Paper
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Determination of the Ground Station Locations for both Dual-Site Ranging and Site-Diversity at Q/V-band Satellite Communication for an Intersatellite System Scenario

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Abstract

Generally, Low Earth Orbit (LEO) satellites are used to collect image or video from earth's surface. The collected data are stored on-board and/or transmitted to the main ground station directly or via polar ground station using terrestrial line. Today, an intersatellite link between a LEO and a GEO satellite allows transmission of the collected data to the main ground station through the GEO satellite. In this study, an approach for a continuous communication starting from LEO through GEO to ground station is proposed by determining the optimum ground station locations. In doing so, diverse ground stations help to determine the GEO orbit as well. Cross-correlation of the long term daily rainfall averages are multiplied with the logarithmic correlation of the sites to calculate the joint correlation of the diverse ground station locations. The minimum values of this joint correlation yield the optimum locations of the ground stations for Q/V-band communication and satellite control operations. Results for several case studies are listed.

Key words: site-diversity, Q/V band, satellite communication, turnaround ranging

1. Introduction

The collected data from earth by LEO satellites can be transmitted to the ground station directly or through a polar ground station by means of a terrestrial line [1]. Using a LEO communication link rather than a GEO link makes the operation relatively longer and dependent to other countries' territories.

The optical intersatellite communication between a LEO and a GEO has been investigated for a couple of decades [2] and been utilized starting from 2001 [3, 4]. Intersatellite communications can be by means of radio frequency (RF) or optical link. But recently, optical link is becoming more popular and some experiments with higher data rates are succeeded between LEO and GEO satellites [3]. Compared to the RF intersatellite communication, an optical link offers benefits such as; less mass, less power, higher data rates, more robustness to interferences etc. [5]. As for the GEO to ground station communication, higher bandwidth shall be implemented in order to be compatible with the optical link. Since the Ku-band spectrum is already saturated, higher frequency bands such as Q/V at about 40-50 GHz ranges are becoming popular [6]. On the other hand, above 10 GHz, rain attenuation becomes more severe and needs to be considered for in satellite communication systems [7]. Different kinds of fade mitigation techniques like 'adaptive coding and modulation' and 'site-diversity' are also suggested in literature [8-10] as an alternative to the over designed systems

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implementing higher link budget margins.

In literature, numerous studies exist that focus on the optical link acquisition and communication [3-5]. GEO satellite position accuracy is crucial to establish the intersatellite link. Accurate position information simplifies the Pointing Acquisition and Tracking (PAT) phase completion [11]. Traditionally, distances between ground antenna together with the satellite and the azimuth-elevation angles of the ground station antenna are used to determine the satellite orbit. Using a single ground site requires a high precision tracking antenna to determine the GEO orbit. However, using two or more geographically separated ground stations provide a less complex and less costly system to determine the accurate GEO satellite position [12].

This study proposes a method to determine the optimum dual ground station locations for ranging (turnaround ranging (TAR)) as well as higher bandwidth GEO to ground Q/V-band satellite communications. In section 2, an overall system is described including a sketch of the system. In section 3, the design constraints are given. In section 4, derivations of the cross-correlation and logarithmic correlations of the dual ground sites are supplied. Section 5 summarizes the case studies for the Q/V-band (40 GHz) downlink. For this study, 99.95% link availability has been targeted.

2. System description

Figure 1 below shows the unscaled view of the whole system including a LEO satellite that collects the data to transmit to the GEO via an optical link, and a GEO satellite that relays the data to the operation center via an RF link, and ground station(s) that are receiving the data coming from the GEO satellite.

As known, intersatellite link operations between LEO and GEO are critical in terms of synchronization. All information supplied by the LEO satellite shall reach to ground in near real-time via GEO satellite. That is why, weather conditions shall not be an obstacle for the relaying GEO satellite. So, in parallel to the LEO to GEO link acquisition, GEO to ground RF link is equally important for the uninterrupted communication. Higher data rate imposes higher bandwidth as well as higher frequency bands like Ka or Q/V [13]. Satellite communication above 10 GHz gets affected from rain attenuation critically and sufficient margin needs to be considered in the communication link budgets. So, to maximize the reliability of the aforementioned RF link, site-diversity shall be implemented to mitigate fading due to rain.

