Trade-Offs in the Design of Satellite Sounding Instruments

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ABSTRACT

In the design of satellite sounding instruments there are many factors that determine the accuracies of the retrieved temperature and moisture profiles. However, the three major factors are: instrument noise, number of channels and weighting function half-widths. The effect of these three factors on retrieved temperatures are examined through simulation studies to determine trade-offs among them. We conclude that the trade-offs among the three factors suggest that very different instrument designs can yield similar accuracies. Consequently, the instrument design that provides optimum performance can be recognized only after a trade-off analysis is made. If the design with the best performance is to be selected, it is particularly important that the designs be given equal benefit of factors which are not intrinsic design differences.

1. Introduction

The retrieval of vertical atmospheric temperature and humidity profiles from satellite radiance measurements is now routine (McMillin *et al.*, 1983), and these profiles have become an important complement to radiosonde measurements. Whether or not temperature and humidity soundings from satellites can ever achieve radiosonde accuracy over thin layers is an open question. However, in working toward that goal several new sounding instruments have been proposed; these include the Advanced Microwave Sounding Unit (AMSU) (Staelin, 1983); the Advanced Moisture and Temperature Sounder (AMTS) (Chahine *et al.*, 1984); and the High Resolution Interferometer Sounder (HIS) (Smith *et al.*, 1979a). While each of these instruments has intrinsic advantages and disadvantages, other factors that determine the final accuracies of the retrieved profiles are extrinsic. The difference between intrinsic and extrinsic factors is that factors such as the use of a filter wheel, a spectrometer or an interferometer which are basic to a particular design are intrinsic; other factors such as detector composition or cooling capability can be applied to any of the designs and are therefore extrinsic.

While there are many factors that affect retrieval accuracy, three are dominant. They are: 1) the FWHM (full-width at half-maximum) of the atmospheric weighting function, 2) the number of spectral intervals (channels), and 3) the instrumental noise level of each channel. (Note that while the location of the channels is also important, it is assumed that the channels are chosen such that their weighting functions are essentially uniformly distributed relative to the scale of the vertical extent. It is well known that once this is done variations in location between channels are of very minor importance.) We shall refer to these three fundamental factors as the "design factors."

The design factors are not always complementary in that, to a certain extent, one factor can be traded off for another. Unfortunately, there is a tendency to consider these factors singly or in pairs rather than as an inseparable triad. For example, Weinreb and Crosby (1972) examined the effects of the number of channels used and instrumental noise on the average residual variance and, hence, on the retrieval accuracy. They found that, as channels are added, the marginal improvement due to an additional channel decreases as the number of channels increases. They also found that, as the instrumental noise increases, the sensitivity of the average reduction in variance to the number and location of channels decreases. However, the evaluation was done at a single weighting function FWHM.

On the other hand, Chahine (1979) examined the effect of instrumental noise on retrieval accuracy for two instruments which differed in the number of channels as well as the weighting function FWHM. Both instruments showed an increase in retrieval accuracy with decreasing noise levels. As expected, the instrument with more channels and narrower FWHMs was more accurate for a given noise level. Chahine attributed the increase in accuracy solely to the narrow weighting function FWHMs. Since both factors—narrower FWHMs and an increase in the number of channels—cause an increase in retrieval accuracy, one cannot rule in favor of one factor without studying the effect of both factors working together. Unfortunately, Chahine did not resolve this issue in his study, nor did he justify his inherent assumption that noise levels for the two instruments would be equal.

It is the purpose of this paper to examine the simultaneous interaction of the three design factors that affect retrieval accuracy. With these results, it will be possible to determine those trade-offs that maximize retrieval accuracy.

2. Simulation sets

It is clear that in order to determine the interactions of the three fundamental design factors affecting retrieval accuracies one must vary these factors independently. It is also clear that an enormous number of combinations of parameters exist. Thus, just to keep the computations manageable, we simulated only a few carefully chosen combinations of channels, noise levels and FWHMs. Our choices started with a set of seven channels, modeled after those on the High Resolution Infrared Radiation Sounder (HIRS) (Smith *et al.*, 1979b), which represents a basic sounding instrument. The channels used were the seven HIRS longwave sounding channels. Weighting functions for these channels are shown in Smith *et al.* (1979b) and have peaks at 30, 60, 100, 400, 600, 800 and 900 mb.

