

# A Comprehensive Evaluation Approach of Navigation Signal Performance Based on Multi-attribute Group Decision Making

Qing Liu, Yanhong Kou and Zhigang Huang

**Abstract** In the process of comprehensive performance evaluation of new-structure satellite navigation signals, some problems may be encountered including the wide varieties of performance indicators/attributes, the lack of a clear attribute system, the complex relationships and strong correlations among different attributes, the differences in user preferences of the significances of various attributes, and so on. Based on the comparative analysis of different models and methods for the fuzzy multi-criteria Group Decision Making (GDM) problems, this paper proposes a comprehensive signal performance evaluation approach that integrates multiple methods seamlessly. Firstly, a three-level signal attribute system is established based on Analytic Hierarchy Process (AHP). Next, the attributes at the bottom level are decorrelated and reconstructed by Fuzzy Clustering and Principal Component Analysis (PCA). Then the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is employed to obtain the Relative Membership Degree (RMD) of each alternative signal option to each attribute unit. Finally, the overall performance of each alternative is calculated using the multi-attribute GDM model. The evaluation of six alternative modulations for GPS L1C signals based on theoretical analysis demonstrates the feasibility and effectiveness of the proposed approach. The approach provides an efficient means for the comprehensive performance evaluation of satellite navigation signals.

**Keywords** Satellite navigation signal · Multi-attribute group decision making · AHP · PCA · TOPSIS · Fuzzy clustering

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## 1 Introduction

With the development of Global Navigation Satellite System (GNSS), various novel navigation signal structures have been proposed. Signal structure design is one of key tasks of GNSS design, and the scientific and comprehensive performance evaluation of different signal structures becomes of great importance for the achievement of function and performance goals of GNSS services.

Multi-criteria/multi-attribute decision making (MCDM/MADM) approaches have been widely applied in the fields of military affairs, transportation, healthcare, mining, hydraulic engineering, and so forth [1–7]. Nevertheless, few literatures can be found about applying these approaches in the evaluation of GNSS signal performances. Several related methods for GNSS signal performance evaluation have been mentioned/studied in [8], including the radar chart method, the expert scoring method, the linear weighting method, and the weighted Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). These methods, however, need to be improved due to their inefficiency of dealing with subjectivity, lack of consideration of correlations among the attributes, or lack of quantitative analysis.

In order to solve these problems, this paper first establishes a hierarchical attribute system for satellite navigation signals. The signal attribute system can be divided into the following three levels: (1) The bottom level is composed of all the computable/measurable performance indicators, i.e., the attributes; (2) The middle level classifies these attributes into several groups, with one group named as an Attribute Unit (AU); (3) The top level forms the Group Decision Making (GDM) target and represents the overall performance of the signal. Then a fuzzy comprehensive evaluation approach is explored to act as the technical means for the optimal selection of signal alternatives, which takes advantage of Analytic Hierarchy Process (AHP), Principal Component Analysis (PCA), Fuzzy Clustering and weighted TOPSIS appropriately. Finally, taking six GPS L1C signal modulation alternatives as a case study [9], the evaluation results select the TMBOC (6,1,4/33) modulation meeting with the interface specification document IS-GPS-800.

## 2 Methodology

The proposed evaluation approach includes the following three steps: (1) to establish the three-level architecture of the signal attribute system for AHP; (2) to calculate the Relative Membership Degree (RMD) of each alternative signal option with respect to each AU; (3) to calculate the overall RMD of each alternative signal option.

## 2.1 *Signal Attribute System*

There is a wide range of attributes indicating different performances of satellite navigation signals. On the other hand, the relative importance of these attributes can vary significantly for different users and applications. As one of the most popular analytical techniques for complex decision making problems, AHP is firstly considered in our methodology to well characterize the signal option decision situation and efficiently incorporate objective as well as subjective attributes into the decision. Taking account of the definition, application requirements, and relevance of these attributes, as well as the summary of available theoretical data and test data for different signal options, a three-level signal attribute system is established for the decision making among different signal alternatives, as shown in Fig. 1. The specific attributes corresponding to the raw measurement/analysis data fall into the bottom level. The second level attributes can be obtained by classifying the first-level attributes with similar characteristics into an AU, such as the anti-interference capability, the measurement accuracy, the receiving threshold, and so forth. The third (top) level is the overall performance indicator corresponding to the evaluation result. This hierarchical architecture helps to reduce the workload, difficulty, subjectivity, and arbitrariness for the Experts, User representatives, and Decision makers (EUD) to assign weights to different attributes because only a few second-level attributes need to be weighted or, more simply, pairwise compared according to the application preferences.

