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Reliability of Sensors Fusion in a Satellite Used for Earthquake Prediction

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Abstract

The reliability of sensors fusion for earthquake satellite prediction is the subject, which will estimate in this paper. Using different sensors in the satellite and fusion of their information will be more helpful for earthquake prediction. In this paper different types of passive and active sensors will review and then with use of FMECA analysis, reliability of each sensor type will calculate and finally reliability of sensors fusion will estimate. Depend on the type of satellite and its mission; different sensors fusion will be used. With the results of this paper, one can choose reliable sensors fusion according to its procedure for earthquake prediction with satellite. The results has shown that using passive microwave sensors with active Synthetic Aperture Radar in earthquake prediction satellite will give the best reliability among other sensors fusion with respect to satellite mission.

Keywords: *reliability- sensors fusion- earthquake- FMECA- critically analysis.*

Introduction

Management of earthquakes as an important natural disaster for high seismic regions is regarded as a critical task. Therefore, definition of high risk seismic regions and prediction of the earthquake is very important. By precise prediction of earthquakes, the hazards and loss of lives and properties would be effectively controlled. Many seismic, geodetic, electromagnetic and biologic earthquake precursors have been reported but scientific communities have often been in doubt about the usefulness of short term earthquake precursors because of the lack of a reliable mechanism for the sources of these precursors.

Satellite remote sensing, which is the monitoring, evaluation and prediction of the resources and features of the earth's surface and its atmosphere from satellites, is an exciting, fast-growing technique used by environmental scientists to improve their knowledge of our planet. These information are used to search for undiscovered mineral resources, to conduct population, land use and resource censuses, to control pests and pollution, to illustrate weather movements on television as well as the application of satellite remote sensing in the study of vegetation, land use, geology, soils, the atmosphere and the hydrosphere.

In 1960, remote sensing was named as a distinctive field of study, or a set of approaches to the human environment. Remote sensing has been used for earthquake research from the ‘70s, with the first appearance of satellite images. A few reviews have covered the field of satellite data applications for natural hazards [1-2]. Only some of them were concentrated on earthquake research [3]. First of all it was used in structural geological and geomorphological research. Active faults and structures were mapped on the base of satellite images [4]. This method is very limited in time series analysis. There was no possibility to measure short term processes before and after the earthquake.

Detecting anomalies in non-stationary signals has valuable applications in many fields especially predicting earthquakes via seismographic data. In [5], two approaches named artificial neural network (ANN) and perspective neural network (PNN) is used to anomaly detection and see how data fusion methods may improve performance.

Wireless sensor networks (WSNs) offer the potential to monitor volcanoes on unprecedented spatial and temporal scales. However, current volcanic WSN systems often yield poor monitoring quality due to the limited sensing capability of low-cost sensors and unpredictable dynamics of volcanic activities [6]. Use of collocated GPS and seismic sensors for earthquake monitoring and early warning is mentioned in [7].

The current situation of remote sensing application for earthquake research indicates a few phenomena, related with earthquakes, particularly the earth's surface deformation, surface temperature and humidity, atmosphere temperature and humidity, gas and aerosol content. Both horizontal and vertical deformations scaled from tens of centimeters to meters are recorded after the shock. Such deformations are recorded by the Interferometric Synthetic Aperture Radar (InSAR) technique with confidence. Pre-earthquake deformations are rather small, on the order of centimeters. A few cases of deformation mapping before the shock using satellite data are known at present time. Future developments lay in precision longwave SAR systems with medium spatial resolution and combined with the GPS technique.

There are numerous observations of surface and near surface temperature increases of 3–5°C prior to earth crust earthquakes. Methods of earthquake prediction are developing using thermal infrared (TIR) surveys. Multiple evidence of gas and aerosol content changes before earthquakes are reported for ground observations. Satellite methods allow one to measure the concentrations of gases in atmosphere. However the spatial resolution and sensitivity of modern systems restricts the application of satellite gas observation in seismology and the first promising

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results have been obtained only for ozone, aerosol and air humidity.

