Chapter 7
Arraying Combinations and Comparisons

7.1 Arraying Combinations

Besides the individual arraying schemes described in the previous chapters, combinations of schemes can be implemented. In particular, SSC can be enhanced with SA and with CA. Similarly, BC can be enhanced with SA and with CA. FSC uses only one set of receiver, subcarrier, and symbol-tracking loops, but, again, the performance of the receiver can be improved with SA.

A comparison of all schemes and arraying combinations is depicted in Figs. 7-1 and 7-2, where the degradations of BC, SSC, FSC, SSC/SA/CA, FSC/SA, BC/SA/CA, FSC/SA, SSC/CA, BC/SA, SSC/SA, and BC/CA are all computed versus P/N_0 for a fixed Δ = 65.9 deg. These curves were computed assuming B_τ = 0.1 mHz and B_n = 135 kHz for the telemetry time-aligning loop, T/B = 0.0008 s^2 for FSC, T/B = 0.075 s^2 for CA (assumed at IF), and a symbol rate of 34 symbols per second (s/s). From Fig. 7-1, it seems that the three schemes with the least degradation at 20 dB-Hz are FSC/SA, BC/SA/CA, and SSC/SA/CA. As mentioned before, the “x” denotes the point where carrier-loop SNR has reached 8 dB and below which significant cycle slipping might occur. Most schemes seem to maintain an 8-dB minimum carrier-loop SNR for P/N_0 as low as 20 dB-Hz, except for SSC and BC, which lose lock at roughly 24 dB-Hz, and BC/CA and SSC/CA, which require a $P/N_0 \geq$ 21 dB-Hz. Recall that the delay adjustment in FSC and FSC/SA was assumed to be perfect, resulting in no degradation. More realistically, a 0.1-dB degradation should be added and, hence, FSC/SA and BC/SA/CA seem to provide very similar degradations.

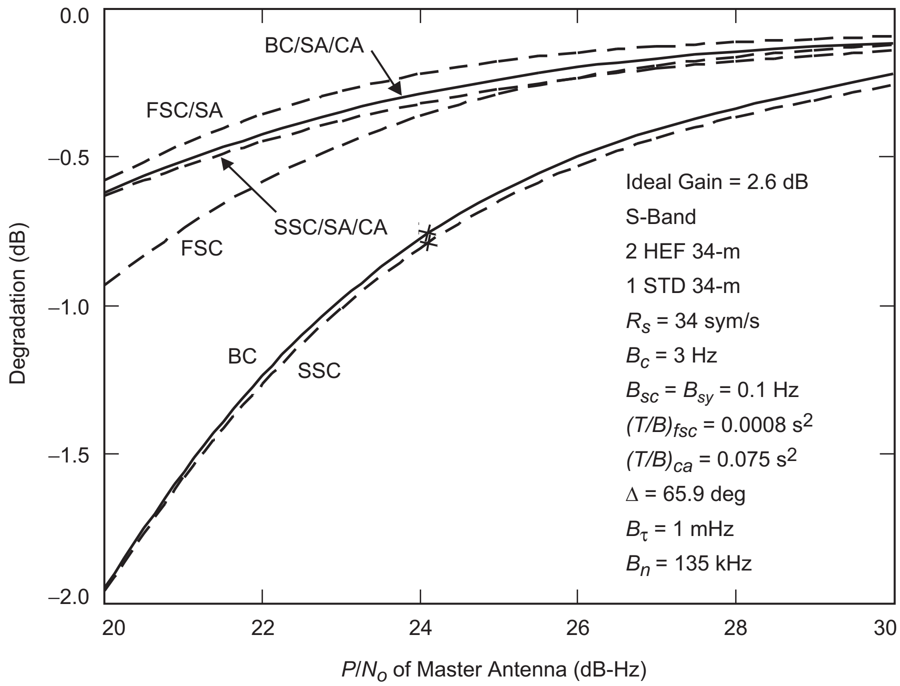

Fig. 7-1. Comparison of SSC, FSC, and FSC/SA with BC, SSC/SA, CA, and BC/SA/CA.

For this particular case, FSC requires 216 seconds of integration time (for T/B = 0.0008 and B = 2 times 135 kHz), a rather unrealistic parameter. For a shorter integration time (on the order of a few seconds), the correlator SNR degrades significantly, and the differential phase cannot be estimated. The bandwidth B can be reduced to pass only the first harmonic of the subcarrier, but that still results in unrealistic integration times. The signal can be passed through a matched filter that passes the subcarrier harmonics and the data modulation but rejects the spectrum in between the harmonics. The effective bandwidth of such a filter would be of the order of the symbol rate and, hence, would result in shorter integration times as long as the subcarrier frequency is a large multiple of the symbol rate [$m >> 1$ in Eq. (6.4-1)]. The drawback of such a filter is that it is too specific to the signal of interest and needs to be modified for each mission. Moreover, it might require frequency tuning to center the signal in the band of interest. Another technique to reduce the bandwidth is to correlate only the residual-carrier components in order to further shorten the integration time. This is precisely the technique employed in carrier arraying, when implemented at IF. It should be pointed out that even though the phase is adjusted at IF, it can and should be estimated at baseband by mixing the received IF from each antenna with a Doppler and a Doppler rate predict of the