## 2.2 *Fuzzy Optimization Model of One AU*

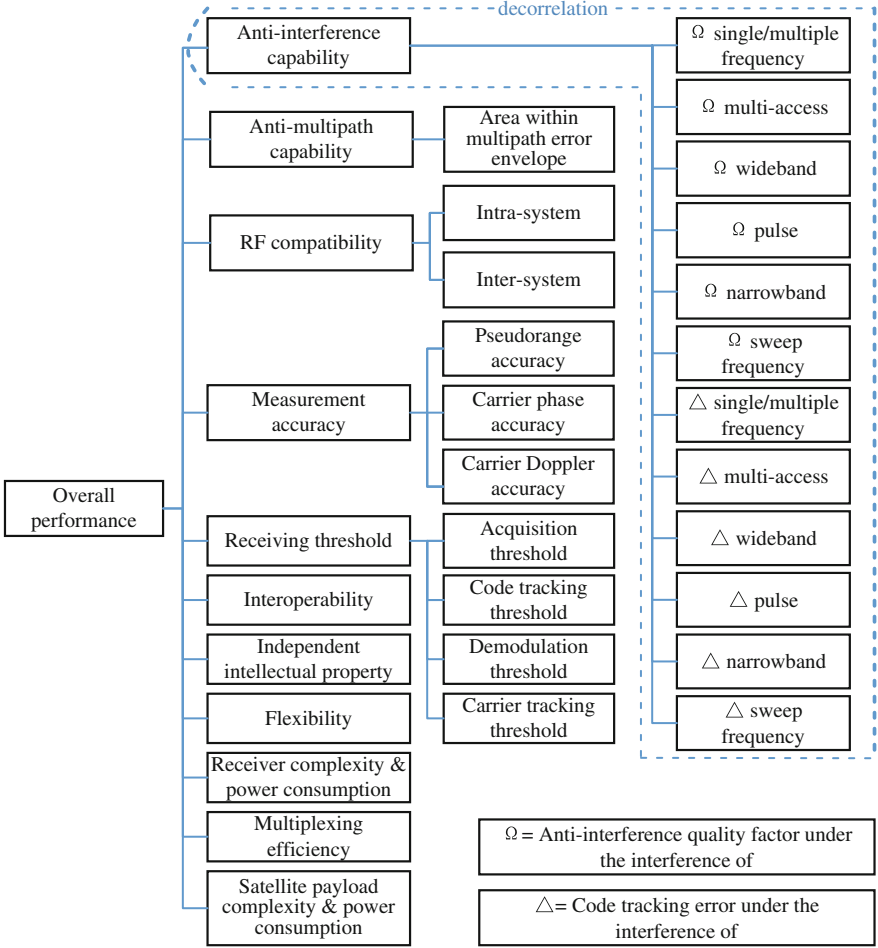
The fuzzy optimization model of one AU includes the following two steps: decorrelation of the attributes and calculation of the RMD of each alternative to each AU.

### 2.2.1 *Decorrelation of Attributes*

Correlations among the attributes can be captured and reduced by employing fuzzy clustering and PCA.

