

IF Fiber Selection Criteria
VLA Memorandum No. 32
Version 7

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Introduction

The expanded VLA will employ an IF system that transmits digitized data from each antenna to the correlator in the control building. The data will be transmitted to the correlator using fiber optics and Dense Wavelength Division Multiplexing, (DWDM). The purpose of this memorandum is to identify which fibers are suitable for the EVLA IF transmission system, and a basic system configuration.

The system requirements for the EVLA determine the overall IF fiber system specifications. The measurable system parameters are shown in Table 1.

Table 1. Measurable IF Transmission System Parameters

a. Bit Rate:	10 Gbits/second per channel
b. Number DWDM Channels:	12 channels
c. Channel Spacing:	200 GHz spacing
d. Channel Wavelengths:	C Band, 1560.61 nm to 1536.61 nm
e. Bit Error Rate:	Beginning of Life, 10^{-9} ; End of life, 10^{-6}
f. Digital SNR (Q):	Beginning of Life, 6; End of life, 4.7
g. Maximum, fiber length	21.6 km
h. Minimum fiber Length	0.625 km
i. Operation Temperature	-12C to 35C

The results of this analysis indicate that a standard single-mode fiber such as Corning SMF-28 is suitable for the EVLA project, although tests should be performed to verify this conclusion. A power budget for the recommended system configuration is provided in Appendix F. The recommended system consists of 1) standard single-mode fiber, 2) 12 channels DWDM on a single fiber, 3) an EDFA optical pre-amplifier, and 4) power margin of over 6 dB. A system without pre-amplifiers is also investigated, but is found incapable of maintaining the required bit error rate.

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Acknowledgements

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1. Fiber Comparison

A brief discussion of the impact of attenuation, dispersion, non-linear effects, and noise are presented in the Appendices. Appendix E shows how these effects impact receiver sensitivity. Appendix F summarizes the recommended system in a power budget analysis.

Three types of fiber are considered for the IF fiber optic Digital Transmission System (DTS). These include:

- 1) Corning SMF-28, Standard single mode optical fiber
- 2) Corning MetroCor, Non-zero dispersion shifted fiber
- 3) Corning LEAF, Large Effective Area Fiber

The difference in maximum attenuation between fiber types for the transmission lengths required for the EVLA is only about 1 dB, so attenuation is not a deciding factor in selecting a fiber. The same can be stated about the impact of non-linear effects; the difference in the non-linear power threshold is only 2 dB between fiber types. Dispersion, though, was found to be an issue using standard single-mode fiber (SMF) at the distances required for the last several antenna pads. Therefore, a power penalty due to dispersion is imposed on a system using SMF.

Results of the comparison are summarized in Table 2. The table assumes a data rate of 10Gbits/s. There are three important points to note from this table. First, for a system using SMF, the maximum bit rate without a power penalty is less than the system bit rate (10 Gbits/s). This shows that a power penalty is required for higher data rates in a system that uses SMF. The limit of the effectiveness of a power penalty due to dispersion is not known, therefore a system test is recommended before purchasing cable. If dispersion is too excessive, alternative forms of compensation will have to be investigated.

The second point to note is that, compared to LEAF or MetroCor, SMF-28 adds 3 dB of losses to the system due to higher attenuation and the dispersion power penalty. A power budget analysis in Appendix F shows that amplifiers are required regardless of the choice of fiber.

Third, SMF-28 can handle more power without non-linear effects affecting the quality of the signal, although this is little advantage for our system.

This analysis shows that SMF-28 has sufficiently high dispersion to be a concern in a 22 km, 10 Gbit/s link, but the amount of dispersion is tolerable. All other physical quantities are similar to the other fiber types. MetroCor, LEAF, and SMF-28 are therefore all acceptable choices of fiber for the EVLA project.

Table 2. Fiber Comparison for the EVLA IF System

Parameter	LEAF	MetroCor	SMF-28
Attenuation (22 km)	5.5 dB	5.5 dB	6.6 dB
Maximum Bit Rate w/o Penalty	16.4 Gbits/s	20.8 Gbits/s	8.2 Gbits/s
Dispersion Power Penalty (22 km)	0.5 dB	0.3 dB	2 dB
Max. Launch Power	3.8 dBm	2.5 dBm	4.3 dBm
Cost Relative to SMF-28	>200%	167%	100%

2. System Configuration

Figure 1 illustrates the signal path of the recommended system. The path from antenna pad A9 with 22 km of SMF fiber is shown. Typical launch power is 0 dBm, and transmission loss through this system is estimated to be 25.4 dB. The amplifier gain is equal to 12 dBm, so the received power after losses is -13.6 dBm.

Ideal receiver sensitivity is -20 dBm. This leaves the power margin a little more than 6 dB. A summary schedule of losses is shown in Table 3, and a summary power budget is shown in Table 4. The power penalty is calculated in Appendix E.