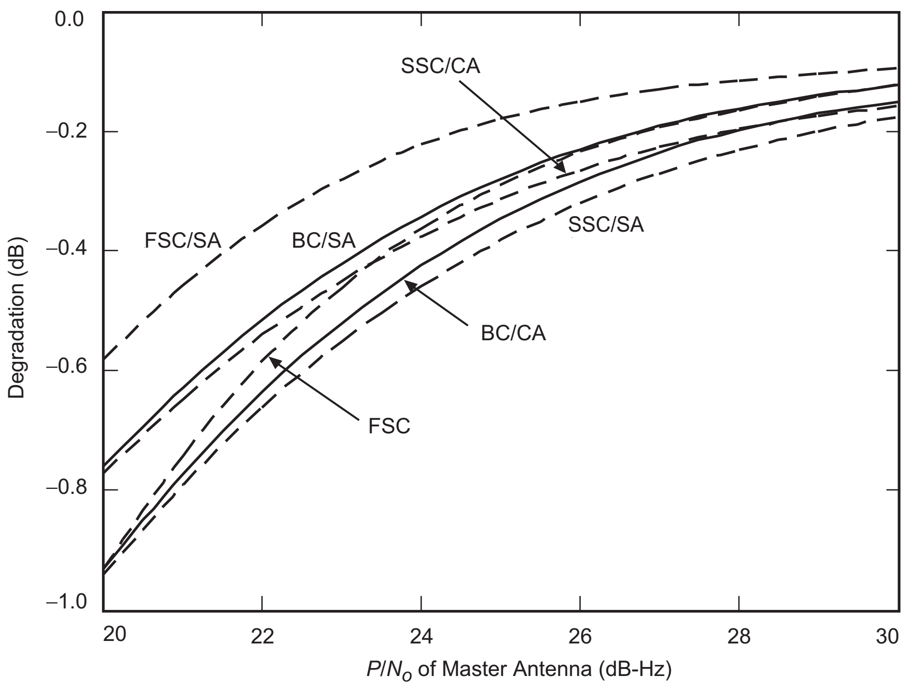

Fig. 7-2. Comparison of SSC, FSC, and FSC/SA with BC/CA, BC/SA, and SSC/CA.

signal. The outputs of the mixers consist of a tone with a very low frequency component that requires a very small bandwidth B prior to the correlation. With $T/B = 0.075$ and $T = 3$ s, $B = 40$ Hz, which requires the frequency predicts to be correct to within ± 20 Hz. Even if the error is larger than ± 20 Hz, a fast Fourier transform (FFT) can be used to reduce the frequency error at the output of the mixers such that it lies well within $B/2$ Hz.

As seen from the above example, FSC/SA and BC/SA/CA provide the least degradation and hence the best performance overall, but BC/SA/CA accomplishes that with reasonable integration times. SA enhances the performance in both cases because the carrier component is so weak due to the high modulation index and relatively low received power. For signals with stronger carriers, FSC and FSC/SA would provide similar degradations for all practical purposes, as would BC/CA and BC/SA/CA. It is worth noting at this point that FSC, as presented in this discussion, compensated for the signal delays up front and then adjusted for the phases. This is the classical arraying performed in radiometry. However, in BC/CA, CA is first employed to lock on the signal (hence, a phase adjustment) and later delay compensation is performed in the baseband assembly (BBA) to coherently add the data. The latter, which is equivalent in performance to FSC (but with shorter integration times), seems to be favored more by communication engineers, whereas FSC seems to be favored more by astronomers. The major difference between FSC and BC/CA is the integration length required to estimate the differential phase. BC/CA offers a significant advantage by requiring much shorter integration times for spacecraft with very weak signals and a large subcarrier-to-data-rate ratio.

In either FSC or BC/CA, atmospheric effects can be significant, especially at higher frequencies and in the presence of thunderstorms. Figure 7-3 depicts the relative phase along baseline "1–3" in the Very Large Array (VLA) on a clear night and in the presence of thunderstorms. In the latter case, the integration time T needs to be short to track the phase variation. The resulting combining degradation can be 0.2 dB or even more depending on the scenario.

7.2 Numerical Examples

The results derived in Chapter 6 were applied to several existing deep-space missions managed by the DSN in order to illustrate the differences in combined symbol SNR performance. The missions considered were Pioneer 10, Voyager II, and Magellan, reflecting weak, medium, and strong signals. As expected, the weaker the signal, the harder it is to array the antennas. The Galileo Mission is treated at greater length in Section 7.2.4, reflecting a weak signal.

7.2.1 Pioneer 10

The signal received from Pioneer 10 represents the weakest signal. It is an S-band signal with the following characteristic as of May 1990: symbol rate R_s = 32 sym/s, subcarrier frequency f_s = 32768 Hz, and modulation index Δ =

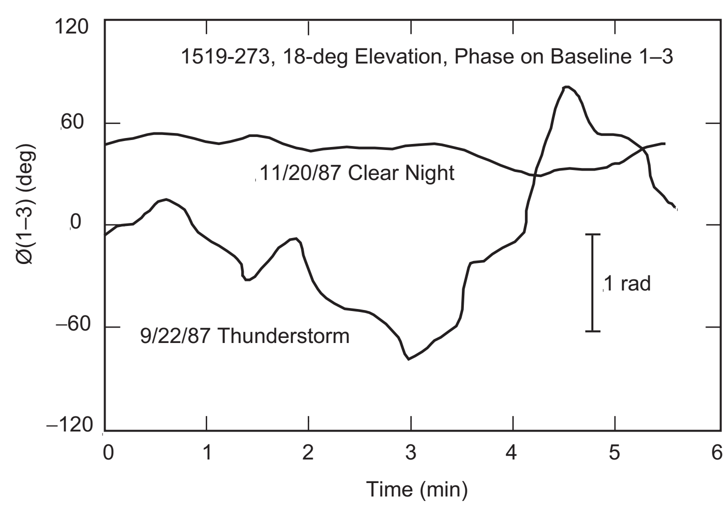

Fig. 7-3. VLA thunderstorm data at 8.4 GHz.