Three more sets of channels were generated from this basic set as follows: 1) the weighting function FWHMs were halved while retaining their original peak locations, 2) the number of channels was doubled to 14 while retaining the original FWHMs, and 3) the number of channels was doubled and the FWHMs were halved as before. The extra channels were added by locating the peaks of the weighting functions midway between existing peaks, with the seventh additional channel having the peak of its weighting function located midway between 1000 mb and the lowest peaking of the original seven channels. The weighting function FWHM of each added channel was identical to that of its higher peaking neighbor. In summary, we now have four sets of channels: seven channels with normal FWHMs, seven channels with halved FWHMs, 14 channels with normal FWHMs and 14 channels with halved FWHMs.

For contrast, a somewhat more sophisticated sounder also was simulated. It consisted of the seven 15-μm channels cited above plus the four most transparent of the shortwave CO_2/N_2O sounding channels on HIRS, whose weighting functions are shown in Smith *et al.* (1979b). The weighting functions of the four additional channels peak at 1000, 950, 700 and 450 mb.

Three more sets of channels were generated from this original set of 11 channels in the same manner as those previously described. The resulting four sets of channels are as follows: 11 channels with normal FWHMs; 11 channels with halved FWHMs; 22 channels with normal FWHMs; and 22 channels with halved FWHMs.

The total of eight sets of channels just described is adequate to study the effects of changing the number of channels and changing the weighting function FWHMs. The third factor, instrumental noise, was varied as follows. First, the nominal noise values given in Schwalb (1978) for the TIROS-N satellite were used as the baseline. An additional error representing uncertainties in the surface parameters was added to each channel that was sufficiently transparent to sense the ground. Then all noise values were multiplied by factors of 0.0, 0.25, 0.5, 1.0, 2.0, 3.0 and 4.0 to determine the effect of various levels of noise on the retrievals. Thus, retrievals were computed for a total of $(4 + 4) \times 7 = 56$ combinations of channels and noise levels.

To assure some validity of the results, temperature data for a range of conditions were needed. Four sets of data which typify the January midlatitudinal, January polar, August midlatitudinal and August polar situations were used. Each of the sets contained between 81 and 308 temperature profiles which were obtained from Uddstrom and Wark (1985).

3. Retrieval method

It is an unfortunate fact that when studying tradeoffs among the three design factors cited the outcome is somewhat dependent upon the retrieval algorithm. However, since it is not our objective to compare retrieval methods, and since we are comparing effects arising from changing various instrumental specifications, relative comparisons are sufficient for our purposes. Therefore it is much more important to choose a reasonable retrieval method and keep it fixed than to worry about minor differences in retrieval methods. In other words, we are seeking qualitative conclusions; there are too many possible choices to draw quantitative conclusions.

The retrieval method used in our study is the minimum-RMS method which is described in Weinreb and Crosby (1972). This method was chosen because it is optimal in the sense that, in addition to using the radiance measurements in the inversion of the radiative transfer equation, it uses *a priori* statistics of the atmosphere. Thus, the question addressed when a factor is varied is: What new information does a given set of radiance measurements add to the statistical information already available? Another feature of this retrieval algorithm is that it uses all channels. A retrieval algorithm that is based on an arbitrary decision to use only a subset of the available channels will naturally miss any advantage that the omitted channels may provide.

The statistical information is introduced into the retrieval algorithm through the temperature covariance matrix $\mathbf{T}$ and the corresponding mean profile, both of which are calculated from the temperature data sets described in the previous section. Noise is provided through a noise covariance matrix $\mathbf{N}$. In addition to assuming that the mean of the noise is zero, we assume that the noise is uncorrelated among channels. These assumptions are valid for a relative comparison of instrument noise, since correlated noise caused by clouds would affect all instruments equally. Therefore, **N** is a diagonal matrix with the diagonal elements being set equal to the variance of the noise for each channel.

Using the derivation given in Weinreb and Crosby (1972), we have that the covariance matrix **S** for the optimal solution is given by

$$\mathbf{S} = \mathbf{T} - \mathbf{TA}^{\mathrm{T}}(\mathbf{ATA}^{\mathrm{T}} + \mathbf{N})^{-1}\mathbf{AT} \quad (1)$$

where **A** is the matrix of products of the atmospheric weighting functions arising from the numerical quadrature of the radiative transfer equation and the derivative of the Planck function, and the superscripts T and -1 represent the matrix transpose and matrix inverse operations, respectively.