Figure 1. IF Optical Signal Path

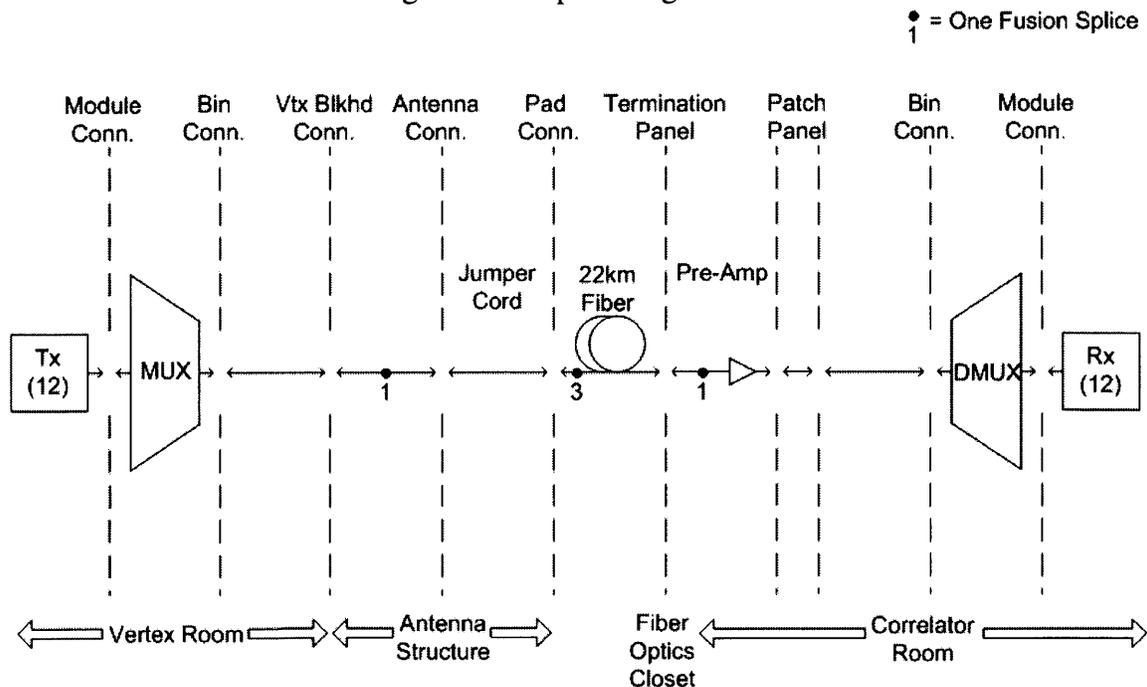


Table 3. Transmission Losses to Pad A9

Fiber	6.6 dB
Connectors, Splices, Bends	6.3 dB
MUX, DMUX	12.5 dB
Total Transmission Losses	25.4 dB

Table 4. Power Budget for Pad A9

Typical Launch Power	0.0 dBm
Transmission Losses	-25.4 dB
Amplifier Gain	12.0 dB
Received Power	-13.6 dBm
Receiver Sensitivity	-20.0 dBm
Margin	6.4 dB

Minimum transmitter digital signal-to-noise ratio (Q) is 31.5, as calculated in Appendix E. System noise impairments, or power penalties, reduce Q during transmission. Table 5 shows that after transmission $Q = 6$, which is sufficient to maintain $BER = 10^{-9}$.

Emphasis should be made that the *minimum* transmitter Q is 31.2 to sustain $BER = 10^{-9}$.

Table 5. Q Budget (linear)

Minimum Transmitter Q	31.2
Power Penalties	25.2
Minimum Receiver Q	6

3. Assumptions

- A. Calculations are for bare fiber only. Cabled fiber will have slightly greater attenuation and Polarization Mode Dispersion.
- B. Launch power, laser output, and transmitter power refer to the modulated input into the fiber and do not reflect the attenuation of the modulator.
- C. Launch power is typically 0 dBm for laser packages considered for EVLA.
- D. Other assumptions are mentioned in the appropriate section.

4. Conclusions

Three different types of Corning fiber were evaluated within the requirements of the EVLA IF system. Standard single-mode fiber (SMF-28), non-zero dispersion shifted fiber (MetroCor), and large effective area non-zero dispersion shifter fiber (LEAF) were all considered. All three of these fibers were found to be adequate for the EVLA system.

Several system configurations were also considered using various combinations of fiber. Certain effects that contribute to system noise were evaluated and analyzed within each system model. All of these systems required amplifiers to provide sufficient power to the receiver, therefore cost became the leading selection criteria. SMF-28 fiber was chosen as the most cost effective solution, and it was shown that a system that uses SMF-28 would operate at the required bit error rate. However, this memorandum cautioned that a prototype system should be assembled to demonstrate that dispersion, or other unforeseen effects, would not be detrimental.

The recommended fiber is a standard single-mode fiber such as SMF-28. Sixteen IF channels can be transmitted on the fiber using wavelength-division-multiplexing. This system will require optical pre-amplifiers with minimum 12 dB gain.

Further work is required to address safety issues related to laser safety and safety controls. A laser safety document will be issued at a later date.

Appendix A: Attenuation

Attenuation is provided as a dB loss per km of fiber. The distance to the farthest antenna was used for comparison, $L = 22$ km. The attenuation for Corning LEAF fiber and MetroCor is 0.25 dB/km.^[8,9] The power loss is 5.5 dB assuming a length of 22 km. Corning SMF-28 has attenuation of not greater than 0.30 dB/km, or 6.6 dB over 22 km of fiber^[7]. Premium SMF-28 is also available with less attenuation, but for our relatively short lengths there is little advantage. Therefore, attenuation by itself is not justification to select any type of fiber over another for the relatively short link lengths used in the EVLA. Table A summarizes fiber attenuation for 22 km of fiber.

Table A. Fiber Attenuation

	SMF-28	MetroCor	LEAF
Attenuation	0.30 dB / km	0.25 dB / km	0.25 dB / km
Total $A_{22\text{km}}$	6.6 dB	5.5 dB	5.5 dB

Appendix B: Dispersion

There are several sources of dispersion in single-mode optical fiber. The two main sources are polarization mode dispersion, and chromatic dispersion. Chromatic dispersion is a characteristic of optical fiber that creates pulse spreading of a transmitted signal. The velocity of a transmitted wave is dependent on its wavelength and the index of refraction of the fiber. Different wavelengths propagating in a fiber with a given index of refraction will travel at different velocities and arrive at the end of the fiber at different times. Presently available lasers are not monochromatic and therefore produce energy at a band of wavelengths centered on a primary frequency. A DBF laser in conjunction with an external modulator, as will be used in the EVLA, can have a spectral width as great as 2.5 times the bandwidth of the signal, or 25 GHz for a 10 GHz bandwidth. This corresponds to a 0.2 nm band of wavelengths.^[6] Because of dispersion, these wavelengths arrive at different times and distort the signal. This distortion is called pulse spreading. For our calculations we will assume a pulse width of 0.1 nm, which roughly coincides with test results.

Polarization mode dispersion is created when the core of the fiber is not circular. The two polarizations of light traveling in an elliptical core will not travel at the same velocity. This is because part of the energy envelope of each polarization travels in the cladding of the fiber, a region of lower index of refraction. When the cladding is not circular one polarization has more energy in the cladding causing that polarization to speed up. This phenomenon is known as birefringence. The different arrival times of the two polarizations will cause the pulse to broaden in a similar manner as chromatic dispersion.