65.9 deg. The receiver is assumed to operate with the following parameters: carrier bandwidth B_c= 1.5 Hz (Block IV Receiver), $B_{sc} = B_{sy}$= 0.1 Hz for the subcarrier- and symbol-tracking loops, B_τ= 0.1 mHz and B_n= 135 kHz for the telemetry time-aligning loop, T/B = 0.075 for carrier arraying (B = 40 Hz and T = 3 s), and T/B = 0.0008. For FSC, two cases are considered: a regular IF filter (B = 2(135) kHz and T = 216 s!) and a matched IF filter (B = 500 Hz and T = 0.4 s). Two array configurations are considered: a 70-m and a 34-m STD antenna array, which can provide 0.68-dB gain (over the 70-m antenna) in the ideal case, and a two-70-m-antenna array (providing an ideal 3-dB gain). The degradations for both arrays are shown in Tables 7-1(a) and 7-1(b), respectively. The 20-dB-Hz signal represents the approximate level at the master antenna—in this case, the 70-m antenna.

In the first array (70 m + STD 34 m), BC and SSC cannot operate due to the inability of the STD 34-m antenna to maintain carrier lock. However, BC/SA and SSC/SA can operate with an 8-dB loop SNR, which is the minimum required to avoid cycle slipping. FSC/SA achieves the highest loop SNR at 18.2 dB, followed by BC/SA/CA and SSC/SA/CA at 17.7 dB, and followed finally by BC/SA, SSC/SA, and FSC at 11 dB. The smallest degradations are obtained with FSC/SA and BC/SA/CA at about 0.53 dB. Note that the combining loss of FSC at 0.19 dB can be reduced by integrating over longer periods. In the two-70-m-antenna array, all schemes maintain lock as expected, with the smallest degradation achieved by FSC/SA at 0.34 dB and the largest achieved by BC at 0.81 dB. FSC/SA seems to be the “best” arraying scheme for Pioneer 10, and the sideband aiding is essential in reducing the degradation. Recall that the long integration time required in FSC/SA renders the scheme impractical and, hence, BC/SA/CA is really the “best” scheme for Pioneer 10.

7.2.2 Voyager II

Unlike Pioneer 10, Voyager II can be tracked by all 34-m antennas. It represents a medium signal in both received power and data rate. The X-band signal processes the following characteristics: symbol rate = 43.2 s/s, subcarrier frequency = 360 kHz, and Δ = 77 deg. The receivers are assumed to operate with the following parameters: B_c = 10 Hz for the carrier tracking, $B_{sc} = B_{sy}$= 1.0 Hz for the subcarrier- and symbol-tracking loops, B_τ= 1 mHz and B_n= 3.2 MHz for the telemetry time-aligning loop, T/B = 0.075 for carrier arraying, and $T/B = 2.0 \times 10^{-7}$ for FSC (B = 3.2 MHz and T = 1.3 s).

Table 7-2(a) provides the degradations for all arraying schemes for a three-element array of one HEF 34-m and two STD 34-m antennas. This array can provide an ideal 3-dB gain over the HEF 34-m master antenna, with

Table 7-1(a). Pioneer 10: one 70-m and one 34-m STD antenna array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	20	No	Carrier	Lock	—	—
BC+SA	20	–0.614	–0.17	–0.25	–0.07	–0.12
BC+CA	20	–0.792	–0.34	–0.26	–0.08	–0.12
BC+SA+CA	20	–0.526	–0.07	–0.26	–0.08	–0.12
SSC	20	No	Carrier	Lock	—	—
SSC+SA	20	–0.670	–0.17	–0.39	–0.11	0.00
SSC+CA	20	–0.849	–0.34	–0.40	–0.11	0.00
SSC+SA_CA	20	–0.583	–0.07	–0.40	–0.11	0.00
FSC	20	–0.874	–0.35	–0.26	–0.08	–0.19
FSC+SA	20	–0.593	–0.07	–0.26	–0.08	–0.19
FSC (Matched filter)	20	–0.874	–0.35	–0.26	–0.08	–0.19
FSC+SA (Matched filter)	20	–0.593	–0.07	–0.26	–0.08	–0.19

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

Table 7-1(b). Pioneer 10: two 70-m antennas array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	20	–0.812	–0.40	–0.19	–0.06	–0.17
BC+SA	20	–0.487	–0.08	–0.19	–0.06	–0.17
BC+CA	20	–0.608	–0.20	–0.19	–0.06	–0.17
BC+SA+CA	20	–0.475	–0.06	–0.19	–0.06	–0.17
SSC	20	–0.768	–0.40	–0.29	–0.08	0.00
SSC+SA	20	–0.444	–0.08	–0.29	–0.08	0.00
SSC+CA	20	–0.565	–0.20	–0.29	–0.08	0.00
SSC+SA_CA	20	–0.432	–0.06	–0.29	–0.08	0.00
FSC	20	–0.509	–0.20	–0.19	–0.06	–0.07
FSC+SA	20	–0.347	–0.04	–0.19	–0.06	–0.07
FSC (Matched filter)	20	–0.509	–0.20	–0.19	–0.06	–0.07
FSC+SA (Matched filter)	20	–0.347	–0.04	–0.19	–0.06	–0.07

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

Table 7-2(a). Voyager 2: one master 34-m HEF and two 34-m STD antennas array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	39	–0.346	–0.16	–0.11	–0.03	–0.04
BC+SA	39	–0.219	–0.04	–0.11	–0.03	–0.04
BC+CA	39	–0.236	–0.05	–0.11	–0.03	–0.04
BC+SA+CA	39	–0.197	–0.02	–0.11	–0.03	–0.04
SSC	39	–0.548	–0.16	–0.31	–0.08	0.00
SSC+SA	39	–0.422	–0.04	–0.31	–0.08	0.00
SSC+CA	39	–0.439	–0.05	–0.31	–0.08	0.00
SSC+SA_CA	39	–0.400	–0.02	–0.31	–0.08	0.00
FSC	39	–0.284	–0.06	–0.11	–0.03	0.09
FSC+SA	39	–0.235	–0.01	–0.11	–0.03	0.09