This solution has several advantages for the kind of study we are conducting:

a) The square roots of the diagonal elements of the matrix **S** are the rms temperature errors over the entire sample set at each pressure level. Consequently, one does not have to retrieve the temperature profiles one at a time and then compute the rms error as is traditionally done. Instead, Eq. (1) is computed once.

b) The mean temperature and radiance vectors are not required; they drop out of Eq. (1) as a consequence of its derivation. This is an advantage because these vectors are data-dependent rather than instrument-dependent. By avoiding the use of mean vectors, one avoids the introduction of extraneous bias errors (Fleming *et al.*, 1983).

c) Results for changes in any of the three design factors we are studying are easily obtained. Changing the FWHM of the weighting functions requires only that the matrix **A** be changed; changes in the number of channels require changing the **A** and **N** matrices; and changes in noise level mean modifying only the matrix **N**.

It is essential that one realize that the rms errors calculated via Eq. (1) are essentially the same as those obtained from the traditional method of calculating rms errors from the ensemble of temperature retrievals on an individual basis. The only difference between the two approaches is that the matrix **A** in Eq. (1) is calculated only once, based on the mean temperature profile of the ensemble, rather than recalculating **A** for each profile in the ensemble. This minor change from the traditional approach linearizes the problem, thereby making possible advantages a through c, while incurring only insignificant errors that are common to all the alternatives. The error in Eq. (1) is small relative to the traditional approach because the matrix **A** is only weakly dependent upon temperature.

For simplicity, the dependences of **A** on water vapor and ozone have been ignored. This has no impact on the conclusions reached because 1) these omissions were made for all the variations of conditions considered in the study and 2) the CO_2 absorption is fundamental while the absorption by the other atmospheric gases plays a secondary role.

4. Results

The data described in Section 2 were applied to Eq. (1) so that the square roots of the diagonal elements of the matrix **S** yielded the rms temperature retrieval errors at the 40 TIROS Operational Vertical Sounder (TOVS) pressure levels (see p. 16 of Weinreb *et al.*, 1981). These 40 rms values were averaged with respect to the logarithm of pressure to produce average rms temperature retrieval errors for the nine 100 mb layers between 100 and 1000 mb. Unfortunately, when these nine error values are multiplied by 56 combinations of channels, FWHMs and noise levels, and by four combinations of season and latitude, one has over 2000 numbers to compare. Therefore, to simplify matters, the nine layer rms error values were collapsed into one value by taking their simple average. These 224 average error values are shown in Table 1 and are consistent with our expectations and earlier results in that the temperature retrieval accuracy increases when:

a) the instrumental noise is reduced,

b) the FWHM of the weighting functions is reduced, and

c) the number of channels is increased.

In addition to confirming earlier results, Table 1 also shows the trade-offs between the various factors. For example, the accuracy of the seven-channel instrument with halved weighting function FWHMs is roughly equivalent to that of the 22-channel instrument with normal weighting functions for the same noise levels.

Because it is difficult to interpret Table 1, we have constructed three additional tables from the given data. In these three new tables, the objective is to examine the trade-offs between design factors. To do this we define "equivalent performance" to occur when for a given statistical data set listed in Table 1 the same average rms error value exists for entries in two different columns. We also define a "noise ratio" to be the ratio of the noise factors in Table 1 associated with any two error entries that have an equivalent performance value (i.e., have the same rms error).

For example, in Table 1 we examine the noise ratios for the January polar data. In the first error column the entry 2.0 has a corresponding noise factor of 0.5, while in the second error column the error value of 2.0 corresponds to a noise factor of 3.0. Consequently, the noise ratio of the seven-channel halved FWHM to the seven-channel normal FWHM is 3.0/0.5 or 6.0. This means that the seven-channel halved FWHM design can have six times the noise of the seven-channel FWHM design and still the two designs have an equivalent performance in terms of their average retrieval errors.

The entries of Table 2 are the noise ratios for the various seasonal and latitudinal data sets when the halved FWHMs are compared with the normal

TABLE 1. Average errors (*K*) for various combinations of noise level, number of channels, and weighting function half-widths (FWHM).