#### *AU Fuzzy Clustering*

The attribute value (measured/calculated/estimated data) matrix for the decision problem with  $m$  attributes of the  $k$ th AU and  $n$  alternatives can be expressed as Eq. (1):



**Fig. 1** Attribute system of satellite navigation signal

$${}_{1k}X = \begin{bmatrix} {}_{1k}X_{11} & {}_{1k}X_{12} & \cdots & {}_{1k}X_{1m} \\ {}_{1k}X_{21} & {}_{1k}X_{22} & \cdots & {}_{1k}X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ {}_{1k}X_{n1} & {}_{1k}X_{n2} & \cdots & {}_{1k}X_{nm} \end{bmatrix} = ({}_{1k}X_{ij})_{n \times m} \quad (1)$$

where  $i = 1, 2, \dots, n$ ;  $k = 1, 2, \dots, t$ ;  $j = 1, 2, \dots, m$ ;  ${}_{1k}X_{ij}$  denotes the attribute value at the first level.

To make the attributes dimensionless and larger-the-better, the raw attribute value matrix can be normalized as follows:

$${}_{1k}X' = \begin{bmatrix} {}_{1k}X'_{11} & {}_{1k}X'_{12} & \cdots & {}_{1k}X'_{1m} \\ {}_{1k}X'_{21} & {}_{1k}X'_{22} & \cdots & {}_{1k}X'_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ {}_{1k}X'_{n1} & {}_{1k}X'_{n2} & \cdots & {}_{1k}X'_{nm} \end{bmatrix} = ({}_{1k}X'_{ij})_{n \times m} \quad (2)$$

where

$${}_{1k}X'_{ij} = \frac{{}_{1k}X_{ij} - \overline{{}_{1k}X_j}}{{}_{1k}S_j} \quad \text{if attribute } j \text{ is a utility-type attribute} \quad (3)$$

$${}_{1k}X'_{ij} = 1 - \frac{{}_{1k}X_{ij} - \overline{{}_{1k}X_j}}{{}_{1k}S_j} \quad \text{if attribute } j \text{ is a cost-type attribute} \quad (4)$$

$$\begin{aligned} \overline{{}_{1k}X_j} &= \frac{1}{n} \sum_{i=1}^n {}_{1k}X_{ij} \\ {}_{1k}S_j &= \sqrt{\frac{1}{n} \sum_{i=1}^n ({}_{1k}X_{ij} - \overline{{}_{1k}X_j})^2} \end{aligned} \quad (5)$$

The correlation matrix of Eq. (2) is calculated as

$${}_{1k}R = ({}_{1k}r_{ij})_{m \times m}, \quad {}_{1k}r_{ij} = \frac{\text{cov}({}_{1k}X_i, {}_{1k}X_j)}{\sqrt{D({}_{1k}X_i)D({}_{1k}X_j)}} \quad (6)$$

Generally, since  ${}_{1k}R$  is not a fuzzy equivalent matrix, its transitive closure  ${}_{1k}R'$  should be further computed. By comparing the elements of  ${}_{1k}R'$  with a threshold  ${}_{1k}\lambda$ , a matrix  ${}_{1k}R'_\lambda$  with binary elements (0 or 1) is obtained. The attributes with value of 1 in one row/column can be classified into the same cluster.

The clustering results depend on the value of  ${}_{1k}\lambda$ . Assuming that  ${}_{1k}R'_\lambda$  divides one AU into  $m_k$  clusters,  $c_1, \dots, c_l, \dots, c_{m_k}$ , where  $c_l$  ( $l = 1, \dots, m_k$ ) represents the  $l$ th cluster, the evaluation objective function of  ${}_{1k}\lambda$  can be estimated by Wang et al. [6]:

$${}_{1k}S = {}_{1k}\delta / {}_{1k}L \quad (7)$$

where  ${}_{1k}\delta$  is the average Hamming distances [10] between the cluster centers and all the sample attributes,  ${}_{1k}L$  is the minimum distance between different cluster centers. By choosing the best  ${}_{1k}\lambda$  corresponding to the smallest  ${}_{1k}S$ , efficient and reasonable clustering can be achieved.