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

P/N_0 =39 dB-Hz. The second array also consists of three elements: one 70-m antenna, one STD 34-m antenna, and one HEF 34-m antenna. Its performance is shown in Table 7-2(b). The master in this case is the 70-m antenna with P_t/N_0 = 45 dB-Hz. This array can provide a maximum gain of 1.43 dB. BC/SA, BC/CA, and BC/SA/CA can provide the least degradations if the combining loss is maintained below 0.01 dB. On the other hand, FSC/SA provides a better performance for a more realistic 0.07-dB IF degradation. For all practical purposes, both FSC and BC/CA perform equally with realistic integration times.

7.2.3 Magellan

The highest data rate signal is transmitted by Magellan at X-band with 537.6 ks/s, a 960-kHz subcarrier frequency, and a 78-deg modulation index. Tables 7-3(a) and 7-3(b) provide the degradations for an array of one HEF 34-m antenna and one STD 34-m antenna (providing a 1.76-dB ideal gain over the HEF 34-m master antenna) and another array of one 70-m antenna, one HEF 34-m antenna, and one STD 34-m antenna (providing a 1.43-dB ideal gain over the 70-m master antenna). The receivers are assumed to operate with B_c= 30 Hz for the carrier tracking, $B_{sc} = B_{sy}$ = 3.0 Hz for the subcarrier- and symbol-tracking loops, B_τ= 10 mHz and B_n= 4.5 MHz for the telemetry time-aligning loop, T/B = 0.075 for carrier arraying, and T/B = 10^{-10} for FSC. In this case, all combining methods provide near-optimum performances for both arrays.

7.2.4 Galileo

The FSC and CSC performance for different combinations of 70-m and 34-m antennas is compared here for the Galileo Mission. The IF signals in FSC typically are transmitted to a central location before being combined and demodulated using a single receiver. However, since the retransmission channel is bandlimited, the most significant harmonics are brought to near baseband before transmission and combining. Million et al. discuss this variation of the FSC scheme in [1]. When the number of subcarrier harmonics present at the combiner input is four, the energy lost is 0.22 dB. The retransmission of CSC signals to a central location, on the other hand, does not result in an energy loss because the symbol rates for Galileo (less than 640 sym/s) can be easily supported by the retransmission channel. The following cases are considered: two 70-m antennas, and one 70-m antenna plus from one to four 34-m STD antennas.

Table 7-2(b). Voyager 2: one 70-m, one 34-m HEF, and one 34-m STD antenna array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	45	–0.130	–0.06	–0.05	–0.01	–0.01
BC+SA	45	–0.084	–0.01	–0.05	–0.01	–0.01
BC+CA	45	–0.091	–0.02	–0.05	–0.01	–0.01
BC+SA+CA	45	–0.077	–0.01	–0.05	–0.01	–0.01
SSC	45	–0.208	–0.06	–0.12	–0.03	0.00
SSC+SA	45	–0.163	–0.01	–0.12	–0.03	0.00
SSC+CA	45	–0.170	–0.02	–0.12	–0.03	0.00
SSC+SA_CA	45	–0.156	–0.01	–0.12	–0.03	0.00
FSC	45	–0.148	–0.02	–0.05	–0.01	–0.07
FSC+SA	45	–0.134	–0.01	–0.05	–0.01	–0.07

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

Table 7-3(a). Magellan: one master 34-m HEF and one 34-m STD antenna array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	59	–0.022	–0.01	–0.01	0.00	0.00
BC+SA	59	–0.022	–0.01	–0.01	0.00	0.00
BC+CA	59	–0.022	–0.01	–0.01	0.00	0.00
BC+SA+CA	59	–0.022	–0.01	–0.01	0.00	0.00
SSC	59	–0.027	–0.01	–0.02	0.00	0.00
SSC+SA	59	–0.027	–0.01	–0.02	0.00	0.00
SSC+CA	59	–0.027	–0.01	–0.02	0.00	0.00
SSC+SA_CA	59	–0.027	–0.01	–0.02	0.00	0.00
FSC	59	–0.036	–0.01	–0.01	0.00	–0.02
FSC+SA	59	–0.036	–0.01	–0.01	0.00	–0.02

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

Table 7-3(b). Magellan: one 70-m, one 34-m HEF, and one 34-m STD antenna array.

Arraying Scheme	P_T/N_o (dB-Hz)	Total Degradation (dB)	Carrier Degradation (dB)	Subcarrier Degradation (dB)	Symbol Degradation (dB)	RTC or IF* Degradation (dB)
BC	65	–0.015	–0.01	–0.01	0.00	0.00
BC+SA	65	–0.015	–0.01	–0.01	0.00	0.00
BC+CA	65	–0.015	–0.01	–0.01	0.00	0.00
BC+SA+CA	65	–0.015	–0.01	–0.01	0.00	0.00
SSC	65	–0.021	–0.01	–0.01	0.00	0.00
SSC+SA	65	–0.021	–0.01	–0.01	0.00	0.00
SSC+CA	65	–0.021	–0.01	–0.01	0.00	0.00
SSC+SA_CA	65	–0.021	–0.01	–0.01	0.00	0.00
FSC	65	–0.031	–0.01	–0.01	0.00	–0.02
FSC+SA	65	–0.031	–0.01	–0.01	0.00	–0.02

* Degradation at the real-time-combiner output (RTC) in the BC cases or the intermediate-frequency output (IF) in the non-BC cases.