A further application of satellite data in seismology is related with geophysical methods. Electromagnetic methods have about the same long history of application for seismology [8]. The advantages of remote sensing are wider coverage of a satellite image, high and medium spatial resolution up to sub-meter, multi-spectral imagery, sometimes stereo mode, cyclic monitoring and etc. On the other hand, the disadvantages are invisible in case of cloud coverage and night time for optical sensor, fixed time and date for data acquisition and normally higher cost of the data. In spite of those disadvantages, remote sensing has been widely used in link with GIS (geographic information system) to monitor disasters such as earthquakes, Tsunamis, floods, volcanic eruption and etc.

At continuation of this paper, different type of sensors that are used in remote sensing will introduce and then reliability of them in the remote sensing satellite for earthquake prediction will calculate.

Type of Sensors

Remote sensing is the art and science of recording, measuring, and analyzing information about a phenomenon from a distance. Humans with the aid of their eyes, noses, and ears are constantly seeing, smelling, and hearing things from a distance as they move through an environment. Thus, humans are naturally designed to be remote sensors. In order to study large areas of the earth’s surface, geographers use devices known as remote sensors. These sensors are mounted on platforms such as helicopters, planes, and satellites that make it possible for the sensors to observe the earth from above.

Every material on the earth shows its own strength of reflection in each wavelength when it is exposed to the electromagnetic waves (visible light and invisible light, such as infrared rays, ultraviolet rays or electric waves). Also, when the material gets hot, it radiates showing its own strength in each wavelength. According to wavelength, it is called as ultraviolet ray, visible light, infrared ray, microwave, etc. Most sensors record information about the earth’s surface by measuring the transmission of energy from the surface in different portions of the electromagnetic (EM) spectrum. Because the earth’s surface varies in nature, the transmitted energy also varies. This variation in energy allows images of the surface to be created. Sensors detect variations in energy in both the visible and non-visible areas of the spectrum.

Energy waves in certain sections of the EM spectrum easily pass through the atmosphere, while other types do not. The ability of the atmosphere to allow energy to pass through it is referred to as its transmissivity, and varies with the wavelength of the radiation. The gases that comprise our atmosphere absorb energy in certain wavelengths while allowing energy with differing wavelengths to pass through. The areas of the EM spectrum that are absorbed by atmospheric gases such as water vapor, carbon dioxide, and ozone are known as absorption bands. Trying to obtain remotely sensed imagery in the absorption bands is nearly impossible; thus, sensors are generally designed not to record information in these portions of the spectrum.

In contrast to the absorption bands, there are areas of the EM spectrum (described in Table 1) where the atmosphere is transparent (little or no absorption of energy) to specific wavelengths. These wavelength bands are known as atmospheric "windows" since they allow the energy to easily pass through the atmosphere to Earth's surface. It is in these windows that sensors are used to gather information about Earth phenomena. Most remote sensing instruments on aircraft or space-based platforms operate in one or more of these windows by making their measurements with detectors tuned to specific frequencies (wavelengths) that pass through the atmosphere. When a remote sensing instrument has a line-of-sight with an object that is reflecting sunlight or emitting heat, the instrument collects and records the radiant energy.

Table 1: Major regions of the electromagnetic spectrum

Region Name	Wavelength	Comments
Gamma Ray	<0.03 nanometers	Entirely absorbed by the earth's atmosphere and not available for remote sensing.
X-ray	0.03 to 30 nanometers	Entirely absorbed by the earth's atmosphere and not available for remote sensing.
Ultraviolet	0.03 to 0.4 micrometers	Wavelengths from 0.03 to 0.3 micrometers absorbed by ozone in the earth's atmosphere.
Photographic Ultraviolet	0.3 to 0.4 micrometers	Available for remote sensing the earth. Can be imaged with cameras and sensors.
Visible	0.4 to 0.7 micrometers	Available for remote sensing the earth. Can be imaged with cameras and sensors.
Near and Mid Infrared	0.7 to 3.0 micrometers	Available for remote sensing the earth. Can be imaged with cameras and sensors.
Thermal Infrared	<0.7 to 3.0 micrometers	Available for remote sensing the earth. This wavelength cannot be captured by film cameras.
Microwave or Radar	0.1 to 100 0.2 centimeters	Longer wavelengths of this band can pass through clouds, fog, and rain.
Radio	>100 centimeters	Not normally used for remote sensing the earth.

At continuation, various types of sensors will introduce. Sensor types are divided into the optical and microwave sensor categories.