		Number of channels							
		7 ch		14 ch		11 ch		22 ch	
	Noise factor	FWHM normal	FWHM halved	FWHM normal	FWHM halved	FWHM normal	FWHM halved	FWHM normal	FWHM halved
January polar	0	1.8	1.1	1.2	0.7	1.2	0.8	0.9	0.3
	0.25	1.9	1.2	1.7	1.0	1.6	1.0	1.4	0.9
	0.50	2.0	1.3	1.9	1.1	1.8	1.1	1.6	1.0
	1.00	2.2	1.5	2.1	1.3	2.0	1.3	1.9	1.2
	2.00	2.5	1.8	2.3	1.6	2.3	1.6	2.1	1.4
	3.00	2.7	2.0	2.5	1.8	2.5	1.8	2.3	1.6
	4.00	3.0	2.2	2.7	2.0	2.6	2.0	2.4	1.8
January midlatitude	0	1.8	1.2	1.3	0.7	1.6	0.8	1.2	0.4
	0.25	1.9	1.3	1.8	1.1	1.7	1.1	1.5	0.9
	0.50	2.1	1.4	1.9	1.2	1.8	1.2	1.7	1.1
	1.00	2.3	1.5	2.2	1.4	2.0	1.3	1.8	1.2
	2.00	2.5	1.8	2.4	1.6	2.3	1.6	2.1	1.4
	3.00	2.7	2.0	2.6	1.8	2.5	1.7	2.3	1.6
	4.00	2.9	2.2	2.7	2.0	2.6	1.9	2.4	1.7
August polar	0	1.3	1.0	1.1	0.6	1.2	0.7	0.9	0.4
	0.25	1.5	1.0	1.4	0.9	1.3	0.8	1.2	0.7
	0.50	1.6	1.1	1.5	1.0	1.5	0.9	1.3	0.8
	1.00	1.8	1.3	1.7	1.1	1.6	1.1	1.5	1.0
	2.00	2.1	1.5	1.9	1.4	1.9	1.3	1.7	1.2
	3.00	2.3	1.7	2.1	1.5	2.0	1.5	1.9	1.3
	4.00	2.5	1.9	2.3	1.7	2.2	1.6	2.0	1.4
August midlatitude	0	1.4	0.9	1.0	0.6	1.2	0.6	0.9	0.3
	0.25	1.5	0.9	1.4	0.8	1.3	0.8	1.2	0.7
	0.50	1.6	1.1	1.5	0.9	1.4	0.9	1.3	0.8
	1.00	1.8	1.2	1.7	1.1	1.5	1.0	1.4	0.9
	2.00	2.0	1.5	1.9	1.3	1.7	1.2	1.6	1.1
	3.00	2.1	1.6	2.0	1.5	1.9	1.4	1.7	1.2
	4.00	2.2	1.8	2.1	1.6	2.0	1.5	1.8	1.3

FWHMs for a given number of channels. The noise ratios are grouped relative to the noise factor for the normal FWHMs, i.e., for noise factors of 0.25, 0.5 and 1.0. The interesting feature of Table 2 is the consistency of the ratios within each noise factor category. In actuality, the noise ratios are even more consistent than shown in Table 1 because they were based on Table 1 in which the error values were rounded off and the partitioning of the noise factor categories was rather course. The consistency of the noise ratios indicates that the trade-off between noise and the FWHM of the weighting functions is independent of latitude, season and number of channels.

Our interpretation of Table 2 is as follows: When the initial noise factor is 0.25 (0.5, 1.0), an increase in noise level by a factor of around 9.5 (6.5, 4.5) has the same effect on retrieval accuracy as doubling the FWHM of the weighting functions. On the other hand, Table 2 also shows that the noise ratio depends strongly on the initial noise level. In other words, at nominal initial noise levels it takes a much smaller increase in noise level to get a performance equivalent to doubling the FWHM than at the lowest noise level category.

Table 3 is constructed from Table 1 in the same manner as Table 2, except that instead of comparing halved FWHMs with normal FWHMs, we compare the initial number of channels with twice that number. In other words, in Table 3 the noise ratios are presented for the various seasonal and latitudinal data sets when the number of channels is doubled compared with the original number. As in Table 2, the noise ratios are grouped relative to the noise factor for the normal (original) number of channels, i.e., for noise factors of 0.25, 0.5 and 1.0.

