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An alternative scheme of round-trip phase correction

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ABSTRACT

In photonic LO (Local) system, a two-wavelength optical beatnote is transmitted by optical fiber from the AOS technical building to antennas. At an antenna, a photo mixer converts the optical beatnote into a microwave-signal which works as a reference signal for the Worm Multiplier Assembly (WMA). The compensation of instability of transmission line is essential for interferometer to obtain fringes, and is an indispensable process for keeping signal coherence. However, it is delicate to measure an optical cable length delay, because the measured delay includes polarization mode dispersion (PMD). In order to accomplish the phase compensation on the optical fiber, we consider a double-difference method with a polarization alignment servo system.

1. BASIC CONCEPT OF DOUBLE-DIFFERENCE METHOD

In order to accomplish the phase compensation on the transmission radio signal, we consider a double-difference method. The basic configuration of a system is shown in Figure 1.

Firstly, for analysis of the instrumental delay, we will discuss the phase relationship of the signals in one of two optical signals. The suffixes (Opt1 and Opt2) denote the optical wavelength.

The input optical signal phase, the source of the signal is the Laser Synthesizer, is defined as $\phi_0(t)$.
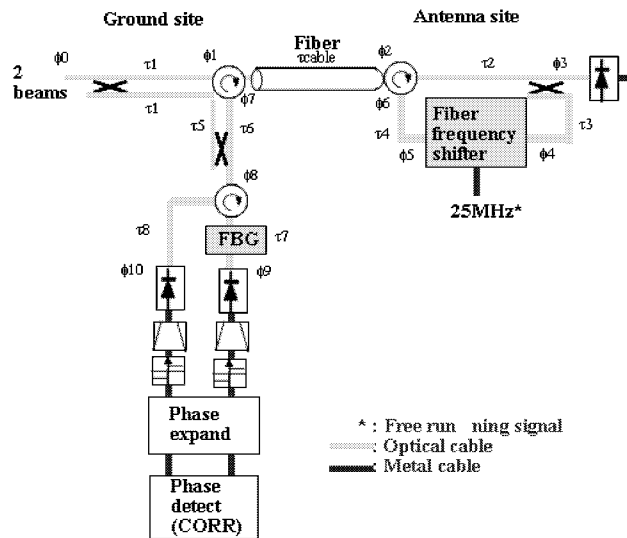
$$\phi_0(t) = \omega_{opt1}(t) + \phi_{opt1}, \tag{1}$$

Figure 1. A round trip phase correction system.

Where ω_{opt1} is an optical angular frequency, t is time, and ϕ_{opt1} is an offset-phase. The time delay caused by the cable from the input to the circulator is assumed to be τ_1, then the phase of the signal is displayed as $\phi_1(t)$.

$$\phi_1(t) = \omega_{opt1}(t - \tau_1) + \phi_{opt1}, \tag{2}$$

And in conformity with $\phi_1(t)$, received lightwave signal phase at antenna is displayed as $\phi_3(t)$, at the point of the optical coupler.

$$\phi_3(t) = \omega_{opt1}(t - \tau_1 - \tau_{cable} - \tau_2) + \phi_{opt1} \tag{3}$$

On the antenna, the received lightwave signal is modulated (frequency shifted) by a microwave signal ϕ_{PLO} (25 MHz) and sent back to the AOS technical building by the same optical cable.

$$
\begin{aligned}
\phi_4(t) &= \phi_3(t - \tau_3), & (4) \\
\phi_{PLO}(t) &= \omega_c(t) + \phi_c, & (5) \\
\phi_5(t) &= \phi_4(t) \times \phi_{PLO}(t) \\
&= (\omega_{opt1} + \omega_c)t - \omega_{opt1}(\tau_1 + \tau_{cable} + \tau_2 + \tau_3) + \phi_{opt1} + \phi_c & (6)
\end{aligned}
$$

Where ω_c is a baseband signal (25 MHz), ϕ_c is a initial phase.
Differential phase $\phi_8(t)$ between transmitting and receiving signals is measured by Michelson's interferometer.