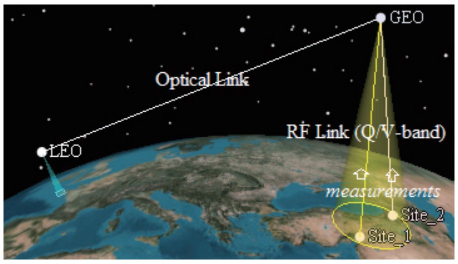

Fig. 1. System over-view of Turkey example (unscaled)

3. Determination of constraints for ground station locations

There are couple of orbit determination methodologies that are in use for GEO satellites. One of them is to use a single antenna, with azimuth, elevation and range between the antenna and the GEO satellite information. Another method is to use multiple antennas by 2-way or 4-way range information between two physically separated antennas to the GEO satellite that is named as TAR [12, 14]. If the ranging measurements have better accuracy, the angle (azimuth, elevation) information of the antennas are of secondary importance as they are relatively less accurate compared to the ranging [12]. Moreover, even though using single station or dual station has almost same accuracy on orbit determination, dual station procurements, setup and operations are significantly cheaper because of less stringent specifications. That is why, the GEO satellite operators are paying attention on TAR systems which employs dual stations because of its benefits such as cost, establishment, operation, dependability etc. But there are a couple of restrictions that need to be addressed due to geographical, political issues and spacecraft antenna beam width etc. [12].

The key parameter in TAR system is the separation distance between the two sites. The desired range and angular accuracies of the measurements imposes this separation between the sites. The required minimum separation, d_t, for any given desired accuracy can be calculated as in Eq. (1) [12].

$$d_t = 2\frac{\delta\gamma}{\delta\theta} \tag{1}$$

where $\delta\gamma$ is the range accuracy in meters and $\delta\theta$ is the angular accuracy in radians.

As can be seen from Eq. (1), less accuracy on the angular data requires closer sites whereas less accuracy on ranging requires farther separated ground stations.

As for the communication, having the ground stations inside the same and considerably smaller satellite spot beam guarantees receiving higher Effective Isotropic Radiated Power (EIRP) levels at both sites. Moreover, there is a relationship between the beam size and the corresponding satellite antenna gain that affects the data rate of the link. The satellite antenna's gain is inversely proportional to the square of the antenna beam width. However, the spot beam is directly proportional to the antenna beam width. Thus, increase in the size of the spot beam causes increase in footprint, decrease on antenna gain and data rate [15]. The diameter of the GEO satellite spot beam, 'd_s, which uses parabolic antenna, can be derived from half power beam width as in Eq. (2);

$$d_s = l\,tan\left(\frac{\lambda}{D\sqrt{\eta}}\right) \tag{2}$$

where, 'l' is the distance between GEO satellite and the spot beam center on earth, 'λ' is the wavelength of the RF signal, 'D' is the diameter of the satellite antenna and 'η' is the efficiency of the antenna.

Theoretically, to have the optimum coverage area, which also complies TAR and site-diversity for fade mitigation requirement, d_s should be equal to d_t. That locates the ground stations at the edge of the coverage area. Nevertheless, it is not possible for all countries and it is not practical too. So, a ring needs to be determined, which has minimum diameter of d_t and maximum diameter of d_s, as shown in Fig. 2. Depending on the width of the ring, the satellite antenna diameter and gain are changed and the EIRP is affected at dedicated locations.

As demonstrated in Fig. 2 below, the d_s value should be greater than the d_t, and a ring is defined as in Eq.(3) below,

$$d_r = \frac{d_s - d_t}{2} \tag{3}$$

From Eq.(1) and Eq.(2) and also assuming $tan\left(\frac{\lambda}{D\sqrt{\eta}}\right) \cong \left(\frac{\lambda}{D\sqrt{\eta}}\right)$, the ring size can be written as in Eq. (4)

$$d_r = \frac{l\,\lambda}{2D\sqrt{\eta}} - \frac{\delta\gamma}{\delta\theta} \tag{4}$$

Decision of the optimum ground station locations requires them to be inside this defined ring and have less simultaneous rainfall occurrences as well.

