the received signal is returned to the transmitting end over an identical fiber. The returned signal is detected and used to

close an electrical servo loop whose effect is to keep constant the phase of the tone at the receiving end.

The technique is useful in large arrays of Earth-based antennas used for space communication or radio astronomy. It is also useful in any situation where precise timing information must be transferred over distances for which optical fiber transmission is appropriate (~10 m to 30 km). It has been used in a demonstration uplink array as part of a technology development for the Deep Space Network.

In the past, other techniques have been used for a similar purpose, but they involve either manipulation of the optical fibers, or they measure and record the phase variation rather than correcting it immediately via a closed-loop servo. The optical methods are generally slow, so they cannot correct

rapid variations. The open-loop methods are less accurate, and they are not useful in situations where real-time correction is needed. The method described here is fast, accurate, and inexpensive to implement. A method similar in principle to this one has been reported earlier, but the new configuration is different and permits variable transmitted frequency and higher correction speed. Related round-trip stabilization methods have been used for signal transmission in coaxial cable and in waveguide

The new method is illustrated by the block diagram in Figure 1. The signal to be transmitted is at frequency f_0 . It is generated by mixing an input at $f_0 + f_1$ (from the first master synthesizer) with a voltage-controlled crystal oscillator (VCXO) at nominal frequency f_1 (77.76 MHz in this implementation). It

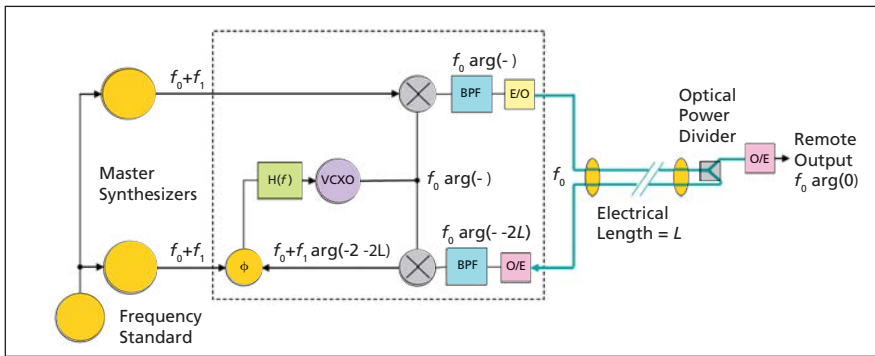


Figure 1: **Simplified Block Diagram** of the phase stabilization system, showing its principle of operation. Components in the dashed box form the reference generator module. Here E/O and O/E denote electrical-to-optical conversion (laser) and optical-to-electrical conversion (photodetector), respectively, and BPF denotes a band-pass filter. Changes in line length L are compensated by a phase-locked loop driving a voltage-controlled crystal oscillator. In this implementation, the VCXO frequency is $f_1 = 77.76$ MHz, and the output frequency f_0 is in the range 437 to 454 MHz.