A. Optical Sensor

Optical sensors observe visible lights and infrared rays (near infrared, intermediate infrared, thermal infrared). There are two kinds of observation methods using optical sensors: visible/near infrared remote sensing and thermal infrared remote sensing.

1) Visible/Near infrared

This is observation method to acquire visible light and near infrared rays of sunlight reflected by objects on the ground. By examining the strength of reflection, we can understand a conditions of land surface, e.g., distribution of plants, forests and farm fields, rivers, lakes, urban areas. During period of darkness, this method cannot observe. Also, clouds block the reflected sunlight, so this method cannot be observed areas under clouds.

2) Thermal infrared

This is observation method to acquire thermal infrared rays, which is radiated from land surface heated by sunlight. Also it can observe the high temperature areas, such as volcanic activities and fires. By examining the strength of radiation, it can be understood surface temperatures of land and sea, and status of volcanic activities and forest fires. This method can observe at night when there is no cloud.

B. Microwave Sensor

Microwave sensors receive microwave, which is longer wavelength than visible light and infrared rays, and observation is not affected by day, night or weather. There are two types of observation methods using microwave sensor: active and passive.

1) Active type

The sensor aboard earth observation satellite emits microwaves and observes microwaves reflected by land surface. It is suitable to observe mountains and valleys.

2) Passive type

This type observes microwaves naturally radiated from land surface. It is suitable to observe sea surface temperature, snow accumulation, thickness of ice. Not being affected by clouds or moisture in air, this sensor can observe the detail of land surface. Rough landform can be clearly seen. The range of wavelength that a sensor can observe depends on the type of sensor. This is because each sensor has a specific observation purpose and wavelength range to operate.

C. Sensors Used in Remote Sensing Satellites

There are several types of sensors that are used in remote sensing satellites. These sensors vary according to the purposes for which they are used. Main types of sensors used in remote sensing are as below.

1) The MultiSpectral Scanner (MSS)

The MSS is a mechanical scanning device that acquires data by scanning the earth's surface in strips normal to the satellite motion. Many lines are swept simultaneously with a scanning mirror and reflected solar radiation so detected is monitored in the detector. This allows monitoring several spectral bands at the same time.

2) The Thematic Mapper(TM)

The Thematic mapper is also a mechanical scanning device as the MSS, but it has improved spectral, spatial, and radiometric characteristics. The thematic mapper can acquire data in both the scan directions.

3) The Microwave Radiometer (MR)

These consist of a microwave antenna and amplifying and detection electronics. As the satellite moves over the earth, the MR antenna picks up the microwaves radiated/reflected by earth and the associated electronic payload detects & stores it. It is capable of detecting sea surface temperature, ocean winds, and moisture content over the land and the sea etc.

4) The Synthetic Aperture Radar (SAR)

The SAR is radar which simulates a large antenna aperture using the fact that a satellite is in motion over the earth and the phenomena of Doppler shift. As the resolution of radar has a direct proportional relation to the aperture area, the SAR is able to acquire data at quite high resolution.

5) The Panchromatic Camera

This is a sensitive camera which is used quite frequently in recent times. Coupled with CCD devices, the camera can directly convert the images into digital format which are then beamed directly or after some on-board processing to earth. Sometimes it is also called the CCD Camera.

D. Passive and Active Sensor Systems

Two types of sensors exist, namely passive and active. A passive sensor system needs an external energy source. In most cases this source is the sun. These sensors generally detect reflected and emitted energy wave lengths from a phenomenon. An active sensor system provides its own energy source.

As an example, a radar sensor sends out sound waves and records the reflection waves coming back from the surface. Passive systems are much more common than active systems. Table 2 shows the sensor types according to NASA standard which classified into two major types passive and active. Each type includes scanning and non-scanning sensor and categorized to imaging and non-imaging device.

Deformation Detection

One of the main directions of remote sensing application for seismology is deformation mapping. Surface deformations in seismic cycles can be divided into three phases: pre-seismic or inter-seismic, co-seismic and post-seismic ones. Co-seismic deformations are evaluated up to meters and tens of meters while pre-seismic movements amount to centimeters. Post-seismic deformations are also measured in centimeters, but subsequent landslides can increase deformations to meters. Most current research is focused on co-seismic and post-seismic (landslide) deformations. To sense these deformations, different sensors could be used which explained at continuation.