#### Construction of Composite Attribute of Each Cluster based on PCA

After the process of fuzzy clustering, it is essential to construct a new attribute for each cluster, which represents the composite performance of all the attributes in the cluster. The attribute values of the  $l$ th cluster of the  $k$ th AU are regrouped as

$${}_{1k}X'' = \begin{Bmatrix} {}_{1k}x''_{11} & \cdots & {}_{1k}x''_{1m_c} \\ \vdots & \ddots & \vdots \\ {}_{1k}x''_{n1} & \cdots & {}_{1k}x''_{nm_c} \end{Bmatrix} \quad (8)$$

where  $n$  is the number of the alternatives,  $m_c$  is the number of the attributes in this cluster,  ${}_{1k}x''_{ij}$  keeps the attribute value of  ${}_{1k}x'_{ij}$  in Eq. (2) and is reordered in the cluster. Normalizing Eq. (8) leads to  ${}_{1k}Z = ({}_{1k}z_{ij})_{n \times m_c}$ , where

$${}_{1k}z_{ij} = \frac{{}_{1k}x''_{ij} - \overline{{}_{1k}x''_j}}{{}_{1k}s''_j} \quad (9)$$

And

$$\begin{aligned} \overline{{}_{1k}x''_j} &= \frac{1}{n} \sum_{i=1}^n {}_{1k}x''_{ij} \\ {}_{1k}s''_j &= \sqrt{\frac{1}{n} \sum_{i=1}^n ({}_{1k}x''_{ij} - \overline{{}_{1k}x''_j})^2} \end{aligned}$$

Thus the  $j$ th column vector of the normalized matrix has a zero mean and a unit variance  $E({}_{1k}Z_j) = 0$ ,  $D({}_{1k}Z_j) = 1$ .

The correlation matrix of  ${}_{1k}Z$  is

$${}_{1k}R_z = ({}_{1k}r_{ij})_{m_c \times m_c} = \frac{1}{n-1} {}_{1k}Z^T {}_{1k}Z \quad (10)$$

$${}_{1k}r_{ij} = \text{cov}({}_{1k}Z_i, {}_{1k}Z_j) \quad (11)$$

Assuming that  ${}_{1k}R_z$  has  $q$  eigenvalues greater than zero  $(\lambda_1, \lambda_2, \dots, \lambda_q)$ ,  $\lambda_i > 0$ , and the corresponding orthonormal eigenvectors are  $A = (a_1, a_2, \dots, a_q)$ ,  $q$  principal components can be computed by

$$\begin{aligned} Y_{n \times q} &= (y_1, y_2, \dots, y_q) = {}_{1k}Z_{n \times m_c} A_{m_c \times q} \\ \begin{bmatrix} y_{11} & \cdots & y_{1q} \\ \vdots & \ddots & \vdots \\ y_{n1} & \cdots & y_{nq} \end{bmatrix} &= \begin{bmatrix} {}_{1k}z_{11} & \cdots & {}_{1k}z_{1m_c} \\ \vdots & \ddots & \vdots \\ {}_{1k}z_{n1} & \cdots & {}_{1k}z_{nm_c} \end{bmatrix} \begin{bmatrix} a_{11} & \cdots & a_{1q} \\ \vdots & \ddots & \vdots \\ a_{m_c 1} & \cdots & a_{m_c q} \end{bmatrix} \end{aligned} \quad (12)$$

As indicated by Yu [11], the principal components in Eq. (9) are independent

$$\text{cov}(y_i, y_j) = \begin{cases} 0 & i \neq j \\ \lambda_i & i = j \end{cases} \quad (13)$$

The contribution of the principal component  $y_i$  to the total variance is estimated as

$$\omega_i = \lambda_i / \sum_{j=1}^q \lambda_j \quad (14)$$

Ranking  $y_1, y_2, \dots, y_q$  in the descending order of  $\omega_1 > \omega_2 > \dots > \omega_q$ , the cumulative variance contribution of the first  $m_\rho$  principal components is:

$$\rho = \sum_{i=1}^{m_\rho} \lambda_i / \sum_{j=1}^{m_c} \lambda_j \quad (15)$$

Different value of  $\rho$  yield different reconstructed attribute  $x_l^{new} = \sum_{i=1}^{m_\rho} \omega_i y_i$  as the composite performance evaluation of the  $l$ th cluster. In addition, large  $\rho$  allows more information kept in the newly constructed attribute.