The data rate of a signal can be limited by dispersion when the pulse spread becomes a significant portion of the signal period. For this discussion, $\frac{1}{4}$ wavelength is considered significant.^[1] For this reason it is important to calculate the dispersion in a length of fiber, the pulse spread caused by dispersion, and then the data rate limit.

Dispersion of Standard Single-Mode Fiber

Standard single-mode silica fiber is designed as a step-index fiber. Step-index fiber has a central core surrounded by a cladding with a lower index of refraction. The lower index of refraction in the cladding causes internal reflection. Single-mode fiber (SMF) has a core small enough to cut-off all modes (angles of reflection) except the one that travels laterally down the fiber ($\theta = 90^\circ$). Today, manufacturers use many different index of refraction profiles to create different fiber characteristics.^[1]

Chromatic dispersion for a standard single-mode fiber with the zero dispersion wavelength around 1310nm is predicted by the following equation ^[1].

$$D_{Chromatic} = \frac{S_0}{4} \left(\lambda - \frac{\lambda_0^4}{\lambda^3} \right) ps / nmkm \quad \text{Equation B.1}$$

Where: S_0 is the slope of the dispersion curve, SMF-28 has slope $S_0 = 0.092 \text{ ps}^2 / \text{nm}^2 \text{ km}$,^[6]
 λ is the operating wavelength, $\lambda = 1550 \text{ nm}$
 λ_0 is the zero dispersion wavelength, $\lambda_0 = 1310 \text{ nm}$

Using Equation B.1, $D_{chromatic} = 17.4 \text{ ps} / \text{nm km}$ at $\lambda = 1550 \text{ nm}$.

The pulse spread due to chromatic dispersion is

$$\Delta t_{ch} = (D_{chromatic})(\Delta\lambda)L = 38.3 ps \quad \text{Equation B.2}$$

Where: $D_{chromatic} = 17.4 \text{ ps} / \text{nm}$,
 $\Delta\lambda = 0.1 \text{ nm}$, a typical spectral width of a good DFB laser diode^[2].
 $L = 22 \text{ km}$.

Using equation B.2, $\Delta t_{ch} = 38.3 ps$

Polarization Mode Dispersion (PMD) of Corning SMF-28 is $\leq 0.2 \text{ ps} / \sqrt{\text{km}}$ ^[6], but bending the fiber can also increase PMD. If the total system PMD is $1 \text{ ps} / \sqrt{\text{km}}$, the pulse spread for 22 km of fiber due to chromatic dispersion is^[1]

$$\Delta t_{pmd} = (1 ps / \sqrt{\text{km}})(\sqrt{22 \text{ km}}) = 4.7 ps \quad \text{Equation B.3}$$

Total pulse spread due to both chromatic and polarization dispersion in this case is

$$\Delta t_D = |\Delta t_{ch}| + \Delta t_{pmd} = 43 ps$$

The maximum NRZ bit rate limited by dispersion induced pulse spreading can be calculated from the quarter-bit interval equation.^[1]

$$BR_D < (4\sigma_t)^{-1} \quad \text{Equation B.4}$$

Where: the RMS pulse spread is $\sigma_t = \Delta t_D / \sqrt{2}$.

Using Equation 4, the maximum bit rate limited by fiber dispersion for 22 km of standard single mode fiber is $BR_D = 8.2 \text{ Gbits/s}$. Conversely, the maximum fiber length limited by chromatic dispersion can be calculated by expressing Equation B.4 in terms of wavelength.^[1]

$$L_{max} = (4\sigma_\lambda D_\lambda BR)^{-1} \quad \text{Equation B.5}$$

Where: the RMS spectral width $\sigma_\lambda = \Delta\lambda / \sqrt{2}$,
 $\Delta\lambda$ is the spectral width of the transmitter laser, $\Delta\lambda = 0.1 \text{ nm}$

D_λ is the absolute value of fiber chromatic dispersion, $D_\lambda = 17.4 \text{ps/nmkm}$
BR=10Gbps.

Calculating equation B.5 using a laser spectral width of 0.1nm, the maximum fiber length limited by dispersion for a bit rate of 10Gbps is $L_{\text{max}}=20.3\text{km}$. Therefore 10Gbps cannot be transmitted on 22km of standard single-mode fiber without a power penalty, regeneration or dispersion compensation using the $\frac{1}{4}$ wavelength rule. Increasing the receiver sensitivity can also compensate this problem, and is addressed in Appendix D.

Dispersion of MetroCor Non-Zero Dispersion Shifted Fiber

Non-Zero Dispersion Shifted Fibers, (NZ-DSF) are similar to standard single-mode fiber except the fiber has been doped to shift the zero dispersion point to a longer wavelength. At lower data rates, especially when only one channel is transmitted on a fiber, it makes sense to shift the zero dispersion point to the transmitted wavelength, i.e. 1550nm. Fiber with a zero dispersion point at 1550nm is not commercially available. As is illustrated in the following sections on Non-Linear Effects, some dispersion is desirable to limit non-linear effects. MetroCor is called a *negative* NZ-DSF because the zero dispersion point has been shifted to about 1613nm so that the dispersion is negative at 1550nm.^[1]

Chromatic dispersion at 1550 nm for Corning MetroCor NZ-DSF from the data sheet is -5.6ps/nm km .^[8] The calculated pulse spread due to chromatic dispersion is $\Delta t_{\text{ch}} = -12.3 \text{ps}$ for a 22 km fiber and using a laser with 0.1nm spectral width. Polarization mode dispersion of Corning MetroCor is the same as for Corning SMF-28, so $\Delta t_{\text{pmd}} = 4.7 \text{ps}$ for a 22 km fiber. The pulse spread due to all dispersion is about $\Delta t_{\text{D}} = 17 \text{ps}$.

The maximum bit rate limited by fiber dispersion for MetroCor using Equation B.4 is 20.8 Gbits/s with a fiber length of 22 km. The 10Gbits/s maximum fiber length without compensation calculated from Equation B.5 is $L_{\text{max}}=63 \text{km}$.