It is assuming that the lightwave in wavelength Opt1 pass through a fiber brag grating (FBG) and detected as a microwave ϕ_9 by a photo-mixer.

$$
\begin{aligned}
\phi_9(t) &= (\phi_5(t - \tau_4 - \tau_{cable} - \tau_6 - \tau_7)) \times (\phi_0(t - \tau_1 - \tau_5 - \tau_7)) \\
&= \omega_c(t) - \omega_{opt1}(2\tau_{cable} + \tau_2 + \tau_3 + \tau_4 + \tau_6 - \tau_5) - \omega_c(\tau_4 + \tau_{cable} + \tau_6 + \tau_7) + \phi_c & (7)
\end{aligned}
$$

This equation means that the round trip delay is measured as the lightwave phase on the angular-frequency Opt1, after that it is converted to a microwave angular-frequency ω_c.
Secondly, we can obtain the phase relationship of the other lighwave signal (wavelength is Opt2) in conformity with Eqs. (1)-(6). It is assuming that the lightwave signal is reflected by the FBG and detected as a microwave ϕ_{10} by the other photo-mixer. The above equations were obtained in the individual lightwave wavelengths. The optical modulation is performed simultaneously in both wavelengths (opt1 and opt2) on the antenna.

$$\phi_{10}(t) = \omega_c(t) - \omega_{opt2}(2\tau_{cable} + \tau_2 + \tau_3 + \tau_4 + \tau_6 - \tau_5) - \omega_c(\tau_4 + \tau_{cable} + \tau_6 + \tau_8) + \phi_c \tag{8}$$

This equation also means that the round trip delay is measured as the lightwave phase on the angular-frequency Opt2, after that it is converted to a microwave angular-frequency ω_c.
Thirdly, difference frequency $\phi(t)$, between $\phi_9(t)$ and $\phi_{10}(t)$ which is double-difference of transmitting and receiving lightwave signals, is calculated as Eq.(9).

$$\phi(t) = -(\omega_{opt1} - \omega_{opt2})(2\tau_{cable} + \tau_2 + \tau_3 + \tau_4 + \tau_6 - \tau_5) - \omega_c(\tau_7 - \tau_8) \tag{9}$$

This equation means that the round trip delay is measured as the microwave phase on the angular-frequency $(\omega_{opt2} - \omega_{opt1})$ which is the first local reference signal.
Lastly, we will discuss the meaning of these Equations. The laser synthesizer output signal is displayed as follows (according to Eq.(1));
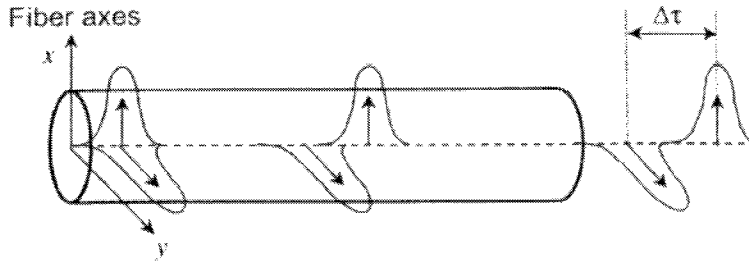
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Figure 2. An image of PMD.

$$\phi_{Loin}(t) = (\omega_{opt1} - \omega_{opt2})(t) + (\phi_{opt1} - \phi_{opt2}), \tag{10}$$

The extracted microwave by the photo-mixer at an antenna is displayed in Eq.(11) according to (3).

$$\phi_{Loout}(t) = (\omega_{opt1} - \omega_{opt2})(t) + (\phi_{opt1} - \phi_{opt2}) - (\omega_{opt1} - \omega_{opt2})(\tau_1 + \tau_{cable} + \tau_2), \tag{11}$$

Comparing Eqs. (10) and (11), it is clear what comprises the instrumental delay.

$$-(\omega_{opt1} - \omega_{opt2})(\tau_1 + \tau_{cable} + \tau_2) \tag{12}$$

If this differential phase is compensated, coherent transmission from AOS building to antenna is realized. Comparing Eqs. (12) and (9),

$$\tau_2 = \tau_3 + \tau_4 \tag{13}$$

$$\tau_5 = \tau_6 \tag{14}$$

$$\tau_7 = \tau_8, \tag{15}$$

if we select the cables length as above, the measured phase in Eq.(9) shows the twice of the differential phase exclude τ_1 in Eq.(12). The phase reference point for this calibration system is not ϕ_0, but the point of ϕ_1. As a result, we can obtain the instrumental delay phase (the twice of the cable delay phase) measured by the transmitted microwave (first local reference) frequency. Moreover, this method eliminates the modulation signal (ω_c) transmission. So, it is not necessary to consider the phase delay on the modulation signal (ω_c).

The measured phase was used compensation for the instrumental delay change and phase change between the point of ϕ_1 and that of ϕ_3, and we can use the value for feedback to fringe rotator in active control or to a correlation processor in offline cable compensation. This approach was necessary for getting fringes.

