VLA-Pie Town Link Test Report

VLA Test Memo # 217

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Abstract

During 1998, development took place on a prototype real-time link between the Pie Town antenna of the Very Long Baseline Array (VLBA) and the Very Large Array (VLA), located approximately 52 km away. This link was funded under the National Science Foundation's Major Research Instrumentation program, with matching funds awarded by Associated Universities, Inc. The development culminated in the first real-time fringes between Pie Town and the VLA during tests in December 1998. Successful demonstrations have been carried out at all 7 bands in common between the VLA and VLBA, from 327 MHz to 43 GHz. Efforts in 1999 will concentrate on making the link operational, in anticipation of full operation when the VLA is in its A configuration in late 2000. The first science with the VLA-Pie Town link, using a mix of prototype and operational systems, will probably be possible during the next A configuration, between June and October 1999.

1 Introduction

The Very Large Array (VLA), an array of 27 radio telescopes on the high plains of New Mexico, has been operational for nearly 20 years. Its younger sister instrument, the Very Long Baseline Array (VLBA), consists of 10 telescopes spread across the United States, and has been operational since 1993. Both arrays are operated by the National Radio Astronomy Observatory (NRAO), under funding from the National Science Foundation (NSF). The VLBA is "centered" on the VLA, with a cluster of antennas in the Southwest U.S., and progressively increasing antenna spacings as the distance from New Mexico increases.

The Pie Town VLBA antenna is located approximately 52 kilometers to the west of the center of the VLA, near the continental divide. The distance from Pie Town to the antenna station at the outer end of the VLA's southwest arm is approximately the same as the diameter of the entire VLA. Therefore, Pie Town is ideally situated to approximately double the size of the VLA in one dimension, hence doubling the resolution of the VLA A configuration.

A plan to upgrade the VLA to modern technology, the "VLA Upgrade Project," is currently under development. Part of that upgrade would be a replacement of the current VLA's waveguide transmission system with fiber optics, while another part would be the construction of as many as eight new antennas spread across New Mexico. These new antennas would fill in the "gaps" between the VLA and VLBA, resulting in a single instrument that could image radio sources over five orders of magnitude in resolution, from less than a milliarcsecond to more than an arcminute.

In 1997, a proposal was made to the NSF's Major Research Instrumentation program for a 3-year project to create an operational real-time command and data link between the VLA and the Pie Town antenna. This connection is made possible by a commercial fiber-optic line that has been installed by Western New Mexico Telephone Company. The proposal was funded by NSF, contingent on the presence of matching funds, which were awarded by Associated Universities, Inc., the non-profit corporation that operates NRAO under cooperative agreement with NSF. Scientifically, this link would increase the resolution of the VLA by a factor of two for sources north of $\sim 40^\circ$ declination, with somewhat less improvement (due to foreshortening) at lower declinations. Technically, this link would demonstrate the capability for real-time fiber-optic connection both of the current VLA antennas and of the other antennas that might be built as part of the VLA Upgrade. This report summarizes the results of the first year of development under the NSF program, through the end of 1998.

2 Design

The operation of the real-time link depends on three key areas. First, a design was required for the overall system to transmit the Pie Town data over 104 km of fiber, as well as sending commands from the VLA real-time system to equipment at Pie Town.[1] Second, the delay range of the VLA correlator had to be expanded from a maximum of 163 microseconds (μsec) to accommodate a maximum delay of about 675 μsec, accounting for the geometric delay of the signal from a radio sources anywhere in the sky as well as the travel time for the analog data across the fiber link. Third, the VLA real-time software had to be extended to control new equipment installed at Pie Town, as well as the new correlator delay hardware, and to make Pie Town "look like" a VLA antenna insofar as is possible.