Note that if the laser spectral width degrades to 0.2nm, the pulse spread will be 24.6ps and the maximum bit rate limited by dispersion will still be greater than 10 Gbits/s.

Dispersion of Large Effective Area Fiber

Most NZ-DSF fibers have a smaller mode field diameter (MFD) than standard single-mode fiber. However, the small MFD makes standard fibers more susceptible to non-linear effects when higher optical power is used, but sometimes it is desirable to use higher power to achieve greater distance without amplifying. This is why manufacturers have designed fibers with larger MFD (and therefore larger effective area). Therefore, large effective area fibers are designed to transmit higher power than regular NZ-DSF while limiting non-linear effects.^[1]

Chromatic dispersion at 1550nm for a NZ-DSF large effective area fiber such as Corning LEAF, calculated from the data sheet, is $7.7 \text{ ps}/\text{nm km}$.^[9] The pulse spread due to chromatic dispersion is $\Delta t_{\text{ch}} = 16.9 \text{ ps}$ for a 22km fiber and 0.1nm spectral width.

Polarization mode dispersion of Corning LEAF is $\leq 1 \text{ ps}/\sqrt{\text{km}}$, so Δt_{pmd} will have a very modest improvement. The total system PMD may still be close to $1 \text{ ps}/\sqrt{\text{km}}$, and Δt_{pmd} would still be close to 4.7 ps for a 22km fiber.

The total pulse spread due to all dispersion in this case is $\Delta t_{\text{D}} = 21.6 \text{ ps}$.

The maximum bit rate limited by fiber dispersion using LEAF is 16.4 Gbits/s over 22km of fiber, and the 10Gbps maximum fiber length without compensation is $L_{\text{max}}=45.9 \text{ km}$.

Conclusions about the Effects of Dispersion on the EVLA IF system

Dispersion will have an impact on the EVLA IF fiber transmission system. The preceding analysis shows the dispersion of standard single-mode fiber, in the worst case, will require some compensation to counteract the effect. It will be shown in Appendix D that increased power to the receiver can compensate for some dispersion, although we cannot state with certainty that this method will be sufficient. Therefore, it is prudent to recommend a full system test before purchasing cable. If tests show that dispersion is too great, other methods of compensation will have to be investigated.

Table B shows the calculated effects of dispersion for each fiber type.

Table B. Worst Case Dispersion Effects Before Compensation

	SMF-28	MetroCor	LEAF
Δt_{D} when $L = 22 \text{ km}$	43 ps	17 ps	21.6 ps
BR_{D} for $L = 22 \text{ km}$	8.2 Gbits/s	20.8 Gbits/s	16.4 Gbits/s
L_{max} at 10 Gbits/s	20.3 km	63 km	45.9 km

Appendix C: Non-Linear Effects

Fiber non-linear effects are anomalies caused by the varying power of a transmitted signal, and can cause noise and distortion. Five non-linear effects are addressed here.

Stimulated Brillouin Scattering

Stimulated Brillouin Scattering (SBS)^[1] occurs when the optical power in a fiber reaches a level sufficient to generate tiny acoustic vibrations in the glass, which in turn causes backscattering of light^[3]. Lasers with narrow line width are likely to stimulate SBS^[4]. Since the bandwidth of SBS is about 20MHz, SBS is a single channel concern. To calculate the 3dB threshold power for SBS, the effective area (A_{eff}) and effective length (L_{eff}) must be known. The effective area (A_{eff}) can often be found in the manufacturer's data sheet Mode Field Diameter by $A_{eff} \approx \pi(MFD/2)^2$ ^[1]. SMF-28 has a calculated effective area equal to $82\mu m^2$, MetroCor has a calculated effective area equal to $50\mu m^2$, and LEAF has a listed effective area equal to $72\mu m^2$.

The effective length (L_{eff}) is characterized by^[4]

$$L_{eff} = \frac{1}{\alpha} (1 - e^{-\alpha L}) \quad \text{Equation C.6}$$

Where: L is the actual fiber length,

α is the fiber attenuation constant in 1/km characterized by the equation.^[1]

$$\alpha = \frac{A}{10 \log e} = .069 / km \quad \text{Equation C.7}$$

Where: Maximum fiber attenuation A = .3db/km.

The EVLA maximum length is 21.6 km, therefore the maximum $L_{eff} = 11.2$ km. The EVLA minimum fiber length is 0.625 km, so the minimum $L_{eff} = 0.61$ km.

The SBS 3dB power threshold follows the equation^[1].

$$P_{th}(SBS) \approx 21 A_{eff} / g_B L_{eff} \quad \text{Equation C.8}$$

Where: the typical SBS gain is $g_B = 5 \times 10^{-11} m/W$,^[1]

$A_{eff} = 50\mu m^2$ for MetroCor,

$L_{eff} = 11.2$ km and 0.61 km.

Using the preceding numbers to find the SBS threshold power for the farthest pad $P_{th}(SBS)= 2.8\text{dBm}$ (1.9mW). This means we can assume 3dB of scattered power due to SBS will occur in the EVLA system above $P_{th}(SBS)=2.8\text{dBm}$ for MetroCor, and implies we should limit launch power to less than 2.8dBm if MetroCor is used. The SBS 3dB threshold power is 4.7dBm (3.1mW) for SMF-28 and 4.3dBm (2.7mW) for LEAF.

Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) ^[1] occurs when the optical power reaches a level sufficient to cause unwanted molecular vibrations. Molecules absorb light, then re-emit light, causing forward scattering and frequency shift. When two channels are placed sufficiently close together, power transfer can occur. ^[3] The bandwidth of SRS is 40THz, so that many WDM channels can be affected. ^[5]

The 3dB power threshold for SRS can be calculated by the following formula. ^[1]

$$P_{th}(SRS) = 16A_{eff} / g_R L_{eff} \quad \text{Equation C.10}$$

Where: the SRS gain $g_R=1 \times 10^{-13} \text{m/W}$ at 1550nm, ^[1]

$A_{eff}=50\mu\text{m}^2$ for MetroCor,

$L_{eff}=11.2 \text{ km}$ and 0.61 km as calculated from Equation B.5.