Once again, we see very strong consistency of the ratios within each noise-factor category. This indicates that the trade-off between noise and the number of channels is also independent of latitude, season and the FWHM of the weighting functions. The interpretation of Table 3 is that doubling the number of channels is roughly as effective as halving the noise for purposes of improving retrieval accuracy. While there is a small dependence of the noise ratio on the initial noise factor (with effectiveness decreasing as the noise factor increases), the dependence is much smaller than in the case of Table 2.

Finally, Table 4 was derived in the exact manner of Tables 2 and 3, except that here the problem being

TABLE 2. Noise ratios for equivalent performance obtained by halving the FWHMs of the four basic instruments.

	Number of channels			
	7	14	11	22
Noise factor = 0.25				
January polar	10	10	8	8
January midlatitude	8	12	12	10
August polar	8	8	8	8
August midlatitude	8	10	10	12
Noise factor = 0.5				
January polar	6	7	6	6
January midlatitude	7	7	7	8
August polar	5	6	6	6
August midlatitude	6	6	6	8
Noise factor = 1.0				
January polar	4	4.5	4	4.5
January midlatitude	4.5	5	4.5	4.5
August polar	3.5	4	4	4.5
August midlatitude	4	4.5	4	4.5

TABLE 3. Noise ratios for equivalent performance obtained by doubling the number of channels of the four basic instruments.

	Number of channels			
	7–14		11–22	
	FWHM normal	FWHM narrow	FWHM normal	FWHM narrow
Noise factor = 0.25				
January polar	2	3	2	2
January midlatitude	2	3	2	2
August polar	2	2	2	2
August midlatitude	2	2	2	2
Noise factor = 0.5				
January polar	1.5	2	1.7	1.5
January midlatitude	1.7	2	2	2
August polar	1.5	2	2	1.5
August midlatitude	1.5	2	2	2
Noise factor = 1.0				
January polar	1.5	1.7	1.5	1.5
January midlatitude	1.5	1.5	1.7	1.5
August polar	1.5	1.7	1.5	1.5
August midlatitude	1.5	1.5	1.5	1.5

TABLE 4. Noise ratios for equivalent performance obtained by adding four 4.3-μm channels to the original seven 15-μm channels and by doubling that number.

	Number of channels			
	7–11		14–22	
	FWHM normal	FWHM narrow	FWHM normal	FWHM narrow
Noise factor = 0.25				
January polar	3	3	2.7	2
January midlatitude	1.5	2	4	2
August polar	2	3	3	3
August midlatitude	4	2	4	3
Noise factor = 0.5				
January polar	2	2	2	1.5
January midlatitude	2.7	2.7	2.7	2
August polar	2	2	2	2
August midlatitude	1.5	3	3	2
Noise factor = 1.0				
January polar	1.7	1.7	2	1.5
January midlatitude	2	1.7	2.5	2
August polar	1.7	2	2	1.5
August midlatitude	2.5	2	3	2

addressed is the impact of adding four 4.3-μm CO_2 channels. The pattern of the noise ratios in Table 4 is like that of Table 3 but sufficiently different that, upon comparing the ratios in Tables 3 and 4, one can conclude that generally adding four (eight) shortwave channels to the original seven (fourteen) longwave channels is more effective than doubling the number of longwave channels. Reasons for this are given in Section 5.

The results of Tables 2–4 are even more illuminating when they are considered in terms of limiting factors. In particular, it is clear from Table 2 that, as the noise factor becomes large, it tends to become more important in determining the final accuracy as indicated by the change in the noise ratios from 9.5 for low noise levels to 4.5 for higher levels. In addition, instruments can be designed with less noise or more channels, but FWHMs are relatively fixed. For current instruments such as HIRS, the FWHM should be the limiting factor since it is the one factor not easily changed. In addition, since noise and number of channels are both more easily changed, a design should be optimal when values for these two factors are chosen so that their effects on retrieval accuracy are nearly equal. Tables 2–4 show that these expectations for an optimal design are met.

They show that FWHM is the most important parameter and noise level and number of channels are less important than FWHM and equal to each other. The equivalence of the effects of noise and channel number is illustrated by the fact that the values in Table 3 become approximately unity when they are normalized by dividing by two to account for the factor 2.0 increase in channel number.