2.1 System Design

The system design relies on slightly modified off-the-shelf VLA modules wherever possible. Both the prototype system and the final design are described briefly here. Four intermediate-frequency signals (IFs) from the Pie Town telescope, between 500 and 1000 MHz, will be sent into a specially designed rack (the "Pie Town rack"), which consists largely

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[1] The commercial telephone fiber does not run directly from Pie Town to the VLA, but takes a more circuitous route, accounting for the fact that a 104-km fiber link is required to traverse 52 km as the crow flies.

of standard VLA modules and a laser-transmission system. The four analog signals are upconverted to standard VLA waveguide subcarrier frequencies of 1325 MHz, 1425 MHz, 1575 MHz, and 1675 MHz by mixing the VLBA IFs with frequencies generated by standard VLA L6 modules. Fringe rotation is performed at Pie Town, as at a VLA antenna, by driving the L6 modules with separate L7 fringe-rotation modules. In the current prototype, only the first right-circularly polarized IF (VLA IF A) is used, with the subcarrier frequency of 1325 MHz. The resulting analog data are modulated on a fiber-optic carrier, transmitted by a 1550-nm laser through the commercial fiber to the VLA, and demodulated from the optical carrier. At the VLA, the resulting IF is sent into a standard VLA "D rack," then sampled and digitized in the usual way before being sent to the VLA correlator.

The one-way analog data link currently uses a single optical fiber. Along with the IF data, it carries a 1200-MHz analog signal produced by an oscillator in the Pie Town rack that is driven by the Pie Town maser. This can be used as a rough measurement of the variation of the transmission delay and the relative frequency offset of the VLA and Pie Town masers. In the final system, a round-trip phase measurement system will be in place, as is currently the case for the VLA waveguide system. This has not yet been implemented, but the requirement will be described further in Section 4.4.

In the prototype system, a separate fiber has been used for a two-way digital link between the VLA and Pie Town. This link provides command data to the Pie Town rack, including local oscillator setting and fringe-rotation, while it also returns monitor data to the VLA on-line system. Ultimately, the plan is to use only a single fiber for the two-way digital communications and two-way analog data, but this will require wavelength multiplexing and optical isolation that is not currently in place. Until such a system is installed, observations will be affected by reflections and backscattering in the fiber, as described in Section 4.3.

2.2 Correlator Delay Modification

The VLA correlator, as originally constructed, provides a single delay range that can accommodate approximately 163 μsec of delay, adequate for the geometric delay as well as the transmission delays for antennas at any location along the three arms of the VLA. For Pie Town, the geometric delay at any point in the sky can be more than 165 μsec, and the estimated transmission delay for 104 km of fiber optics is an additional 505 μsec. Therefore, a total delay range of more than 670 μsec is required. This has been accommodated by a piggyback board designed by the correlator group in Socorro. Delay cards in the correlator are modified to accept piggyback boards which contain four additional bulk steps of 163 μsec of delay. The total delay range is then more than 800 μsec, meeting the requirements for the real-time link of the Pie Town antenna. A total of over 200 such piggybacks are needed for the VLA correlator, accommodating the sine and cosine multipliers for each of two polarizations in each of two IFs for each of the 27 antennas (i.e., $2\times2\times2\times27$ piggybacks), as well as a few additional devices required for the correlator selftest. Currently, 12 piggyback devices have been constructed, enough for one polarization and one IF in each of six antennas (Pie Town plus five VLA antennas).

The original piggyback design made use of a chip that did not always power up properly after a "hot swap" was made (i.e., after the piggyback delay card was installed without powering down the correlator). A second set of prototypes was produced using a chip from a different manufacturer; these prototypes have proven immune to any hot-swap problems. A modification of the original design thus was required for the operational system; that design is now complete.

2.3 Software

Software requirements include (1) control of the modified delays in the correlator; (2) control of the VLA back-end equipment in the Pie Town rack by means of commands sent over the digital fiber-optic link; (3) oversight of the Pie Town rack by means of monitor data points transmitted over the digital link; (4) calculation of the proper oscillator settings to match the Pie Town sky frequency to the VLA sky frequency, as well as the fringe-rotation rate for Pie Town; and (5) integration into the VLA. Currently, a prototype system is in place that makes use of the prototype fiber-optic and back-end equipment, and relies on "donation" of a D-rack and an identity ("DCS," or Digital Control System) from an existing VLA antenna. The actual front-end of the Pie Town antenna (pointing and frequency selection) is controlled in a standard way by the VLBA operator, while the Pie Town rack is commanded by the VLA real-time system.