If several clusters have been generated in the fuzzy clustering process for an AU, the above process should be repeated to reconstruct a separate attribute for each cluster.

### 2.2.2 Calculation of RMD to Each AU Based on Weighted TOPSIS

After the decorrelation of the attributes, a new attribute value matrix  $(1_k x^{new})_{n \times m_k}$  for the  $k$ th AU is obtained. The weights of these reconstructed attributes can be determined by Wang [2]

$$1_k \omega_j = \sum_{i=1}^n 1_k r r_{ij}^{new} / \sum_{i=1}^n \sum_{j=1}^{m_k} 1_k r r_{ij}^{new} \quad (16)$$

where  $1_k \omega_j$  denotes the weight of the  $j$ th attribute of the  $k$ th AU, and  $1_k r r_{ij}^{new} =$

$\frac{1_k x_{ij}^{new} - \min_i \{1_k x_{ij}^{new}\}}{\max_i \{1_k x_{ij}^{new}\} - \min_i \{1_k x_{ij}^{new}\}}$  is the RMD of  $1_k x_{ij}^{new}$ . Using this objective weighting method, the trouble and arbitrariness of subjective weighting of a large number of attributes can be avoided.

According to the optimization rule of minimizing the sum of squares of the weighted distances to both the ideal and negative ideal solutions, the RMD of the  $i$ th alternative to the  $k$ th AU can be calculated by Wang [12]

$$u_{ik} = 1 / \left( 1 + \left\{ \sum_{j=1}^{m_k} [\omega_j (1 - 1_k r r_{ij}^{new})] / \sum_{j=1}^{m_k} [\omega_j \cdot 1_k r r_{ij}^{new}] \right\}^2 \right) \quad (17)$$

Equation (17) is the fuzzy optimization result representing the composite performance of each alternative to one AU. For an AU without decorrelation process, the same process of weighting and calculation of the RMD as shown Eqs. (16)–(17) can be conducted.

### 2.3 Multi-level Multi-attribute GDM Model

This model will output the final evaluation results by performing the following two steps: (1) assembly of the weights of attributes at the second level of AHP according to the judgements of all the EUDs; (2) calculation of the overall performance RMD of each alternative signal option.

#### 2.3.1 Group Decision of Weights of AUs

In the previous section, one attribute for one AU has been obtained. The  $t$  attributes at the second level of signal attribute system are denoted as  $O = \{o_1, o_2, \dots, o_t\}$ . Scaling the relative importance of the attributes using the Fuzzy degree value defined in Table 1, the Pairwise Comparison Matrix (PCM) [13] can be obtained

$$\beta = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1t} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{t1} & \beta_{t2} & \cdots & \beta_{tt} \end{bmatrix} \quad (18)$$

where  $\beta_{kl} = 1 - \beta_{lk}$  denotes the importance fuzzy degree of  $o_k$  relative to  $o_l$ . When  $o_k$  is more important than  $o_l$ ,  $0.5 < \beta_{kl} < 1$ ; when  $o_k$  and  $o_l$  are of the same importance,  $\beta_{kl} = 0.5$ ; Otherwise  $0 < \beta_{kl} < 0.5$ .

The mood operators in Table 1 comes from the judgments of the EUDs. Since the navigation signals of different frequencies lay particular stress on different applications, different EUDs may be endowed with different weights for a specified signal. Assuming that  $\alpha_k$  ( $k = 1, \dots, p$ ) is the weight of the  $k$ th EUD and  $\beta_k$  represents the PCM given by the  $k$ th EUD, the  $p$  PCMs can be assembled by linear weighting

$$\bar{\beta} = \sum_{k=1}^p \alpha_k \beta_k \quad (19)$$

**Table 1** Pairwise comparison scale of attributes according to mood operator

MO of the relative importance	Equally	Slightly more	Moderately more	Strongly more	Extremely more	Absolutely
FD	0.50	0.60	0.70	0.80	0.90	0.10

*Annotation* “MO” represents “mood operator”, “FD” represents “fuzzy degree”



The normalized sum of a row in the matrix  $\bar{\beta}$  represents the relative importance of the corresponding attribute

$$W'_i = \sum_{j=1}^t \bar{\beta}_{ij}, \quad i = 1, 2, \dots, t; \quad i \neq j \quad (20)$$

$$W_i = W'_i / \sum_{i=1}^t W'_i \quad (21)$$

Thus the weight vector of the  $t$  AUs is  $W = (W_1, W_2, \dots, W_t)^T$ .