2. POLARIZATION MODE DISPERSION COMPENSATION

The phase fluctuation is due to the absolute polarization change (cause by the fiber movement) of the two lightwaves, and the phase fluctuation magnitude is inversely proportional to the degree of polarization alignment of the two lightwaves (Bill Shillue[1]). As the SOP(state of polarization) change, the DGD(differential group delay) will be converted into Lo phase jitter. To reduce the PMD affect, the received SOP rotation need to be stabilized (Pengbo Shen[2]). PMD arises from the anisotropic nature of the fiber cross section (θ_x and θ_y). The image of PMD effect is shown in Fig. 2.

The differential group delay estimation cause of the PMD was described (Hai Xiao[3]), we quote the essence following two equations. The variance of the differential group delay is estimated by Eq. (16). This is called the first order PMD effect.
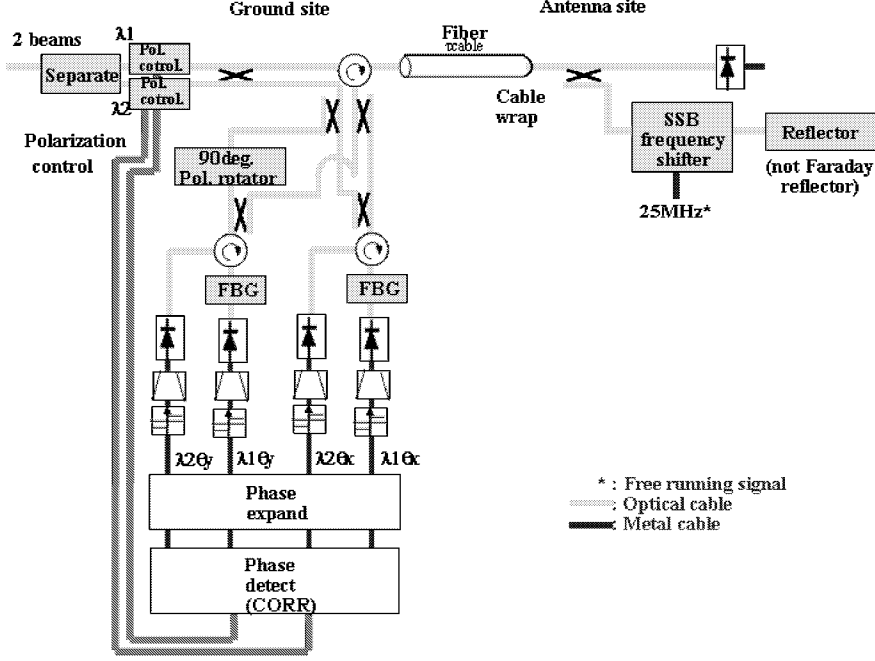
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Figure 3. Phase and PMD calibration system.

$$\sigma_\tau = D_p\sqrt{L} \qquad (16)$$

Where D_p is the fiber PMD parameter $[ps/\sqrt{km}]$, L is fiber length [km].
Second order PMD describes the wavelength dependence of the propagation delay of different polarization modes. The birefringence of an optical fiber is wavelength dependent; therefore, different wavelength will experience different PMD. The deviation of the propagation delay caused by the second order PMD is as follow;

$$\sigma_{\tau2} = \frac{2\pi c D_p^2}{\lambda^2\sqrt{3}}\Delta_\lambda L \qquad (17)$$

Where Δ_λ is different frequency between the master laser and the slave laser on the lightwave wavelength λ.
DGD is calculated by co-variance of the two deviations of the propagation delay. According to the baseline plan, a fiber length correction is realized by active line stretchers. The SOP will change rapidly by the stress. And the system is not able to maintain the SOP. So it might be inevitable the PMD effects (first-order and second-order).
The double-difference method described on the section 1, as the phase compensation measurement is done not on the lightwave frequency but on the transmission first local reference frequency by using a double-difference of adjacent two lightwaves (different angular frequency is $2 \times \omega_c = 50$ MHz), second order PMD effect can be reduced (estimated deviation value is less than 0.003 fs). Furthermore, it excludes mechanical systems, it is free from self induction polarization effects.

We consider a PMD compensation method by stabilizing the received SOP at antenna, which is a polarization alignment servo system. A block diagram is shown in Fig. 3. This is a system combining the double-difference method (in Section 1) and a polarization alignment servo (SOP measurement).