3 VLA-only Tests

System tests of all aspects of the prototype commenced at the VLA in early November 1998. The Pie Town rack and a 104-km spool of fiber-optic cable were installed in the VLA electronics room. A series of tests of progressively increasing complexity was performed, with one VLA antenna mimicking Pie Town by donating the analog data, while another VLA antenna donated its DCS number and D rack. Throughout this series of tests, hardware and software were debugged and modified in order to make the system more robust. In the last of these tests, carried out on November 25, digital control signals and monitor data were sent through half of the fiber-optic spool, while analog antenna data were transmitted through the remaining half. Interference fringes were successfully obtained between the donor antenna and other VLA antennas, using the Pie Town rack, the prototype delay piggybacks, and the prototype control software. This demonstration tested all aspects of the real link with the exception of the actual commercial fiber-optic cable.

4 Pie Town-VLA Tests

At the beginning of December, the Pie Town rack was moved from the VLA and installed at Pie Town. On December 3, the first of a series of real-time tests commenced using Pie Town and five VLA antennas, employing a single right-circularly polarized IF channel. Within a few minutes of the time when the VLA antennas were pointed at the quasar 3C 345, successful interference fringes were seen at a frequency of 5 GHz (4.885 GHz, to be precise). It took another 30 minutes to center the delay accurately; the measured fiber-optic delay differed by only 1.5 μsec from the predicted value of 505 μsec. A display of the first fringes is shown in Figure 1.

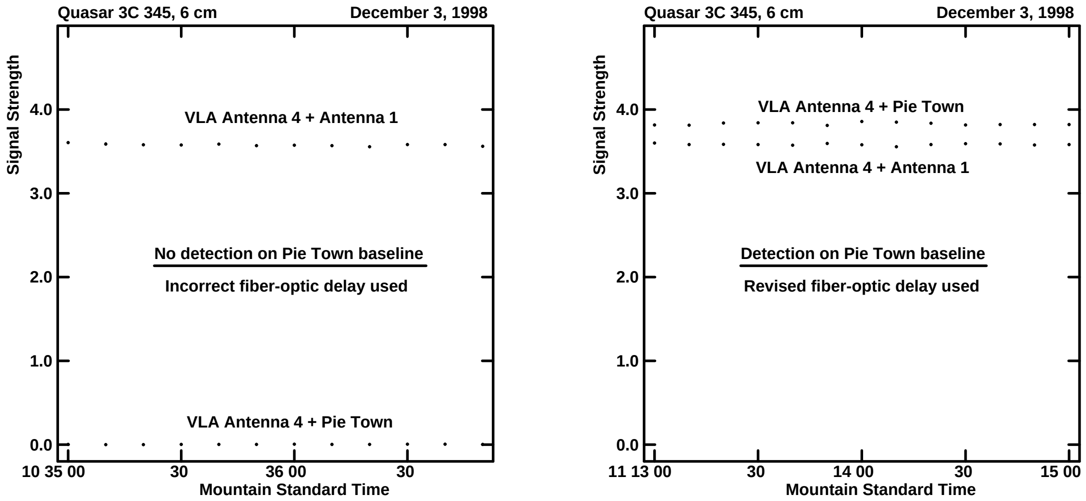

Figure 1: Correlated amplitude (uncalibrated) on a VLA baseline and on the baseline between a VLA antenna and Pie Town, at 6 cm wavelength (5 GHz frequency). *Left:* No fringes on Pie Town baseline (link set-up still incomplete. *Right:* Fringes between VLA and Pie Town, after centering the residual delay.

Over the ensuing weeks, successful correlation took place in all seven frequency bands in common between the VLA and the VLBA. A variety of different combinations of sidebands are present between the two arrays; a summary of the fringes and the sidebands is given in Table 1.