### 2.3.2 Calculation of Overall Performance RMD

Now that the RMD of each alternative corresponding to each AU has been given by Eq. (17) and the weight of each attribute given by Eq. (23), the final decision making vector can be obtained by simple linear weighting

$$U_{n \times 1} = \begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_n \end{bmatrix} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1t} \\ u_{21} & u_{22} & \cdots & u_{2t} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & \cdots & \cdots & u_{nt} \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_t \end{bmatrix} \quad (22)$$

where  $u_{ij}$  is the RMD of the  $i$ th alternative corresponding to the  $j$ th AU;  $U_i$  is the overall performance RMD of the  $i$ th alternative. So, the alternative with the maximum value of  $U_i$  represents the optimal signal option with the best overall performance.

## 3 Case Study

Taking the selection of GPS L1C signal modulation scheme as a case study, this section shows the evaluation process of the following six signal modulation options: BPSK(1), BPSK(2), BOC(1,1), TMBOC(4,1,4/33), TMBOC(5,1,4/33), and TMBOC(6,1,4/33). The raw value of each attribute is only based on theoretical calculation, with the preconditions and the attribute values shown in Tables 2 and 3 respectively. Note that only parts of the attributes in Fig. 1 have been taken into account. As shown in the first column of Table 3, the attributes have been grouped into six AUs. Additionally, the interoperability performance is calculated using the method proposed by Liu [14], and other attribute values are obtained according to the methods introduced in [15].

**Table 2** Preconditions of theoretical calculation of signal performance

Parameter	Considerations	Value
Front-end bandwidth	Main lobe bandwidth of the signal	Main lobe bandwidth
Correlator spacing	$d < v/(2u)$	0.08 chip
DLL bandwidth	Typical receiver design	1 Hz
PLL bandwidth	Typical receiver design	15 Hz
Integration time	One code period	10 ms
Carrier to noise ratio (C/N0)	Nominal signal power level and thermal noise background	44 dB-Hz
Multipath to direct path ratio (MDR)	Typical value for test and analysis	-6 dB
L1 C/A signal power	Typical value for test and analysis of intra-system RF compatibility	-128.5 dBm
Interference to signal power ratio ( $C_I/C_s$ )	Typical value for test and analysis	40 dB
Interference	Typical parameters for test and analysis	Wideband: bandwidth covering signal main lobe
		Narrowband: 5 % of the main lobe bandwidth
		Pulse: 2 ms period, 200 us duration
		Single frequency: center frequency of the signal
		Sweep frequency: 1 kHz step, 1 ms period

Annotation “v” and “u” are originated from  $BOC(u, v)$  signal parameters

The PCMs given by four user representatives has been assembled into

$$\beta = \begin{pmatrix} 0.5 & 0.45 & 0.6 & 0.25 & 0.35 & 0.65 \\ 0.55 & 0.5 & 0.65 & 0.3 & 0.4 & 0.7 \\ 0.4 & 0.35 & 0.5 & 0.15 & 0.25 & 0.55 \\ 0.75 & 0.7 & 0.85 & 0.5 & 0.6 & 0.9 \\ 0.65 & 0.6 & 0.75 & 0.4 & 0.5 & 0.8 \\ 0.35 & 0.3 & 0.45 & 0.1 & 0.2 & 0.5 \end{pmatrix} \quad (23)$$

Thus the weight vector of the 6 AUs is:

$$\omega = (0.1556 \quad 0.1722 \quad 0.1222 \quad 0.2389 \quad 0.2056 \quad 0.1056) \quad (24)$$