7.2.4.1 Array of Two 70-Meter Antennas. The signal characteristics and receiver parameters are those given in Fig. 7-4, with a symbol rate of 400 sym/s. FSC performance for the Galileo scenario is obtained by adding 0.22 dB to the FSC degradation in Fig. 7-4. The shifted FSC curve along with the CSC degradation (which is the same as in Fig. 7-4, since no energy is lost in CSC) is plotted in Fig. 7-5. Notice that both techniques have equal performances when $B_{sc}w_{sc} = B_{sy}w_{sy} = 1.2$ mHz. In addition, Fig. 7-5 shows results using the same parameters as in Fig. 7-4, but now with a symbol rate of 200 sym/s (combined $E_s / N_0 = -5.0$ dB). In this case, FSC and CSC have equal performances when $B_{sc}w_{sc} = B_{sy}w_{sy} = 3.0$ mHz. The degradations due to individual components (carrier, subcarrier, symbol, and correlator) are discussed in the following paragraph to show the relative contribution of each to the total degradation shown in Fig. 7-5 for a symbol rate of 400 sym/s.

The degradation due to any single synchronization step is defined as the degradation that would be observed when all other synchronization steps are operating ideally. For example, in FSC, the degradation due to the carrier loop is given as $D_{fsc} = 10 \log_{10} \overline{C_c^2}$, which is derived by setting the combiner SNR, the subcarrier loop SNR, and the symbol-loop SNR to infinity in Eq. (6.1-47). The degradations due to individual components are shown in Figs. 7-6 through 7-9. The combiner degradation for both schemes is negligible. Also, the carrier degradation is the same for FSC and CSC since the carrier-loop SNR for both schemes is the same. The subcarrier degradation and symbol

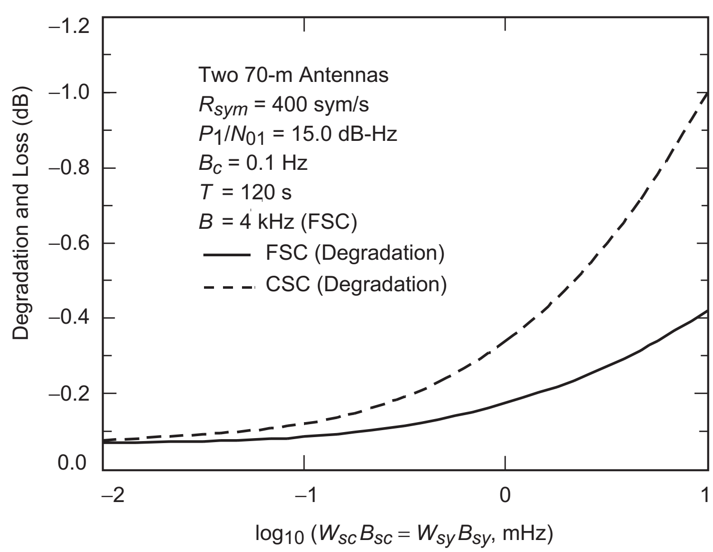

Fig. 7-4. Degradation versus subcarrier and symbol window-loop bandwidth.

degradation, however, are significantly different for FSC and CSC, the degradation from the latter being greater than FSC due to the carrier not being tracked and the signal not being combined until after the subcarrier and symbol loops.

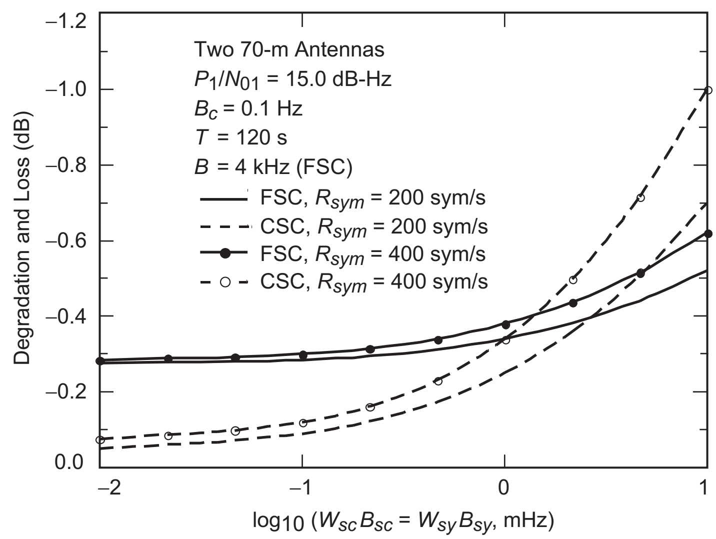

Fig. 7-5. Practical FSC and CSC degradation versus subcarrier and symbol window-loop bandwidth.

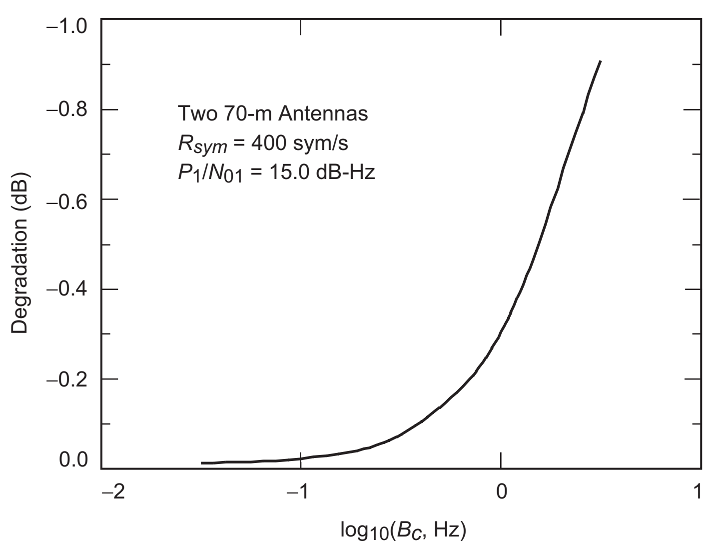

Fig. 7-6. Comparison of degradation due to individual components: carrier degradation versus carrier bandwidth.