Using equation 10, $P_{th}(SRS)=28.5 \text{ dBm}$ (714mW) for a single channel to the farthest pad using MetroCor. Since SMF-28 and LEAF have a greater effective area, their SRS threshold will be even greater. Therefore SRS will not be a concern for the EVLA IF system.

Self-phase Modulation

The index of refraction of a fiber is weakly dependent upon power intensity. ^[4] Self-Phase Modulation (SPM) is caused by slight variations of the index of refraction created by the power of the transmitted signal. As a pulse travels through the regions of varying index of refraction, the pulse speeds up or slows down. The variation in speed creates a slight modulation of frequency, or chirp. Chromatic dispersion will then cause pulse spreading. ^[3] The non-linear index coefficient (n^*) takes into account this power dependency, and a typical value for silica fibers is $n^* \approx 3.2 \times 10^{-20} \text{m}^2/\text{W}$. ^[5]

Before the phase shift of the pulse can be calculated, the nonlinear propagation coefficient must be known. The nonlinear propagation coefficient is estimated by ^[4]

$$\gamma = \frac{2\pi n^*}{\lambda A_{eff}} \quad \text{Equation C.11}$$

Where: the nonlinear index coefficient $n^* \approx 3.2 \times 10^{-20} \text{m}^2/\text{W}$,

$\lambda=1550\text{nm}$,
 $A_{\text{eff}}=50\mu\text{m}^2$ for MetroCor and SMF-28, $72\mu\text{m}^2$ for LEAF.

The calculated nonlinear propagation coefficient is then $\gamma=2.6 \times 10^{-3}/\text{Wm}$ for MetroCor, $\gamma=1.6 \times 10^{-3}/\text{Wm}$ SMF-28, $\gamma=1.8 \times 10^{-3}/\text{Wm}$ for LEAF.

The phase shift can now be estimated by ^[5]

$$\Phi(SPM) = \gamma P_{\text{in}} L_{\text{eff}} \quad \text{Equation C.12}$$

Where: $L_{\text{eff}}=11.2 \text{ km}$,
 $P_{\text{in}}=\text{launch power}$,
 $\gamma=2.6 \times 10^{-3}/\text{Wm}$ for MetroCor.

SPM phase shift in a NRZ digital system becomes significant ($\Phi_{\text{SPM}} \approx \pi/2$ or $1/4T$) when $P_{\text{in}}L_{\text{eff}}=1\text{Wkm}$. ^[4] If our launch power is 2mW (3dBm), the phase shift is 0.058rad and $P_{\text{in}}L_{\text{eff}}=0.002\text{Wkm}$ using MetroCor. In fact, for our system $\Phi_{\text{SPM}} \approx \pi/2$ when $P_{\text{in}}=54\text{mW}$ (17dBm), and greater for SMF-28 and LEAF. Thus we can assume SPM will be insignificant for the EVLA system.

Cross-Phase Modulation

Cross-Phase Modulation is similar to SPM except the phase shift of one channel depends on the power of other channels. The power of other channels traveling down the fiber creates variations in the index of refraction and cause modulation, or chirp, in another channel. Since XPM requires the power of other channels, it only occurs in WDM systems. The XPM phase shift of a pulse in a single channel can be estimated by adapting the formula used for SPM phase shift as follows. ^[1]

$$\Phi_1(XPM) = \gamma L_{\text{eff}} (P_1 + 2P_2 + \dots + 2P_n) \quad \text{Equation C.13}$$

Where: $L_{\text{eff}}=11.2 \text{ km}$,
 $P_{\text{in}}=\text{launch power}$,
 $\gamma=2.6 \times 10^{-3}/\text{Wm}$ for MetroCor, and
 $n=\text{the number of channels}$.

Like SPM, the XPM phase shift in a NRZ digital system becomes significant when $\Phi_{\text{XPM}} > \pi/2$, or $1/4T$. If the launch power for each of the 16 planned channels is 3dBm (2mW), $\Phi_{\text{XPM}}=1.8\text{rad}$, (a little over $\pi/2$). If launch power for 16 channels in MetroCor fiber is limited to 2.5dBm (1.7mW), then $\Phi_{\text{XPM}}=1.5\text{rad} \approx \pi/2$. Launch power is limited to 4.3dBm (2.7mW) in SMF-28, and 3.8dBm (2.4mW) in LEAF.

XPM therefore becomes the primary limitation on the launch power for the EVLA IF system.

Four-Wave Mixing

When two or three wavelengths from WDM channels interact through the electric susceptibility of the fiber, a wave can be generated at frequency $f_{ijk} = f_i + f_j - f_k$.^[4] The new frequency will be generated if the efficiency of power transfer between the original waves is sufficient. The new frequency will generally be located in one of the system channels, and so the transferred power becomes noise in that channel. Greater spacing between channels, uneven spacing of channels, lower launch power, or dispersion can reduce the efficiency.

A key parameter in the equation for FWM efficiency (η) is $\Delta\beta$. $\Delta\beta$ is the FWM phase mismatch due to dispersion of the original waves. $\Delta\beta$ is given by^[4]

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk} = \left(\frac{2\pi c}{\lambda^2} \right) \left(\frac{dD}{d\lambda} \right) \left(\frac{\lambda_i + \lambda_j}{2} - \lambda_0 \right) (\lambda_i - \lambda_k)(\lambda_j - \lambda_k) \quad \text{Equation C.14}$$

Where: $dD/d\lambda$ is the dispersion slope (also known as S_0),

$\lambda_i, \lambda_j, \lambda_k$, the three original wavelengths,

λ_0 is the zero-dispersion wavelength,

λ is the transmission wavelength in a vacuum (1550nm).

The slope and zero-dispersion wavelength can often be found on manufacturers' data sheets, but in the case of MetroCor the slope must be assumed linear and these values calculated from the data provided. The calculated slope for MetroCor from 1530nm to 1605nm is 0.12ps/nm²km, and the calculated zero-dispersion wavelength is 1613nm. When the channel spacing of the original wavelengths is 100Ghz (.8nm at 1550.4nm, 1549.6nm, and 1548.8nm), $\Delta\beta=8541$ /km for MetroCor. For SMF-28, where $dD/d\lambda=0.092$ ps/nm²km, and $\lambda_0=1310$ nm, $\Delta\beta=24946$ /km. LEAF has a calculated slope $dD/d\lambda=0.16$ ps/nm²km, and $\lambda_0=1512.5$ nm, so $\Delta\beta=6779$ /km.