The 12 anti-interference attributes of the first AUs in Table 3 need to be decorrelated and reconstructed. According to Eqs. (2)–(6), the correlation matrix of the 12 raw attributes is

**Table 3** Theoretical value of each attribute

Modulation	BPSK	BPSK	BOC	TMBOC	TMBOC	TMBOC
Attribute	(1)	(2)	(1,1)	(4,1,4/33)	(5,1,4/33)	(6,1,4/33)
$\Delta$ wideband (m)	12.78	4.00	3.17	0.86	0.66	0.54
$\Delta$ narrowband (m)	0.38	0.97	0.22	0.21	0.18	0.18
$\Delta$ single frequency (m)	1.37	0.59	5.99	1.56	1.24	1.05
$\Delta$ multi-access (m)	12.78	4.008	4.22	1.16	0.96	0.78
$\Delta$ pulse (m)	1.73	0.62	0.49	0.23	0.20	0.18
$\Delta$ multi-frequency (m)	2.53	4.11	1.03	1.00	0.78	0.39
$\Omega$ wideband	1.50	1.50	4.02	6.80	7.86	8.93
$\Omega$ narrowband	10.04	10.04	24.75	11.15	9.40	8.17
$\Omega$ single frequency	1	1	2.47	2.71	2.71	2.71
$\Omega$ multi-access	1.50	1.50	3.03	3.59	3.58	4.50
$\Omega$ pulse	1	1	2.24	2.47	2.47	2.47
$\Omega$ sweep frequency	43.31	43.32	45.70	42.18	41.74	41.49
Area within multipath error envelope (chip · m)	5.72	5.72	3.66	2.38	2.39	1.82
RF compatibility (dB)	0.14	0.10	0.09	0.07	0.07	0.06
Code tracking jitter (m)	0.92	0.46	0.38	0.16	0.14	0.14
Carrier tracking jitter (°)	1.98	1.98	1.98	1.62	1.62	1.62
Code tracking threshold (dB-Hz)	31.6	31.9	25.1	19.6	19.2	19.2
Carrier tracking threshold (dB-Hz)	26.47	26.47	26.47	24.73	24.73	24.73
Interoperability	0.32	0.33	0.57	0.57	0.57	0.57

*Annotation* “ $\Delta$ ” represents “code tracking jitter under the interference of”; “ $\Omega$ ” represents “anti-interference quality factor under the interference of”

$${}_{11}R = \begin{pmatrix} 1 & 0.280 & 0.036 & 0.997 & 1.000 & 0.528 & 0.804 & -0.053 & 0.788 & 0.798 & 0.789 & -0.361 \\ 0.280 & 1 & -0.347 & 0.246 & 0.280 & 0.956 & 0.796 & 0.108 & 0.802 & 0.796 & 0.802 & -0.204 \\ -0.036 & -0.347 & 1 & 0.043 & -0.054 & -0.308 & -0.214 & -0.931 & -0.342 & -0.248 & -0.335 & -0.815 \\ 0.997 & 0.246 & 0.043 & 1 & 0.995 & 0.498 & 0.783 & -0.124 & 0.757 & 0.774 & 0.759 & -0.422 \\ 1.000 & 0.280 & -0.054 & 0.995 & 1 & 0.530 & 0.803 & -0.038 & 0.790 & 0.799 & 0.791 & -0.344 \\ 0.528 & 0.956 & -0.308 & 0.498 & 0.530 & 1 & 0.926 & 0.042 & 0.924 & 0.932 & 0.924 & -0.293 \\ 0.804 & 0.796 & -0.214 & 0.783 & 0.803 & 0.926 & 1 & 0.006 & 0.991 & 0.997 & 0.992 & -0.378 \\ -0.053 & 0.108 & -0.931 & -0.124 & -0.038 & 0.042 & 0.006 & 1 & 0.143 & 0.026 & 0.136 & 0.898 \\ 0.788 & 0.802 & -0.342 & 0.757 & 0.790 & 0.924 & 0.991 & 0.143 & 1 & 0.991 & 1.000 & -0.249 \\ 0.798 & 0.796 & -0.248 & 0.774 & 0.799 & 0.932 & 0.997 & 0.026 & 0.991 & 1 & 0.991 & -0.346 \\ 0.789 & 0.802 & -0.335 & 0.759 & 0.791 & 0.924 & 0.992 & 0.136 & 1.000 & 0.991 & 1 & -0.256 \\ -0.361 & -0.204 & -0.815 & -0.422 & -0.344 & -0.293 & -0.378 & 0.898 & -0.249 & -0.346 & -0.256 & 1 \end{pmatrix}$$