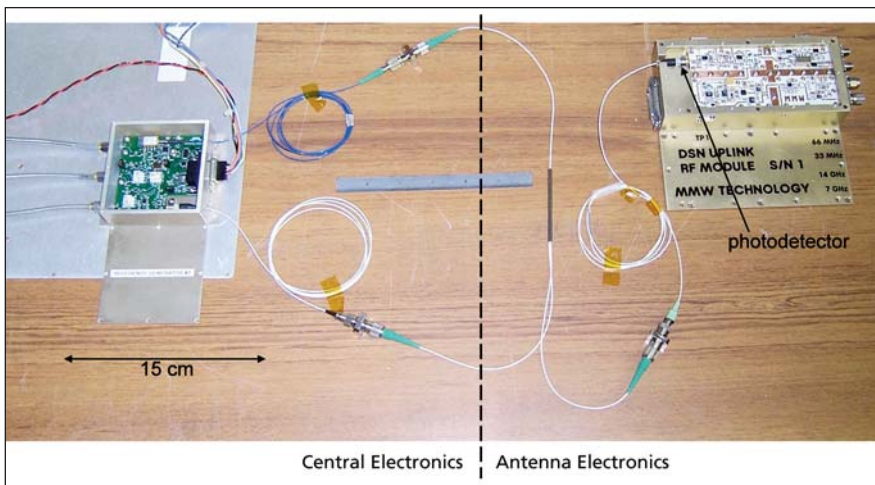


Figure 2: **System Undergoing Laboratory** testing is shown with short fiber connections. The Reference Generator Module is the 5x5 cm box at the left. It includes the laser and photodetector for electrical/optical conversion. The blue fiber at the top carries the outgoing signal and the white fiber at the bottom carries the returned signal. At the right is equipment intended for installation at the remote location, including an optical power divider and a module that includes the photodetector along with circuitry for this application that uses the output signal.

is then used to modulate a diode laser coupled to the outgoing fiber. At the far end of the fiber, the signal is optically split and half of its power is converted back to electrical form in a photodetector, producing the desired output. The other half is returned to the stabilization system over a nominally-identical fiber in the same cable. The returned signal is converted to electrical form, then down-converted in frequency by mixing with the same VCXO, and the result is compared in phase against an input from the second master synthesizer at $f_0 - f_1$. The phase difference is used to drive the frequency of the VCXO via filter $H(f)$, forming a phase-locked loop. If the input signals are considered to have phase zero, it is easy to show that the loop will drive the phase θ of the VCXO so that $2\theta = (2L) \bmod 2\pi$, where

L is the electrical length of the line in each direction, causing the phase of the signal at the turn-around point to remain constant as L is changed. The actual phase there has a two-fold ambiguity; it could be either 0 or π . (These expressions neglect delays in the electronics, but those cancel if they are equal in the two directions. If they are unequal but stable, the output phase remains stable even though the electrical length of the fiber varies.) The important assumption is that the variation in fiber electrical length is the same in the two directions.

The system can be used to generate coherent signals at multiple remote locations by duplicating the assembly labeled Reference Generator Module (RGM) in Figure 1 and driving all RGMs with the same master synthesizer signals. If all RGMs and photodetectors are iden-

tical, and if each pair of fibers is reciprocal (same electrical length in both directions), then the output signals at all remote locations have equal phase, even if the fiber pairs to the various locations have vastly different lengths.

This system has an advantage over those that rely on manipulation of the fiber because it can correct variations in the fiber length much faster. In some applications, the dominant cause of changes in fiber length is temperature variation, but there are also circumstances where the fiber is subject to varying mechanical stress, such as when it must traverse the rotation axes of a movable reflector antenna. Temperature changes are often slow (and can be further slowed by adding insulation), but mechanical changes can be rapid. Here the correction speed is limited only by the round-trip signal time; for the loop to be stable, it must have a time constant at least several times the round-trip time.

It is also possible to vary the transmitted frequency f_0 while maintaining constant phase differences among multiple remote locations. The rate of frequency change need only be slow enough that all of the correction loops remain phase locked.

This system was implemented for operation in the range $f_0 = 437$ to 454 MHz and was used to provide coherent reference signals to the antennas of a 5-element microwave phased array. In this frequency range, the RGM can be made small and inexpensive, as shown in Figure 2. Before deploying it in the array, the innovators conducted tests using a 305-m long spool of multi-fiber cable where both ends of the cable were in the laboratory so that the input and output phases could be compared. The spool was kept outdoors and subjected to diurnal temperature cycling over several days. With the correction loop disabled, phase changes of 26.5° peak-to-peak were observed at 450 MHz with 23.9°C peak-to-peak temperature change; this corresponds to a delay coefficient of 6.2 ps/ $^\circ\text{C}$, which is about as expected for this length of standard single-mode fiber. With the correction loop enabled, no variation with fiber temperature was detectable, and the measurements placed an upper limit on the coefficient of 0.054 ps/ $^\circ\text{C}$.

This work was done by Larry R. D'Addario and Joseph T. Trinh of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-46711.