Table 1. Pie Town-VLA Real-Time Fringes

Frequency	PT sideband	VLA sideband	First Fringes
0.3 GHz	Upper	Upper	23 December
1.4 GHz	Lower	Upper	7 December
5 GHz	Upper	Upper	3 December
8.4 GHz	Lower	Lower	3 December
8.4 GHz	Upper	Lower	14 December
15 GHz	Upper	Lower	7 December
22 GHz	Upper	Upper	3 December
43 GHz	Upper	Upper	7 December

Following the first detection of fringes, the tests during December 1998 have largely been used to check out the software and all aspects of the fiber-optic link. These tests have used the Pie Town antenna together with five VLA antennas that are situated on the southwest arm in the fairly compact C configuration. Several areas have been investigated, and are summarized below.

4.1 Delay Offsets

There are significant delay offsets introduced by the differences between the Pie Town antenna and the VLA antennas. For instance, the elevation and azimuth axes at the Pie Town antenna do not intersect, but are offset by more than 2 meters. This axis offset (amounting to about 7.14 nanoseconds) has now been entered (with the correct sign) for the Pie Town antenna when used with the VLA. There was an initial delay error of about ±20 nanoseconds (nsec) over different parts of the sky, due to an incorrect position that was used for Pie Town. That error has now been reduced to 1–2 nsec, but there still appears to be a small error of up to 0.5 meters in position for the Pie Town antenna when referenced to the VLA coordinate frame. In addition, there are significant delay differences of tens of nanoseconds as a function of band, due to the differing relative signal paths of (apparently) up to 10 meters in VLA and VLBA antennas. As an example, Figure 2 shows the phase slope throughout the bandpass for a VLA-Pie Town baseline at 1.4 GHz, caused by a delay offset of approximately −33 nsec relative to the delay at 5 GHz. Table 2 gives the rough delay offsets for most of the frequency bands, relative to 5 GHz. Further tests will be required to confirm the constancy of these offsets.

Table 2. Pie Town-VLA Delay Offsets	
Frequency	PT−VLA delay
0.3 GHz	TBD
1.4 GHz	−33 nsec
5 GHz	≡ 0 nsec
8.4 GHz	−26 nsec
15 GHz	+12 nsec
22 GHz	+8 nsec
43 GHz	−17 nsec