(25)

It can be seen that about 50 % of the elements in Eq. (25) are larger than 0.7. In the process of fuzzy clustering the minimal  ${}_{11}S = 0.178$  (with  ${}_{11}\delta = 1.49$  and  ${}_{11}L = 8.361$ ) can be achieved when using  ${}_{11}\lambda = 0.7$ . Consequently, two clusters for the anti-interference AU are generated from the raw 12 attributes. With one attribute

reconstructed for one cluster by employing PCA, the correlation matrix of the new attribute value matrix  $({}_{11}x^{\text{new}})_{6 \times 2}$  becomes

$${}_{11}R^{\text{new}} = \begin{pmatrix} 1.0 & -0.25 \\ -0.25 & 1.0 \end{pmatrix} \quad (26)$$

It can be seen that the fuzzy clustering and PCA can effectively mitigate the correlation among the attributes and reduce the number of attributes as well.

The RMDs of the six AUs are calculated using weighted TOPSIS as introduced in Sect. 2.2, and then incorporated into the multi-level multi-attribute GDM model in Sect. 3. The overall performance RMD vector of the six alternatives is

$$U = (0.21 \quad 0.3094 \quad 0.3064 \quad 0.8281 \quad 0.8258 \quad 0.8521) \quad (27)$$

Equation (27) ranks the six signal modulation options as follows: {TMBOC(6,1,4/33), TMBOC(4,1,4/33), TMBOC(5,1,4/33), BPSK(2), BOC(1,1), BPSK(1)}. The selected TMBOC(6,1,4/33) modulation coincides with the GPS LICP signal specification in the IS-GPS-800 document.

It is important to note that the short-list of signal attributes and the values of the attributes affect the evaluation results directly. Not all the signal attributes have been considered, and only the attribute values theoretically calculated with the ideal channel assumptions are inputted to the evaluation process of the case study. In practical applications, the signal performances will be degraded by channel imperfections to different extents for different signal structures. Nevertheless, the proposed evaluation approach is still applicable to the comprehensive performance evaluation of signal structures if complete attributes and practical values of attributes are incorporated. In addition to theoretical data, the testing or measured data of signal performances can also serve as the raw attribute values.

## 4 Conclusion

This paper has proposed a multi-attribute GDM approach for the comprehensive evaluation of the overall performances of satellite navigation signal options. The approach is an organic combination of AHP, fuzzy clustering, PCA, weighted TOPSIS, and GDM. On account of the complexity of raw signal attributes, a hierarchical attribute system has been established for using AHP to characterize the situation and efficiently incorporate objective and subjective factors into the decision. Correlations among the attributes are captured and reduced by fuzzy clustering and PCA. The subjective weighting necessary for the group decision-making is conducted by pairwise comparison of the relative importance of a few attribute units. The evaluation process of six GPS L1C signal modulation options has been shown as a case study. The proposed approach can mitigate the workload, difficulty,

subjectivity, and arbitrariness, and provide an effective means for comprehensive performance evaluation of satellite navigation signal options.

Some limitations in this paper and future work should be pointed out here: (1) Including more signal attributes will improve the reliability of the evaluation results, such as the receiver/payload complexity and power consumption, whereas the calculation and estimation of the attribute values are still under investigation. (2) The change of attribute values with different preconditions should also be included in the evaluation process, especially the degradations of signal performances under various imperfections of satellite payload, propagation, and receiver channels. (3) Reasonable integration of theoretical analysis, real measurements, and special test data is also worth exploring.

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