A. Optical Sensors

The first application of satellite images in seismology was related to structural geology and geomorphology. Active faults and neotectonics were the research aims. Epicenter zones of recent earthquakes were studied on the space images. Image interpretation depended on visual methods. The interpreter selected faults with sharp borders, shift of river valleys, etc.

InSAR technique provides precise measurements a few kilometers away from the faults but usually cannot generate complete deformation map in the near-fault zone. Optical displacement method can supplement InSAR technique to cover this disadvantage of the InSAR technique.

Table 2: Sensor classification according to NASA standard

Sensor Type				
Passive	Non scanning	Non imaging	Microwave radiometer	
			Magnetic sensor	
			Gravimeter	
			Fourier spectrometer	
			Others (Resistivity, etc)	
		Imaging	Camera	Monochrome
				Natural Color
				Infrared
				Color Infrared
				Others
	Scanning	Imaging	Image plane scanning	TV camera
				Solid scanner
			Object plane scanning	Optical mechanical scanner
				Microwave radiometer
Active	Non scanning	Non imaging	Microwave radiometer	
			Microwave altimeter	
			Laser water depth meter	
			Laser distance meter	
	Scanning	Imaging	Image plane scanning	Passive phased array radar
			Object plane scanning	Real aperture radar
				Synthetic aperture radar

The application of optical methods for deformation mapping has limited use now due to cloud problems. It does not allow one to get long time image series for analysis. On the other hand, the physical basis of optical sensor applications for deformation mapping before the shock is not clear.

B. InSAR

The InSAR technique is used to examine small-scale features in the deformation field associated with earthquakes. Satellite interferometry is based on multitemporal radar observations. InSAR is a method by which the phase differences of two or more SAR images are used to calculate the differences in range from two SAR antenna having slightly different viewing geometries to targets on the ground. As a result, displacements on the earth's surface in range of centimeters and millimeters can be measured.

C. GPS

As GPS observations are not strictly a remote sensing application. It was mentioned that InSAR technique is more sensitive for vertical deformations, while the GPS method is capable of recording long period horizontal movements.

D. Gravity

The detection of an earthquake by a space-based gravitation measurement was reported in 2006. Co-seismic deformation produces sudden changes in the gravity field by vertical displacement of earth's layered density structure and by changing the densities of the crust and mantle.

Reliability Concept

The objective of a reliability prediction is to determine if the equipment design will have the ability to perform its required function for the duration of a specified mission profile. One of the most critical considerations in the design of any system, for example a space system, is the implementation of a reliability plan.

A system is a collection of components, subsystems and/or assemblies arranged to a specific design in order to achieve desired functions with acceptable performance and reliability. The types of components, their quantities, their qualities and the manner in which they are arranged within the system have a direct effect on the system's reliability. From the start of the satellite design, hardware and software must be designed to achieve reliable operation. The process of design for reliability starts in the conceptual design phase with the determination of system reliability requirements and allocation of these requirements to the satellite subsystems. Searching for and identifying the ways in which sensors of earthquake prediction satellite can fail is a basic part of the design for reliability.

The failure modes of the sensors can be analyzed in several ways. For example, the all-part method simply analyzes each of the satellite's sensors to determine the effect of its failure. On a large satellite this method requires a lot of work, but it is straightforward and easy to do. The all-part method requires analyzing shorts and opens circuit on the wires or printed traces on circuit boards that can cause failure if opened or shorted together. The potential effect of reliability on the sensors fusion for the design of earthquake prediction satellite should be considered by examining failures from wear out and random causes. The reliability defined as

$$R = e^{-\lambda t} \quad (1)$$

where λ is the failure rate, t is the time and R is the probability that the item will operate without failure for time t. Therefore the probability of failure, F, is defined by:

$$F=1-R \quad (2)$$

For the remote sensing satellite, the system (or series) reliability, R_s, or success probability is computed as

$$R_s = \prod_1^n R_i = e^{-\sum \lambda_i t} \quad (3)$$

where R_i $(i = 1 \ldots n)$ is the reliability and λ_i the failure rate of the individual sensors.