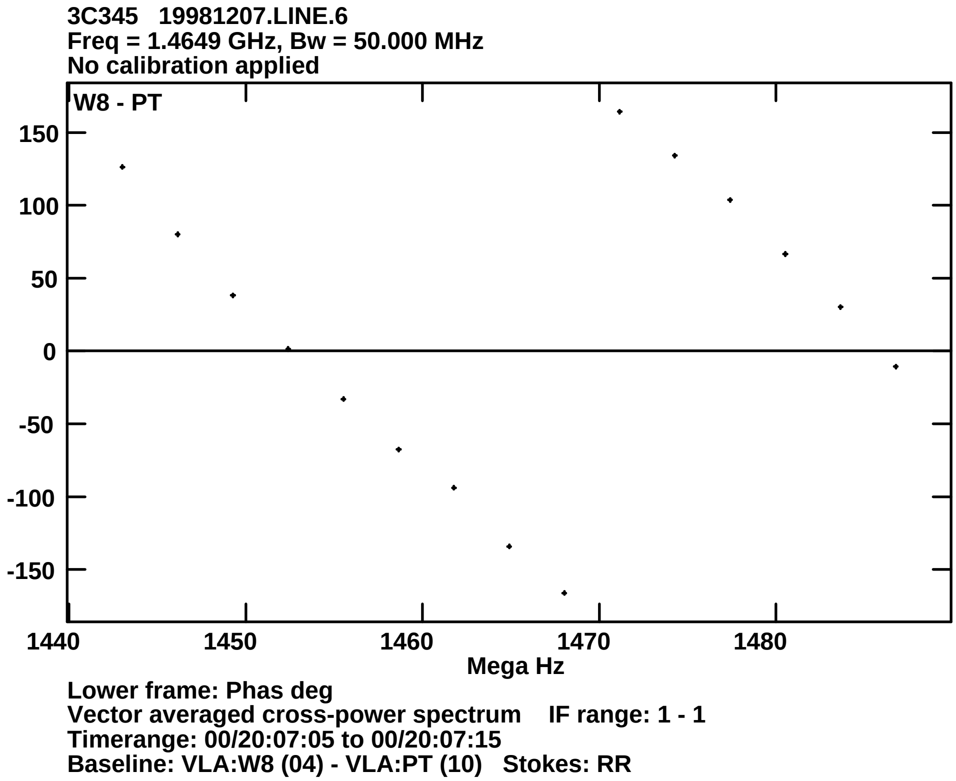

Figure 2: Phase slope vs. frequency in a 50-MHz bandpass at 1.4 GHz, on a baseline between a VLA antenna and Pie Town, corresponding to a delay error of about −33 nsec. The delay error at 5 GHz was set to less than 1 nsec before the switch to 1.4 GHz was made.

4.2 Bandpass Spikes

In early tests at 5 GHz, a significant interference spike was seen near 20 MHz in the bandpass, causing ringing throughout the bandpass. After some troubleshooting, it was determined that this spike was caused by an oscillator setting of 539.9 MHz that was used to convert the VLBA IF frequency to a DC value of 1300 MHz. The second harmonic of 539.9 MHz at 1079.8 MHz was mixing with a frequency reference at 1200 MHz to create a spur at 1320.2 MHz, which showed up in the final spectrum of the Pie Town antenna at 20.2 MHz above DC. This spike has been eliminated by use of a narrower filter in the Pie Town rack, with a sharper cutoff outside the allowed frequencies.

Figure 3 shows the autocorrelation spectrum for the Pie Town data before and after removal of the spike in the spectrum. The spurious signal was seen only in the autocorrelation spectrum and not in the cross-correlation, so it should not have affected interferometer data. Harmonics of some possible local-oscillator settings (instead of their reflections) will fall within the transmission bands of the four IFs, but should neither affect the cross-correlation nor be strong enough to increase the system temperature. Further tests will be carried out in all bands to insure that no harmonics generated in the conversion of the VLBA IF cause any interference with cross-correlation data.

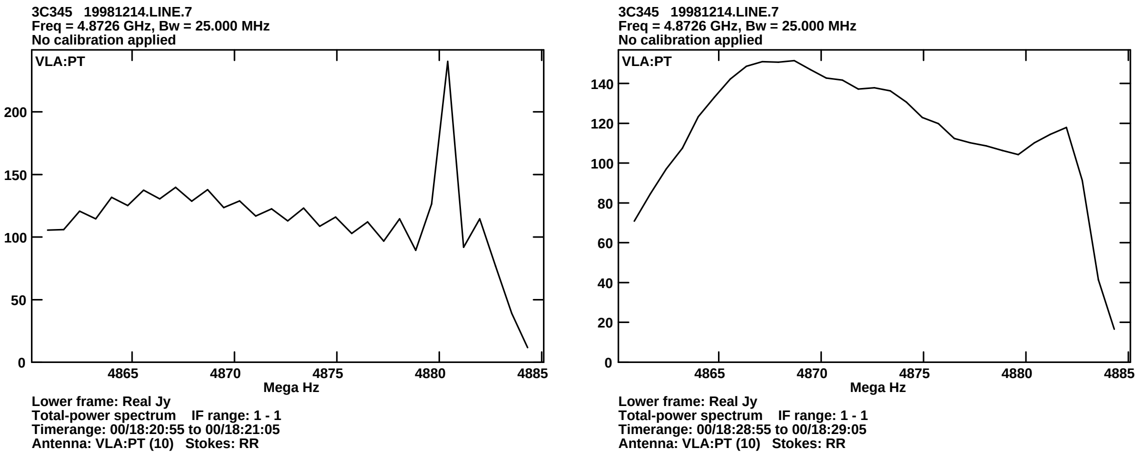

Figure 3: Autocorrelation spectrum for the Pie Town antenna on December 14. *Left:* Interference spike and spectral ringing due to the spurious signal generated by the frequency-conversion system. *Right:* Spectral shape after insertion of a bandpass filter to remove the spurious signal.