5. Conclusions

Table 1 illustrates the interrelationships among noise levels, number of channels and the FWHMs of the weighting functions for typical combinations of infrared channels. While trade-off information can be extracted from that table, the situation is more tractable if the information is broken out in the form of equivalent performance based on noise ratios as is done in Tables 2–4. Table 2 shows the trade-off between noise and narrowing the FWHMs; Table 3 illustrates the trade-off between noise and increasing the number of channels and from Table 4 one can see the effectiveness of adding channels from a different spectral band.

More specifically, Table 4 demonstrates that the shape of the weighting functions also plays a role in their effectiveness in increasing retrieval accuracy. For example, the seven longwave channels that were added to the original seven had the same shaped weighting functions as the original seven; whereas the additional four shortwave channels had somewhat differently shaped weighting functions from the original seven. Since the latter additional four channels had a greater positive impact than the former seven additional channels, one can assume that the shape of the weighting function also plays a role in retrieval accuracy. However, one must also keep in mind that the nominal noise levels of the additional shortwave channels also are different from those of the additional longwave channels as is the location of the weighting functions in the atmosphere.

As an aside, it is interesting to note that for the zero noise case (exact measurements), the role of number of channels and their distribution and shapes of weighting functions is reversed. In the noise free case of Table 1, the 14-channel cases generally are more accurate than the 11-channel cases.

Of course, the ultimate objective of this study is to relate the findings to the design of sounding instruments. For example, the normal FWHMs of the weighting functions used in our study are typical of filter radiometers such as the currently operational HIRS instrument. On the other hand, when the FWHM is halved it represents close to the theoretically achievable limit for a monochromatic measurement. These narrow widths can be achieved only with a spectrometer or interferometer. Thus the narrowness of the FWHM of the weighting function is an advantage that is intrinsic to these types of sounders.

Conversely, the narrowing of the weighting function usually is accompanied by some other negative effect. In the case of the HIS, the weighting functions become negative for parts of the atmosphere while the AMTS becomes severely limited in input energy and thus subject to increased noise. Although the AMTS recovers some of the signal to noise ratio over a filter design because each channel is viewing continuously, additional noise reduction is necessary. This can be accomplished by

a) increasing integration time,
b) decreasing detector area,
c) increasing detector sensitivity,
d) increasing the viewed solid angle,
e) increasing the area of the collecting optics,
f) increasing the overall transmission of the radiometer,
g) averaging fields of view.

Unfortunately, all seven of these compensations are extrinsic in that they are not unique to a particular instrument technology. In others words, all of these improvements are available to any type of radiometer.

Hence, it is quite likely that a less than optimum design can be selected if the designs are not properly compared. As an example, a radiometer that minimizes the FWHM of the weighting function may need to compensate for the increase in noise by cooling the detector and the instrument. If the radiometer that minimizes the FWHM is compared with a current filter design, it may well provide more accurate results. However, when the instrument with narrower FWHM and the enhanced cooling it requires is compared with a filter design with equivalent cooling, it may no longer have an advantage in retrieval accuracy. This is because, if the cooler is also applied to the filter radiometer, there will be an increase in accuracy due to its lower noise levels.

Similar arguments can be made for the number of channels used in doing soundings. Both spectrometers and interferometers have the intrinsic advantage over filter radiometers of potentially providing larger numbers of channels. However, from a practical point of view, only a small subset of these channels can be used because of the lack of mathematical independence among weighting functions placed too close together (statistically, the channels are too highly correlated) relative to the noise level.

We conclude that, since different satellite instruments differ in terms of both intrinsic and extrinsic design features, a simple comparison of a new design with an old instrument is not sufficient to evaluate a new design. This is true because the extrinsic differences are often the result of advances in technology which could improve the performance of the old design as well. Instead, a careful evaluation of the differences is required in which only the intrinsic features differ. Although this is more difficult to do, it is the only way to assure that the best instrument is selected. Failure to consider and equalize extrinsic factors could easily have the effect of causing designers to vacillate between alternatives as technology improves. While the results of our study provide some general guidelines for evaluating instruments based on current technology, our study is not a substitute for a proper evaluation when specific instruments are being considered. Of course, a proper evaluation includes the consideration of all three design factors since consideration of only one or two can easily lead to the wrong conclusions.

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