The equation for efficiency follows.^[4]

$$\eta = \left(\frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \right) \left(1 + \frac{4e^{-\alpha L} \sin^2(\Delta\beta L/2)}{(1 - e^{-\alpha L})^2} \right) \left(\frac{\sin(N_A \Delta\beta L/2)}{\sin(\Delta\beta L/2)} \right)^2 \quad \text{Equation C.15}$$

Where: attenuation constant $\alpha=0.69$ /km,

$L=22$ km,

$N_A=16$ channels,

$\Delta\beta$ is calculated above.

This makes the efficiency $\eta_{\square} = 2.6 \times 10^{-7}$ for MetroCor, $\eta_{\square} = 7.7 \times 10^{-10}$ for SMF-28, and $\eta_{\square} = 1.1 \times 10^{-8}$ for LEAF. Clearly, very little power will be transferred.

The power of the generated wavelength is ^[4].

$$P_{ijk} = \left(\frac{D_{ijk}}{3} \gamma L_e \right)^2 P_i P_j P_k e^{-\alpha L} \eta \quad \text{Equation C.16}$$

Where: D_{ijk} , the degeneracy factor, is 3 for 2-tone products, or 6 for 3-tone products,
 $\gamma=2.6 \times 10^{-3} / \text{Wm}$, the non-linear propagation coefficient from the SPM section,
 $L_{\text{eff}} = 11.2 \text{ km}$, the effective length from in the Dispersion section,
 $P_{i,j,k}$ =launch power of the original wavelengths,
 $\alpha=0.69 / \text{km}$ is the attenuation constant from the Dispersion section,
 $L=22 \text{ km}$ is the link length, and
the efficiency (η) is calculated above.

Assuming the launch power is limited to 2.5dBm, the power of the three-tone product is only -149dBm in MetroCor. The power of the products is even less for SMF-28 and LEAF because the larger effective area decreases the non-linear propagation coefficient (γ). This confirms that FWM will not be a concern in the IF system even with 100Ghz channel spacing with launch powers less than 2.5dBm.

Conclusions about Non-Linear Effects on the EVLA IF system

Dispersion in the fiber, and our relatively short fiber length, will limit the non-linear effects in the EVLA system. The non-linear effects that impose the greatest limitation on the EVLA system come from Cross-Phase Modulation and Stimulated Brillouin Scattering. However, it is shown that this would be a small effect in MetroCor fiber if the transmitter launch power were not greater than 2.5dBm. SMF-28 and LEAF fiber are even less affected because of their larger effective area.

Reinforcing this conclusion, Agrawal states that when actual fiber length is much less than the non-linear length (i.e.1/10), non-linear effects are not significant in pulse propagation. The non-linear length is given by ^[5]

$$L_{NL} = (\gamma P_{in})^{-1} \quad \text{Equation C.17}$$

Where: $\gamma=2.6 \times 10^{-3} / \text{Wm}$, the non-linear propagation coefficient for MetroCor,
 $P_{in}=1.78 \text{ mW}$ or 2.5dBm.

Using Equation C.17 with $L=21.6 \text{ km}$ and $L_{NL}=216 \text{ km}$ the transmitter power limit is 2.5dBm. Non-linear effects will have negligible impact on our system using MetroCor below 2.5dBm launch power, and no power penalty to receiver sensitivity will occur. However, if the transmitter power is allowed to increase to 3dBm, $L_{NL}=192 \text{ km}$ and non-linear effects may begin to be a problem. This method also confirms the limits previously calculated for SMF-28 and LEAF. Results are summarized in Table C.

Table C. Fiber Non-Linear Power Limits

	SMF-28	MetroCor	LEAF
Effective Area	82 μm	50 μm	72 μm
Non-Linear Power Threshold	4.3dBm	2.5dBm	3.8dBm

The preceding analysis of non-linear effects shows SMF-28 is the best choice of fiber in terms of non-linear effects. SMF-28 has a higher power threshold because of a larger effective area and higher dispersion. MetroCor and LEAF are also acceptable for the EVLA if the power limitations can be maintained within the power budget. However since the difference between fiber types is small for the lengths involved, the decision to use a particular fiber for the EVLA is not likely a result of non-linear effects.

Appendix D: Power Penalties

There are several noise sources that degrade a received signal to a degree that error rates increase due to Inter-Symbol Interference (ISI). These effects can be compensated, to a degree, by increasing the required signal-to-noise ratio. This essentially means more power is required at the receiver to avoid ISI. These impairments can be thought of as a power penalty imposed on the digital signal to noise ratio (Q).

Power Penalty Due to Dispersion

Dispersion causes ISI through pulse spreading. ISI begins to be an issue when the pulse spread approaches 25% of the bit rate. At 25% it will be necessary to compensate by adding a power penalty to the power budget. When pulse spread is severe, dispersion compensation or regeneration may need to be implemented. The effective reduction of receiver sensitivity at a given bit rate can be calculated using the following equation ^[1].

$$P_D(dB) = -10 \text{Log}_{10} \left\{ e^{[-0.25(\Delta t_D)^2 (\pi BR)^2]} \right\} \quad \text{Equation D.1}$$

Where: P_D is the power penalty to receiver sensitivity,
 Δt_D is the total pulse spread due to dispersion,
 πBR is the radian frequency bit rate.

The results of the power penalty calculation are listed below. Values for pulse spread are derived in Appendix B.

Table D.1 Power Penalty Due to Dispersion.