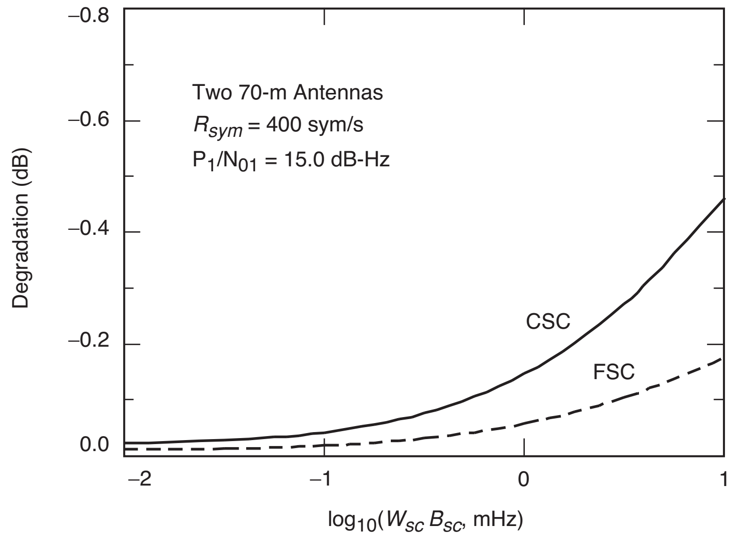

Fig. 7-7. Comparison of degradation due to individual components: subcarrier degradation versus subcarrier window-loop bandwidth.

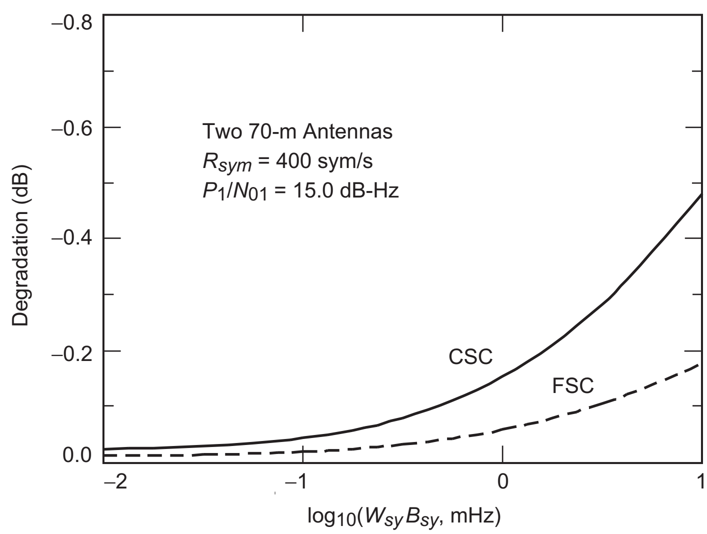

Fig. 7-8. Comparison of degradation due to individual components: symbol degradation versus symbol window-loop bandwidth.

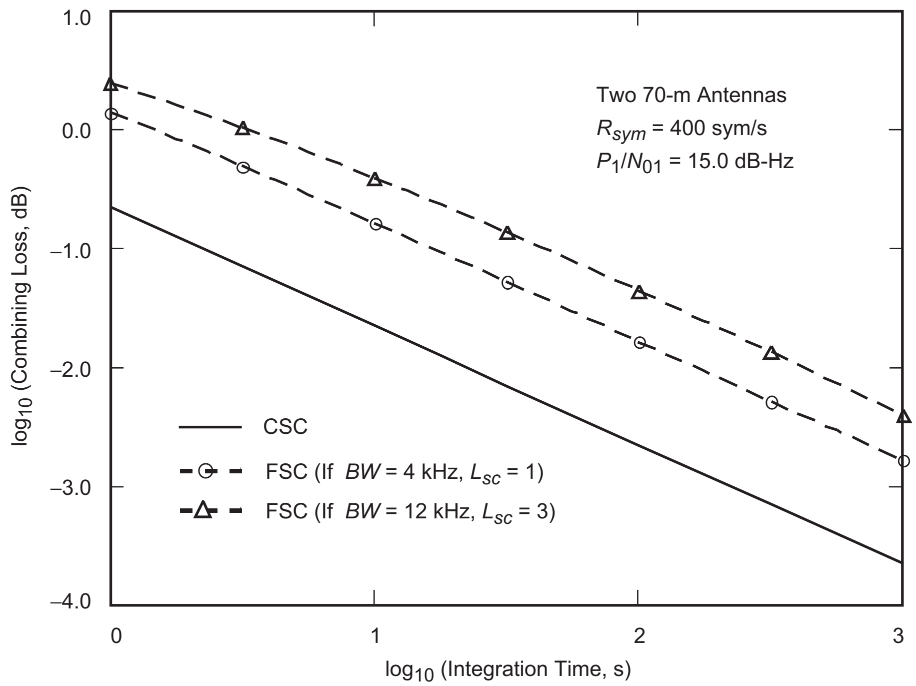

Fig. 7-9. Comparison of degradation due to individual components: combining loss versus integration time.