For failure probabilities (λt) less than 0.1 or reliability greater than 0.9, the following approximation is frequently used

$$e^{-\lambda t} \approx 1 - \lambda t \quad (4)$$

Where a system consists of parallel and series elements reliability, R_p, for parallel and R_s, for series elements is given in Fig. 1.

Remote Sensing Reliability Estimation

Failure Mode and Effects Analysis (FMEA) or Failure Modes Effects and Criticality Analysis (FMECA) is an analysis technique which facilitates the identification of potential problems in the design or process by examining the effects of lower level failures. Recommended actions or compensating provisions are made to reduce the likelihood of the problem occurring and mitigate the risk, if in fact, it does occur.

The FMEA determines, by failure mode analysis, the effect of each failure and identifies single failure points that are critical. It may also rank each failure according to the criticality of a failure effect and its probability of occurring. The FMECA is the result of two steps FMEA and Criticality Analysis (CA).

The FMECA assumes that the ways in which equipment can fail can be identified and the effect analyzed. The key to this process is identifying and eliminating single point failure modes that by themselves can shut down the satellite and kill the satellite mission. If they cannot be eliminated, then their probability of occurrence must be controlled.

Criticality Analysis

Criticality Analysis used to rank each failure mode's severity classification in the FMEA, according to probability of occurrence. The failure mode criticality number for each failure mode (C_m) is calculated as below.

$$C_m = \beta.\alpha.\lambda_p.t \quad (5)$$

where C_m is failure mode critically number, β is conditional probability of failure effect, α is failure mode ratio, λ_p is part failure rate per million hours and t is duration of the relevant mission phase.

The criticality number of each assembly (or system) is calculated per each severity category as follows:

$$C_r = \sum_{n=1}^{j} (\beta.\alpha.\lambda_p.t)_n \quad (6)$$

where n is the current failure mode of the item being analyzed and j is the number of failure modes for the item being analyzed. The resulting FMECA analysis will enable a criticality matrix to be constructed. The criticality matrix displays the distribution of all the failure mode criticality numbers according to the severity category and referring to the criticality scale with five levels.

- Level A – Frequent, is defined as a probability which is equal or bigger than 0.2 of the overall system probability of failure during the operation.
- Level B - Reasonable probable, is defined as probability which is bigger than 0.1 but less than 0.2 of the overall system probability of failure during the operation.
- Level C - Occasional probability, is defined as a probability, which is more than 0.01 but less than 0.1 of the overall system probability of failure during the operation.
- Level D - Remote probability, is defined as a probability, which is more than 0.001 but less than 0.01 of the overall system probability of failure during the operation.
- Level E - Extremely unlikely probability, is defined as probability which is less than 0.001 of the overall system probability of failure during the operation.

Severity Classification

A severity classification will categorize according to its effects of a system operation. The severity classification is consistent between MIL-STD-1629 and MIL-STD-882, and classified as below.

- Category I - Catastrophic - A failure which may cause death or weapon system loss.
- Category II - Critical - A failure which may cause severe injury, major property damage, or major system damage which will result in a mission loss.
- Category III - Marginal - A failure which may cause minor injury, minor property damage, and minor system damage which will result in a delay or loss of availability or mission degradation.
- Category IV - Minor - A failure not serious enough to cause injury, property damage or system damage, but which will result in unscheduled maintenance or repair.

Applying FMECA to Remote Sensing

According to Table 2 and Fig. 1 different types of sensors for remote sensing satellite will be considered. For each sensor according to its application, different parameters are estimated. In Table 3, failure rate, failure mode, failure mode ratio, C_m and C_r of different sensor types of remote sensing satellite is calculated. In calculations Eq. (1) to Eq. (6) is used.

In Table 3, we assume two conditions for each component which is open circuit or short circuit, although they may be in the middle state, but generally we have these two conditions.

Table 4, shows the reliability for different usage of sensors in remote sensing satellite. Base on relations that mentioned in Fig. 1, final reliability of sensors fusion according to Table 3 is estimated and inserted in Table 4. According to Table 4, using microwave and SAR in satellite has the best reliability, which microwave could be passive and SAR is an active sensor, therefore combination of them will be effective in remote sensing satellite for earthquake prediction.