4.3 Amplitude Drops

Amplitude drops have been seen in the fringe visibility throughout the tests, with a typical frequency of once every few minutes. Monitoring showed a large number of parity errors in the commands going to the Pie Town rack; commands are ignored when parity errors are detected. The bit errors are statistically random in nature, so there also must be a much smaller number of two-bit command errors. Since the latter do not cause a parity error, incorrect communications are accepted, and result in erroneous commands being issued to oscillators or fringe rotators. Since the command interval is 1.25 seconds, these typically result in drops of $\sim$10%–15% in a single 10-second record, or as much as 70% in an occasional record if the integration time is shortened to $1\frac{2}{3}$ seconds.

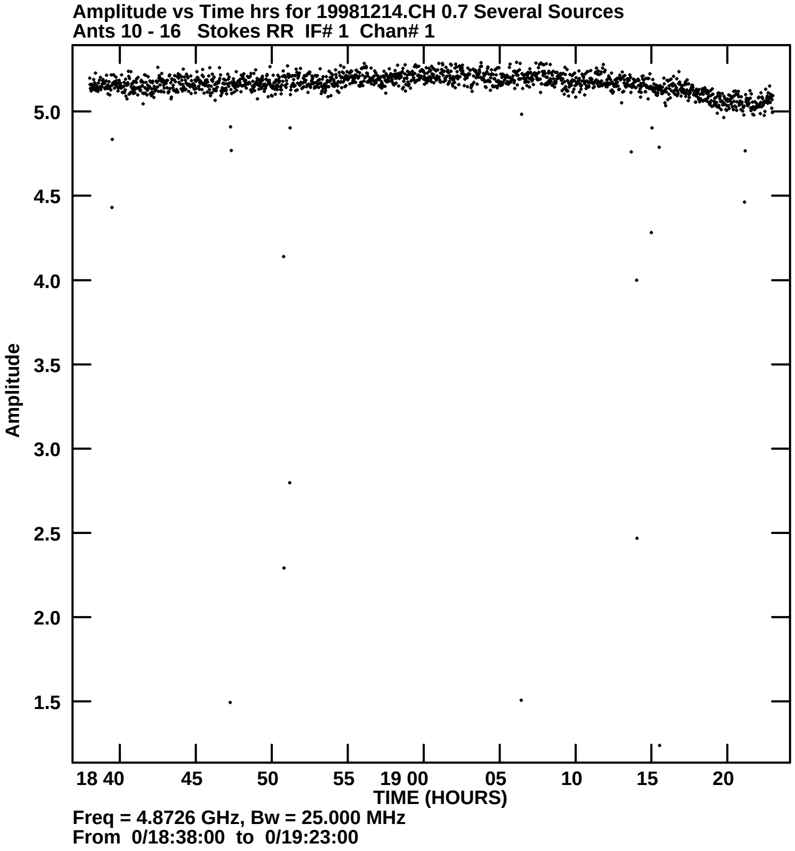

Figure 4: Uncalibrated amplitude as a function of time for a 45-minute observation at 5 GHz, with an integration time of $1\frac{2}{3}$ seconds. The amplitude dropouts reflect the effect of incorrect settings in the Pie Town rack, due to corruption of the digital commands in the fiber link. (Note that Pie Town masquerades as antenna 10, due to its "borrowed" DCS number.)

It now appears that the command errors are being caused by "Rayleigh backscatter" in the single fiber which is being used for two-way transmission of the digital data; errors also are caused in the monitor data. This problem was expected for the prototype system, although its exact manifestation and the level of the problem was not predictable. The rate of occurrence of the command errors appears to be highly variable; amplitude data on a "good" day are shown in Figure 4. The final system design will incorporate wavelength multiplexing and optical isolators to eliminate the contamination by reflected signals.

4.4 Delay and Frequency Drifts

There are significant delay and frequency drifts between Pie Town and the VLA, caused by the use of two different masers and by variations in the transmission delay through the fiber optics. The Pie Town maser is used to drive all oscillators in the VLBA antenna and the Pie Town rack, so its difference from the VLA maser effectively causes an offset of the sky frequency. Variation in the transmission delay shows up as a drift in phase at IF, which is expected to have a diurnal signature.