	SMF-28	MetroCor	LEAF
Δt_D when L = 22 km	43 ps	17 ps	21.6 ps
P_D at 10 Gbits/s	2 dB	0.3 dB	0.5 dB

Power Penalty Due to Non-Ideal Extinction Ratio

Extinction ratio of a transmitter is the ratio of the output power while sending a one-bit to the output power while sending a zero-bit. Ideally, a one-bit is represented by twice the average power, and a zero-bit is represented by zero power, and the extinction ratio is infinite. Practically, a zero-bit level is not zero, so that the ratio is typically 10 to 20. In amplified systems, the signal-independent non-ideal extinction ratio power penalty is obtained by^[6]

$$PP_{sig-dep} = -10 \log \left[\frac{r-1}{r+1} \cdot \frac{\sqrt{r+1}}{\sqrt{r+1}} \right] \quad \text{Equation D.2}$$

Where: r is the extinction ratio of the transmitter.

Assuming the transmitter used has an extinction ratio of 10, the power penalty for that device is $PP_{sig-dep}=1.86\text{dB}$.

Power Penalty Due to Crosstalk

Crosstalk between channels can occur within system devices such as filters, couplers, switches, or multiplexers. Crosstalk can also occur within the fiber through non-linear effects, and was addressed in Appendix C. Two types of crosstalk occur in system devices: inter-channel crosstalk comes from channels outside the electrical bandwidth of the receiver; intra-channel crosstalk comes from channels within the electrical bandwidth of the receiver. Intra-channel crosstalk is much greater than Inter-channel Crosstalk in most systems.^[6]

Since Inter-channel Crosstalk is caused by interference from channels outside the bandwidth of the receiver, and all EVLA channels will be within that bandwidth, this source of crosstalk can be neglected.

The signal-dependant power penalty due to Intra-channel crosstalk follows the equation^[6]

$$PP_{sig-dep} = -5\log(1 - 2\sqrt{\mathcal{E}}) \quad \text{Equation D.3}$$

Where: $\sqrt{\mathcal{E}} = \sum_{i=1}^N \sqrt{\mathcal{E}_i}$, is the average received crosstalk power, and N is the number of channels in the system.

For multiplexers and de-multiplexers, isolation of adjacent channels is typically better than 25 dB, and non-adjacent channels better than 45 dB.^[10] If average power to the multiplexers and de-multiplexers is 0 dBm, the root-sum of the average crosstalk power of the two adjacent channels $\sqrt{\mathcal{E}_{adj}} = -9.5$ dBm, for the 14 non-adjacent channels $\sqrt{\mathcal{E}_{non-adj}} = -11$ dBm, and the total root-sum of the average received Intra-channel crosstalk power is $\sqrt{\mathcal{E}} = -7.2$ dBm. The power penalty for both the multiplexer and de-multiplexer is then 2.0 dBm.

Power Penalty Due to Polarization Dependant Loss

The loss associated with devices such as connectors and multiplexers is partly dependant on the polarization of the signal. This Polarization Dependant Losses (PDL) is listed on manufacturer data sheets. The sum of these losses is used as a power penalty. The table below lists the typical PDL from each device in the EVLA system.

Table D.2 Polarization Dependant Loss in the EVLA System.

	No. Units	Loss/Unit (dB)	PDL (dB)
Connectors ^[6]	13	0.1	1.3
Multiplexers	2	0.1	0.2
Receiver	1	0.12	0.12
Amplifier	1	0.5	0.5
Total PDL			2.12

Summary of Power Penalties

The Table D.3 shows all power penalties calculated above. In addition, a penalty for component aging is added. These penalties are only approximations, so a margin is also added. The non-linear power penalty is assumed to be zero because IF launch power will not exceed the non-linear threshold.

Table D.3 Power Penalty Budget

EVLA IF System Power Penalties (in dB)	
Extinction Ratio	1.86
Crosstalk	2.00
Chromatic Disp. (SMF-28)	2.00
PMD	0.04
Nonlinearities	0.00
PDL	2.12
Component Aging	3.00
Margin	3.00
Total Power Penalties (dB)	14.02
Total Power Penalties (Linear)	25.23

Power penalties represent impairments of noise sources on the system digital signal-to-noise ratio (Q). The noise sources discussed above cause Q to decrease through the system. Consequently, the power penalties calculated in Appendix D must be added to the ideal receiver Q to maintain the required BER. This adjusted Q accounts for system noise, and can be thought of as the minimum transmitter Q.

To maintain the EVLA start-of-life Bit Error Rate of 10^{-9} , an ideal receiver will require a digital SNR (Q) equal to 6. Power penalties in the EVLA system decrease Q by 25.2, so minimum transmitter Q is 31.2.^[6]

Appendix E: Receiver Sensitivity

Receiver sensitivity is the minimum received power necessary to sustain a required bit error rate.

Receiver Sensitivity of a Thermal Noise Limited System

Sensitivity of a thermal noise limited system follows the equation ^[1]

$$P_{sens} = Q\sqrt{4k_BTB_{PD} / R_L} / R \quad \text{Equatio}$$

Where: Q = digital signal to noise ratio,
k_B = 1.38 X 10⁻²³ J/K, Boltzman's constant,
T = 300 K, temperature in Kelvin,
B_{PD} = 10 Gbits/s, the bandwidth of the photo detector,
R_L = 100Ω, assumed load resistance,
R = 0.8 A/W, typical responsivity of a PIN photo detector.

Equation E.1 makes the ideal P_{sens} = 9.7 μW (-20 dBm) for the ideal Q = 6. This sensitivity is a practical number today.

Appendix F: EVLA IF System Power Budget

The power budget for the EVLA IF link is shown in Table E.1. The table shows a typical launch power equal to 0 dBm. Also, each source of loss is tabulated including the fiber attenuation calculated in Appendix A, and the ideal receiver sensitivity calculated in Appendix E. Standard single-mode fiber is assumed. Note that this system has a negative power margin and would not work.

If NZ-DSF is used instead of SMF, about 3 dB might be recovered due to lower attenuation and no dispersion power penalty, but this still would not be sufficient. Even for the nearest pad, where fiber attenuation is only 0.2 dB, the margin would still be negative.

Although all specified values used in these equations are worst-case figures, we can assume a thermal noise limited system will not operate at the required BER.