Table 3: Definition of parameters failure rate, failure mode, failure mode ratio, C_m and C_r of different sensor types

Row	Sensor Type	λ_p	Failure Mode	α	β	C_m	C_r
a	Microwave (radiometer , altimeter)	0.002	Open	0.90	0.90	0.001620	0.002010
			Open	0.80	0.10	0.000160	
			Short	0.10	0.85	0.000170	
			Short	0.20	0.15	0.000060	
b	Magnetic/ Gravimeter	0.001	Open	0.70	0.80	0.000560	0.001005
			Open	0.60	0.20	0.000120	
			Short	0.30	0.75	0.000225	
			Short	0.40	0.25	0.000100	
c	Camera	0.010	Open	0.85	0.80	0.006800	0.010050
			Open	0.75	0.20	0.001500	
			Short	0.15	0.75	0.001125	
			Short	0.25	0.25	0.000625	
d	Solid scanner	0.005	Open	0.85	0.75	0.003188	0.005025
			Open	0.75	0.25	0.000938	
			Short	0.15	0.70	0.000525	
			Short	0.25	0.30	0.000375	
E	Optical Mechanical Scanner	0.020	Open	0.60	0.40	0.004800	0.020200
			Open	0.70	0.60	0.008400	
			Short	0.40	0.50	0.004000	
			Short	0.30	0.50	0.003000	
f	Laser (Water depth meter, distance meter)	0.001	Open	0.85	0.80	0.000680	0.000990
			Open	0.90	0.20	0.000180	
			Short	0.15	0.60	0.000090	
			Short	0.10	0.40	0.000040	
g	Passive phased array radar	0.005	Open	0.90	0.90	0.004050	0.005000
			Open	0.90	0.10	0.000450	
			Short	0.10	0.85	0.000425	
			Short	0.10	0.15	0.000075	
h	Real/Synthetic aperture radar	0.002	Open	0.90	0.90	0.001620	0.002000
			Open	0.90	0.10	0.000180	
			Short	0.10	0.85	0.000170	
			Short	0.10	0.15	0.000030	

Table 4: Reliability of remote sensing satellite with different sensors according to Table 3

Sensors Fusion		Reliability Criteria
Passive	a & c	0.987960
	a & d	0.992975
	a & e	0.977831
	b & c	0.988955
	b & d	0.993975
	b & e	0.978815
Active	a & g	0.993000
	a & h	0.995994
	f & g	0.994014
	f & h	0.997012

Conclusion

A wide spectrum of satellite remote sensing methods is applied in seismology nowadays. The value of these methods for earthquake research is varied. Optical methods have limited applications, mostly for rapid assessment of damages in an epicentral zone. Vigorous extension of InSAR methods applications in seismology is observed now which is limited by the high data cost and complex data analysis. Reliability in remote sensing satellite is an important issue, which should be estimated before launching the satellite. In this paper, first the different types of sensor that will use in remote sensing satellite is reviewed and then reliability for different fusion of them is calculated. Calculations shows using microwave sensors with SAR as passive and active sensors respectively in remote sensing satellite could give the best reliability among other sensors fusion according to operational application assumption of these sensors.

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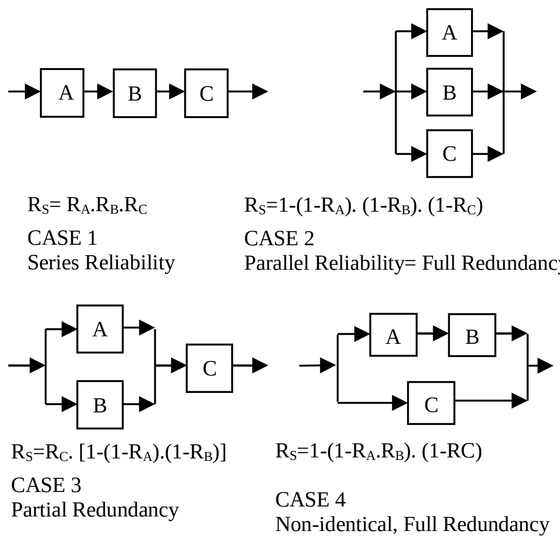

Fig. 1: Series and parallel reliability models. R_S is the system reliability. R_A, R_B and R_C denote the reliability of the A, B and C components respectively.

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