A one-way phase drift has been measured in the prototype system by transmitting a 1200-MHz carrier (driven by the Pie Town maser) from Pie Town to the VLA. The phase of this carrier is compared to that of the 1800-MHz signal driven by the VLA maser, providing a measurement of the combined effects of relative maser drift and the change in (one-way) transmission time across the fiber-optic link. An approximate "round-trip" phase correction has sometimes been applied in real time in an effort to reduce the effects on the interferometer data; the exact scaling of this correction is currently unknown, because one measurement is used to correct for two effects with quite different signatures. Because of the maser drift, the round-trip phase goes through a complete cycle once every 10–20 minutes; the current software resets the phase after a complete 2π drift. This causes a phase jump of 45° between Pie Town and the VLA at 5 GHz, and would lead to jumps of different amounts in other bands. The effect of the maser drift and the attempt to correct the interferometer phase is shown in Figure 5. Further efforts to correct for relative maser drifts and the link delay await a multi-day measurement of the characteristics of the fiber link, and hardware to separately measure the clock drift and path-length changes.

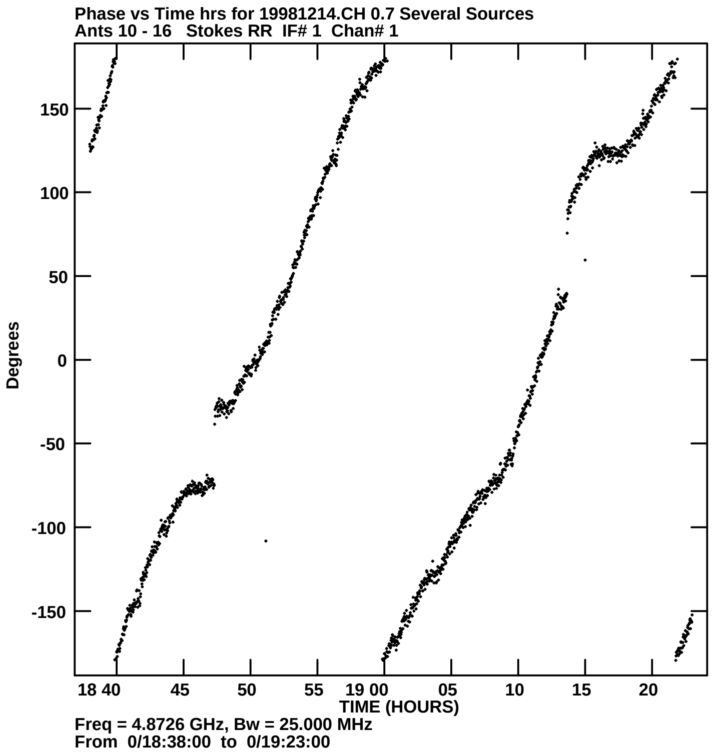

Figure 5: Interferometer phase as a function of time for the same 45-minute period shown in Figure 4. The 45° phase jumps reflect resets in the round-trip phase after the corrections have gone through a full 2π cycle. Other momentary phase jumps may be due to the same command errors that cause amplitude drops, which occasionally (but not always) cause phase jumps as well.

4.5 Delay Piggybacks

Tests have shown that the second set of prototypes for the delay piggybacks have no problem coming up if they are swapped in when the correlator is powered up. These tests have resulted in a new design for the final operational piggyback units. More than 25% of the VLA delay cards have now been modified to accept piggybacks; the remaining modifications should take place during the first quarter of 1999.

4.6 Noise-Diode Switching

For calibration purposes, the noise diodes in the VLA antennas switch at a rate of 9.6 Hz, while the diodes in the VLBA telescopes usually switch at 80 Hz. Real-time system temperature measurements of the Pie Town telescope in a manner consistent with the VLA will require its noise tube to switch at the 9.6-Hz rate. Preliminary tests have shown that the Pie Town noise diode can be switched by the VLA timing signals, but actual on-line system-temperature corrections have not yet been attempted.