7.2.4.2 Array of One 70-Meter Antenna and One 34-Meter STD Antenna. The performance of one 70-m antenna and one 34-m STD antenna array is shown in Fig. 7-10, with P_1 / N_{01}= 15 dB-Hz and P_2 / N_{02}= 7.3 dB-Hz, i.e., $\gamma_1 = 1$ and $\gamma_2 = 0.17$. Figure 7-10 also shows the results when the symbol rate is 200 sym/s. At these signal levels, the 34-m antenna is not expected to achieve subcarrier and symbol lock without being aided by the 70-m antenna. Consequently, the CSC arraying scheme is implemented by passing frequency and phase information from the 70-m antenna to the 34-m antenna. As a result, the effective subcarrier- and symbol-loop SNRs of the 34-m antenna are identical to those of the 70-m antenna. The modified CSC is called complex-symbol combining with aiding (CSCA). In this scenario, the practical FSC outperforms CSCA when $B_{sc} w_{sc} = B_{sy} w_{sy}$ is greater than 4.5 mHz at a symbol rate of 400 sym/s and 10.0 mHz at a symbol rate of 200 sym/s.

7.2.4.3 Array of One 70-Meter Antenna and Two 34-Meter STD Antennas. The result for an array of one 70-m antenna and two 34-m antennas is shown in Fig. 7-11. For this case, FSC outperforms CSCA when $B_{sc} w_{sc} = B_{sy} w_{sy}$ is greater than 4.0 mHz at a symbol rate of 400 sym/s and 8.5 mHz at a symbol rate of 200 sym/s.

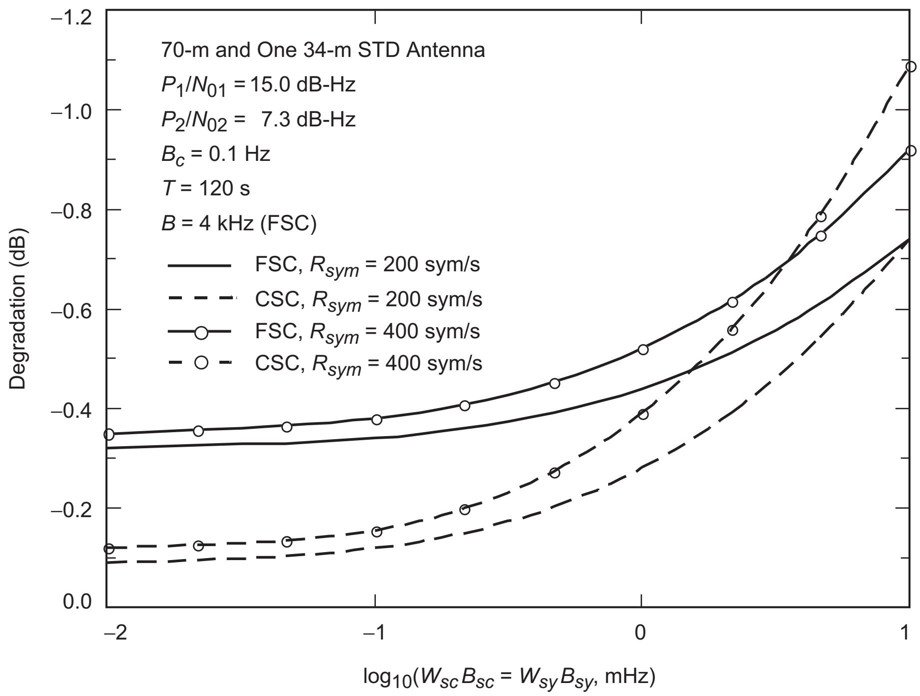

Fig. 7-10. Comparison of degradation for various array configurations: one 70-m antenna and one 34-m STD antenna.

7.2.4.4 Array of One 70-Meter Antenna and Three 34-Meter STD Antennas. The result for an array of one 70-m antenna and three 34-m antennas is shown in Fig. 7-12. FSC outperforms CSCA when $B_{sc}w_{sc} = B_{sy}w_{sy}$ is greater than 3.5 mHz at a symbol rate of 400 sym/s and 8.2 mHz at a symbol rate of 200 sym/s.

7.2.4.5 Array of Four 34-Meter STD Antennas. The result for an array of four 34-m antennas is shown in Fig. 7-13 for a symbol rate of 50 sym/s with a correlator bandwidth of 400 Hz. For this array, FSC has less degradation than does CSC when $B_{sc}w_{sc} = B_{sy}w_{sy}$ is above 0.32 mHz. Practical FSC is able to operate for the given $B_{sc}w_{sc} = B_{sy}w_{sy}$ without losing lock (assume the loops are able to lock to the signal if their respective loop SNRs are greater than 12 dB). For CSC, however, the maximum $B_{sc}w_{sc} = B_{sy}w_{sy}$ that can be supported without losing lock is about 0.9 mHz.

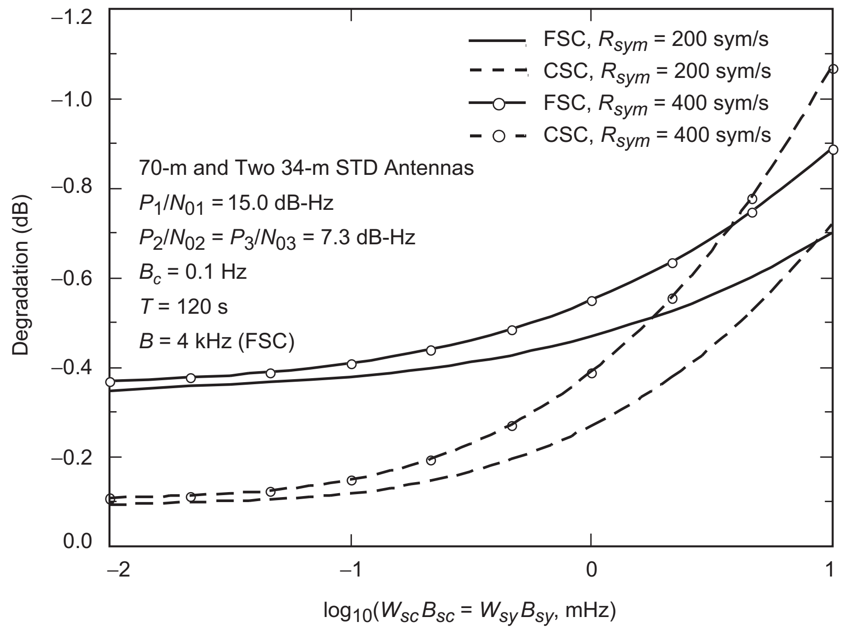

Fig. 7-11. Comparison of degradation for various array configurations: one 70-m and two 34-m STD antennas.