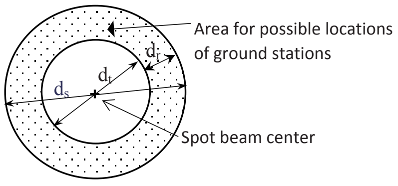

Fig. 2. GEO satellite beam parameters

4. Determination of ground station location

As detailed in section 2 and 3, large-scale site-diversity is used. To determine the optimum ground stations, a minimum number of key design parameters such as satellite antenna diameter, corresponding beam width and measurement accuracies of ground antennas are utilized. In addition to that, long term rainfall statistical data for the country are used to pinpoint cities with less correlated rain regimes. Long term correlation coefficient of daily rainfall averages is found by using Eq. (5) below,

$$\rho_w = \frac{\sum(C_A C_B) - \frac{\sum C_A \sum C_B}{N}}{\sqrt{\sum C_A^2 - \frac{\sum C_A^2}{N}}\sqrt{\sum C_B^2 - \frac{\sum C_B^2}{N}}} \tag{5}$$

where;

ρ_w; the correlation coefficient that depends on the daily rainfall of the city pairs,

C_A and C_B; the long term daily rainfall average of the city pairs,

N is the total number of rainfall data.

ρ_w, varies between [-1, +1]. If it is close to -1, the city pair, has less dependent rain regime. If the result is close to +1, the cities are either closer to each other or have similar rain regimes.

Distance between the city pairs is used to find the logarithmic correlation coefficient proposed by Paraboni-Barbaliscia as expressed in Eq. (6) where d is the distance between sites in km. and this formulation is valid for d > 50 km. [16, 17].

$$\rho_n = 0.94exp\left(-\frac{d}{30}\right) + 0.06exp\left(-\left(\frac{d}{500}\right)^2\right) \tag{6}$$

The joint correlation between the corresponding sites is calculated by using Eq. (7) below to determine the ground stations pair.

$$\rho = \rho_w \rho_n \tag{7}$$

The minimum 'ρ' value needs to be considered to determine the optimum ground station locations. As mentioned in section 3, both of the stations have to be inside the same ring. Minimum ρ value means the city pairs with less simultaneous rainfall probability and larger separation from each other at the same time.

As a result, the stations shall be kept close to each other as much as possible for higher EIRP but shall be located apart from each other as much as possible to have better accuracy on GEO satellite orbit determination. The distance between the sites (d); shall vary between dt and d_s ($d_t < d < d_s$) and shall satisfy the minimum ρ at the same time. The flow chart shown in Fig. 3 below summarizes the process for optimum site location determination.

5. Case study for determination of ground station

Turkey is investigated for our case study. Logarithmic correlations, daily simultaneous rainfall correlations and joint correlation coefficients are calculated for all possible city pairs. For the long term daily rainfall averages, the meteorological data from 1974 to 2014 provided by Turkish State Meteorological Service, are used. Fig. 4 below shows the joint correlation coefficients of the city pairs in Turkey which are separated from each other less than 700 km.

Figure 4 demonstrates that some city pairs have higher joint correlations due to their similar rain regimes and closer distance. However, some city pairs apart from each other between 200 to 400 km, have less or even negative joint correlations which makes them more attractive for optimum ground station locations. This is due to less correlation on rain regime and farther separation at the same time.

The design constants that are used in calculation of the optimum locations are listed in Table 1.

For different case studies, range accuracy is taken to be varying between 10 and 20 meters and the angular accuracy between 5 and 10 mdeg [11]. Couple of cases are listed in Table 2 by using different ground station capabilities. For the spot beams, three different GEO satellite antennas and corresponding spot beams are selected to calculate each example case in Table 2.