Table E.1. EVLA IF Power Budget (Non-Amplified System)

Elements	No. Units	Loss/Unit (dB)	Loss/Element(dB)
<i>IF Rack to Vertex Room Bulkhead</i>			
Launch Power			0.00
16ch WDM MUX	1	-6.00	-6.00
Connector	3	-0.30	-0.90
Fiber (km)	0.004	-0.30	0.00
<i>Vertex Room Bulkhead to Antenna Pad</i> $P_{\text{vtx bulkhead}} = -6.90$			
Connector	1	-0.30	-0.30
Fiber (km)	0.02	-0.30	-0.01
<i>Farthest Antenna Pad to CB Termination Panel</i> $P_{\text{last antenna pad}} = -7.21$			
MIL Connector	2	-0.50	-1.00
Connector	1	-0.30	-0.30
Fiber (km)	22	-0.30	-6.60
Splice	2	-0.10	-0.20
Bends	18	-0.10	-1.80
<i>CB Termination Panel to Patch Panel</i> $P_{\text{termination panel}} = -17.11$			
Connector	3	-0.30	-0.90
Fiber (km)	0.02	-0.30	-0.01
<i>Correlator Patch Panel to Correlator Receiver</i> $P_{\text{IF patch panel}} = -18.01$			
Fiber (km)	0.004	-0.30	0.00
Connector	3	-0.30	-0.90
16ch WDM DMUX	1	-6.50	-6.50
<i>Received Power</i>			-25.41
<i>Receiver Sensitivity</i>			-20.00
<i>Loss Margin</i>			-5.41

Table E.2 illustrates the power budget for an amplified system. This configuration uses the same losses as Table E.1, but includes the gain from an EDFA and the values for Q derived in Appendix D. The power margin for this system is 6 dB.

Table E.2 EVLA IF Power Budget (Amplified System)

Elements	No. Units	Loss/Unit (dB)	Loss (dBm)	Q (linear)
<i>IF Rack to Vertex Room Bulkhead</i>				
Launch Power			0.00	31.20
16ch WDM MUX	1	-6.00	-6.00	
Connector	3	-0.30	-0.90	
Fiber (km)	0.004	-0.30	0.00	
<i>Vertex Room Bulkhead to Antenna Pad</i> $P_{\text{vtx bulkhead}} = -6.90$				
Connector	1	-0.30	-0.30	
Fiber (km)	0.02	-0.30	-0.01	
<i>Farthest Antenna Pad to CB Termination Panel</i> $P_{\text{last antenna pad}} = -7.21$				
MIL Connector	2	-0.50	-1.00	
Connector	1	-0.30	-0.30	
Fiber (km)	0.7	-0.30	-0.21	
Splice	2	-0.10	-0.20	
Bends	18	-0.10	-1.80	
<i>CB Termination Panel to Patch Panel</i> $P_{\text{termination panel}} = -10.72$				
Connector	3	-0.30	-0.90	
Fiber (km)	22	-0.30	-6.60	
EDFA Gain	1		12.00	
<i>Correlator Patch Panel to Correlator Receiver</i> $P_{\text{IF patch panel}} = -6.22$				
Fiber (km)	0.004	-0.30	0.00	
Connector	3	-0.30	-0.90	
16ch WDM DMUX	1	-6.50	-6.50	
<i>Received Power</i>			-13.62	-25.20
<i>Receiver Sensitivity</i>			-20.00	6.00
<i>Margin</i>			6.38	0.00

Appendix G: IF Channel Assignments

The Proposed EVLA IF system is very similar to the ALMA IF system. With t in mind, channel assignments have been coordinated with ALMA and are listed below. These are standard International Telecommunications Union (ITU) wavelengths. All sixteen channels lie in the EDFA flat gain range between 1530nm and 1560nm.

Table F. IF Channel Assignments

ITU Channel	Frequency	Wavelength
Channel 21	192.1 THz	1560.61 nm
Channel 23	192.3 THz	1558.98 nm
Channel 25	192.5 THz	1557.36 nm
Channel 27	192.7 THz	1555.75 nm
Channel 29	192.9 THz	1554.13 nm
Channel 31	193.1 THz	1552.52 nm
Channel 33	193.3 THz	1550.92 nm
Channel 35	193.5 THz	1549.32 nm
Channel 37	193.7 THz	1547.72 nm
Channel 39	193.9 THz	1546.12 nm
Channel 41	194.1 THz	1544.53 nm
Channel 43	194.3 THz	1542.94 nm
Channel 45	194.5 THz	1541.35 nm
Channel 47	194.7 THz	1539.77 nm
Channel 49	194.9 THz	1538.19 nm
Channel 51	195.1 THz	1536.61 nm

Appendix H: Monitor Requirements

Bit Error Rates

Bit Error Rates (BER) will be continuously counted in the IF receiver deformatter and reported in “real-time” to the Monitor and Control System. A low BER indicates that the data stream has sufficient amplitude and SNR for the receiver to correctly convert the optical signal to electronic bits. An increase in BER above the end-of-life threshold of 10^{-6} indicates a problem that requires system repair. A BER of 10^{-6} is about 10,000 errors per second and a BER of 10^{-9} is about 10 errors per second.

Optical Power

The IF link may have up to sixteen laser transmitters. A small power degradation of any one of those lasers would be a small fraction of the whole. Therefore monitoring the total broadband optical power could generally only indicate if the link is on or off and is not recommended. A gradual loss of power is more practically found in an increase of the BER. Once identified, the channel could be characterized using an optical spectrum analyzer.

Eye Pattern

A bit pattern from a channel produces an eye pattern that can be viewed on an optical spectrum analyzer. The eye pattern is used to measure noise margin, jitter, distortion, and rise and fall times^[3]. Ultimately, the eye pattern can be used to measure Q. Predetermined bit patterns will be generated in the transmitter board. These patterns will produce known eye patterns and will facilitate troubleshooting and repair.

Test Points

For troubleshooting purposes, a 1% optical power tap from each laser on the transmitter board, and a 1% optical power tap between the WDM de-multiplexer and the receiver shall be provided. These test points provide a convenient location to measure channel power level and eye patterns. The power taps will be permanently installed. Electronic test points at the output of each photo detector should be provided to check the response of the receiver using these same tests.

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