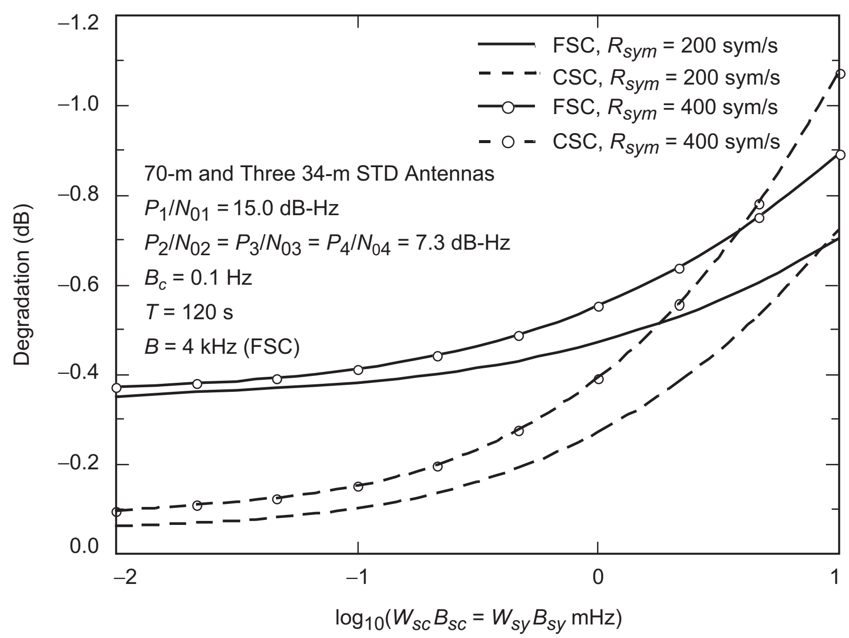

Fig. 7-12. Comparison of degradation for various array configurations: one 70-m and three 34-m STD antennas.

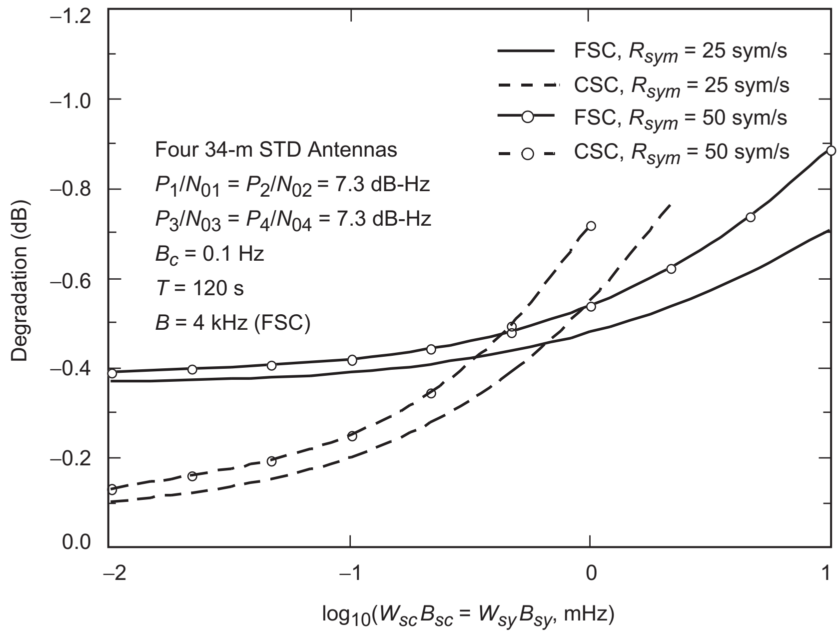

Fig. 7-13. Comparison of degradation for various array configurations: four 34-m STD antennas.

7.3 Conclusions

Five arraying schemes have been investigated—full-spectrum combining, complex-symbol combining, symbol-stream combining, baseband combining, and carrier arraying. For maximum telemetry performance, the best scheme is full-spectrum combining, which performs correlation at IF. After the signal combiner, it requires just one carrier, one subcarrier, and one symbol loop. The next in performance is the complex-symbol combining scheme, which requires L subcarrier and L symbol loops implemented as IQ-loops for maximum performance and just one carrier loop operating at baseband. About the same performance can be obtained with baseband combining augmented by carrier arraying. The simplest scheme to implement is symbol-stream combining, which requires L carrier, L subcarrier, and L symbol loops, but has poorer performance when compared with the previous schemes. It also has a drawback in that, at a low signal level, the carrier loops might not be able to lock on the signal. Of course, with sideband aiding, all these schemes receive an additional boost in performance.

Reference

[1] S. Million, B. Shah, and S. Hinedi, "A Comparison of Full-Spectrum and Complex-Symbol Combining Techniques for the Galileo S-Band Mission," *The Telecommunications and Data Acquisition Progress Report 42-116, October–December 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 128–162, February 15, 1994. http://ipnpr.jpl.nasa.gov/progress_report/