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We think that polarization maintaining is available on both sides (AOS building and antenna). The considered system is performed on SOP control at the AOS building side. We consider a PMD compensation method by the received SOP rotation at antenna to be stabilized, which is a combined system between the double-difference method and a polarization alignment servo (SOP measurement) system. It is assumed that the Single Mode Fiber (SMF) displayed as τ_{cable} in Fig. 3 are used to lightwave transmission which include cable wrap in the antenna. We think polarization maintaining fibers (PMF) is required for the Front-end rack, Analog rack on the antenna and First Lo photonic distributor in the AOS building. In case of using LN-modulator (Lithium Niobate modulator: displayed as SSB frequency shifter) for maintaining the polarization, the modulator involves a polarizer which is the key component, and we set the polarizer coincident with the polarization at the angle to get the maximum output beatnote amplitude from the photo mixer(on the antenna). It is also assumed that the Laser synthesizer is polarization stable and that a high extinction ratio is maintained.

The Laser Synthesizer signals are led to the antennas from the AOS building. During the transmission, PMD effect arises from rotating and coupling the fiber cross section (θ_x and θ_y) signals. At each antenna, frequency-shift modulation is performed to the received lightwave signals by the modulator and polarization is uniquely selected by the polarizer. The signals are reflected by an optical reflector (which is not Faraday reflector because Faraday reflection is non-reciprocal) and return back to the modulator. In case of using Faraday reflector, go and return paths are not coincident in the fiber. After re-modulation, the signals are sent back to the AOS building in the reciprocal path through the same optical fiber. The returned (round trip) signals grow fainter when the polarization is not coincident with that of the polarizer. If we control the transmitted signal polarization to keep the returned signal power in maximum on each lightwave signal, this is equivalent to the stabilization of the received SOP at the antenna. The polarization and amplitude detection of the round trip signal is made by correlating of the orthogonal polarization signals which are generated by 90-degree polarization shift of the transmitted signal (Laser Synthesizer signal). From $\lambda_1\theta_x$ and $\lambda_1\theta_y$ in Fig. 3, the polarization angle and amplitude of the λ_1 lightwave signal are calculated, and these of the λ_2 lightwave are calculated from $\lambda_2\theta_x$ and $\lambda_2\theta_y$. These values are fed back to polarization controllers. Otherwise, it might be able to detect them by only power detection after polarization separation.

The polarization control is performed by polarization control modules on the market. After polarization stabilization, the phase rotation on the first LO reference caused by the optical fiber is calculated by using $\lambda_1\theta_x$ and $\lambda_2\theta_x$, which is the same way as the Section 1. In this case, it is equivalent to materialize of Eq.(9).

2.1. Advantages and disadvantages

The advantages of the double-difference method with polarization alignment servo are

> (i) Cable delay is measured in the first LO reference frequency phase instead of single lightwave phase.
> (ii) The modulation signal (ω_c) transmission is not required.
> (iii) The modulation signal (ω_c) phase compensation is not required.
> (iv) Reduction of the PMD problems.
> (v) It excludes movable parts like as a line stretcher.

As a result, we can obtain the instrumental delay phase (the twice of the cable delay phase) measured by the transmitted microwave (first LO reference) frequency.

To enable the independent polarization controls for two different light waves (λ_1 and λ_2), the input light should be separated into two light beams. This could be done either inserting optical filters to separate the light waves or inserting the polarizers in the two optical paths in the laser synthesizer. There is a concern in the first method that it is difficult to balance the phase delays in the two optical paths and residual phase might be a problem. The second method requires separate laser synthesizer for each antenna and increase the cost of the LO system. Prototyping is necessary to address those technical problems.

3. CONCLUSION

LO signal transmission delay compensation is an indispensable technique in an interferometer. We discuss points for improving the cable calibration system. The effect of PMD error is a serious problem in the interferometer. As the PMD delay error is related to the lightwave polarization and wavelength, the precision of the obtained delay after double-difference calculation with polarization compensation may becomes more accurate than with a single lightwave wavelength measurement as the baseline plan. We consider the double-difference method with polarization alignment servo to decrease the effect of PMD.

REFERENCES

1. Bill Shillue, "ALMA first Lo reference: elimination of large phase fluctuations due to lightwave polarization effects," ALMA memo 483.
2. Pengbo Shen, "PMD effects on the analogue signal transmission," ALMA memo 506.
3. Hai Xiao, "PMD effects in the photonic Lo baseline plan," BEND-56.00.00.00-011-A-REP.
4. Bill Shillue, S. AlBanna, "ALMA first Lo reference: Elimination of large phase fluctuation due to lightwave polarization effects," ALMA memo 507.