4.7 Waveguide Gaps

Because of the large delay required to accommodate Pie Town, some invalid data should spill outside the period when the correlator output is blanked due to the VLA waveguide gaps. It is thought that this should show up as DC offsets, which would give rise to spurious sources at the image center. Preliminary tests do not show any additional signal above the noise at the field center, and also show no significant difference if longer correlator blanking is invoked. However, the small number of antennas and the lack of imaging capability in the first tests make it difficult to pursue this possibility in detail.

5 Primary Activities for 1999

A few problems remain to be debugged, and will be under active investigation in early 1999. The most urgent concerns are the characterization of the maser and link drifts, and resolution of the problem with dropouts of command and monitor data. These will require significant hardware modifications in moving from the prototype to an operational system, as described in Sections 4.3 and 4.4. Several measurements of the band-dependent delay offsets between Pie Town and the VLA are also required to confirm the expectations that these offsets are constant. Further tests of correlator blanking, and searches for DC offsets, will be attempted. Finally, it will be necessary to derive a Pie Town position that is completely consistent with the VLA reference frame.

The modification of delay cards to accept piggyback boards, and complete installation of the new cards and piggybacks, is now scheduled to take place by the end of March 1999. This would mean that all antennas and all IFs could be available for initial science observations with the real-time link during the A configuration in June through October 1999. However, all IFs will only be available after a higher-power laser transmitter has been installed; the current prototype is not sufficient to send all four IF channels from Pie Town. On-line software and link hardware will be upgraded in stages from the prototype systems to more operational versions. Included in this will be incorporation of a new DCS number (octal 34) for Pie Town, to remove the current confusion over the identity of the antenna using the donated VLA D-rack.

Operational scenarios and off-line software will begin to be developed in more detail during 1999. There are a number of tricks required in using the current system, such as the need to drive the IF switching at the Pie Town antenna (SCHED does not currently permit the user to change VLBA default IF channels from B and D to A and C). More attention will be paid to the understanding and elimination of such peculiarities in 1999.

In its final incarnation, it is believed that the link will be used operationally only during the trimester when the VLA is in its most extended, A configuration. Thus, Pie Town would work with the VLA for 4 of every 16 months. (Of course, occasional tests outside this period will also be necessary.) The general philosophy will be to make the use of the Pie Town antenna as simple as possible for the average VLA user, while making the loss of Pie Town have a minimal impact on the simultaneous VLBA program. The means by which observers will control the Pie Town antenna as part of the VLBA will be determined, as will the general policy for replacement of Pie Town in the VLBA by one of the 27 VLA antennas. These will require some software development as well as a great deal of careful thinking about minimizing any degradation of operational efficiency. Ultimately, the goal is to make the Pie Town antenna available routinely, on request, for programs using the A configuration during the trimester beginning in October 2000.

Acknowledgments

The initial success of the VLA-Pie Town real-time link is due to the efforts of a large number of individuals in addition to the authors of this report. Contributors in the engineering and software areas have included Nelson Atencio, Jack Campbell, Terry Cotter, Ray Ferraro, Wayne Koski, Rob Long, Jim Oty, Bill Sahr, Mario Torres, Bob Treacy, Pete Ulbricht, and Willy Zamora. In operations, Eric Carlowe has been of great assistance at the Pie Town antenna. Phillip Hicks, Dave Medcalf, Peggy Perley, Paul Rhodes, and Dave Van Horn assisted in enabling tests that made use of software and maintenance time in addition to the scheduled test time, and all the VLA and VLBA operators have contributed to making the November and December tests successful. On the scientific staff, Barry Clark, Mark Claussen, and Craig Walker have contributed significantly in various ways, ranging from general suggestions to real-time instructions on how to control the Pie Town antenna. The original MRI proposal was due largely to the efforts of Alan Bridle, Rick Perley, and Dick Sramek. Finally, we thank Western New Mexico Telephone Company for their assistance and the use of their fiber-optic line.