To find the optimum ground stations, flow chart as shown in Fig. 3 is used and joint correlations are calculated for all city pairs inside the corresponding ring. After that, the city pairs, that have minimum ρ, listed in Table 3,

Table 1. System constants used for the case study

Link availability (at both sites)	α_{av}	99.95	%
Rx antenna diameters (at both sites)	Dr	5	m
Rx antenna efficiencies (at both sites)	ηRx	0.65	-
Gas absorption losses (at both sites)	Lg	1	dB
Pol. and misalign. losses (at both sites)	Lp	1	dB
GEO satellite longitude	L	50.00	Degree (East)
GEO satellite transmitter antenna diameter	D	60, 90 or 110	cm
Transmitter antenna efficiency	ηTx	0.65	-
Transmission frequency /polarization	f	40.00	GHz / Circular
Transmission losses	Lt	1.00	dB
Transmitter power	Pt	150.00	W
Roll off factor	α	0.35	-
Bandwidth	BW	800.00	MHz

Table 2. Turkey case study for proposed system

Example#	δγ [m]	δθ [mdeg]	d_t [km]
I	20	7	327.4
II	20	8	287.5
III	20	9	254.6
IV	20	10	229.2
V	10	10	114.6
VI	15	10	171.9

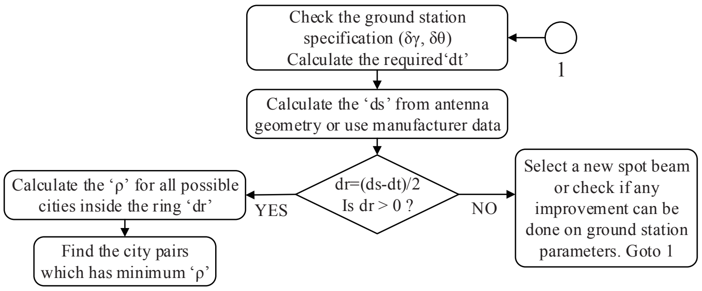

Fig. 3. Ground station determination algorithm flow chart

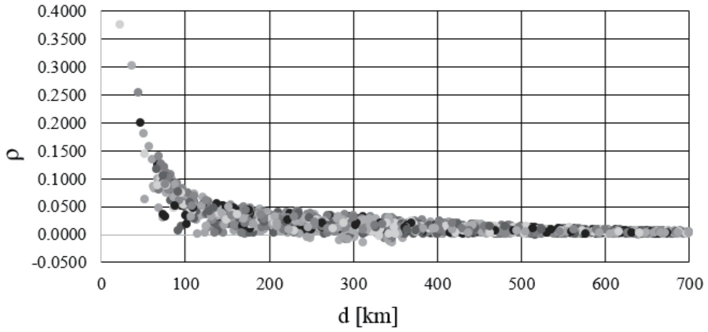

Fig.4. Joint correlation of cities in Turkey

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are detected. The cities are shown in Fig. 5 below. In the link budgets, the site-diversity gains of the locations are added too as per reference [18]. It should be noted here that, because of the relationship between GEO satellite antenna diameter and the spot beam size, the EIRP and corresponding Signal to Noise Ratio (SNR) levels will be different for each case.

Figure 5 demonstrates Example I for D=90 cm. In this figure, the d_t is shown in red circle with diameter of 327.4 km, whereas d_s is shown in blue circle with diameter of 369 km. As can be seen from Fig. 5, AR, KR and TN are inside the same ring but AR-TN has the minimum ρ value. As in Example II for D=90 cm case, if the d_r is enlarged by reducing the d_t, AR-BG will become the selected city pair since they have smaller ρ value than AR-TN.

The cities appearing in Table 3 are the optimum pairs inside the defined rings. As detailed in flow chart at Fig. 3, if the desired city pair does not satisfy the communication requirements, practically d_r can be enlarged to find another city pair which has smaller joint correlation (ρ).

On the other hand, it shall be noted that, having limited observability, may affect the orbit determination accuracy of the GEO satellite. Due to the weather conditions, some of the measurements may be lost in one of the stations or both of them at the same time. To be more precautious, not to degrade the performance of orbit determination of the GEO satellite, the measurement campaign durations need to be arranged with margins. In practice, at least 40% margin shall be implemented for measurements during a 48 hours campaign as TURKSAT does.

6. Conclusion

The optimum locations of a dual ground station are determined by means of cross correlation of daily rainfall averages and logarithmic correlation of city pairs for both; GEO satellite orbit determination and high bandwidth/data rate communication from a LEO to ground station(s) via a GEO satellite. The joint correlation of logarithmic correlation and daily rainfall averages are computed for all possible city pairs of Turkey. Depending on the ground station measurement accuracies, the required separation between the sites are determined. This separation satisfies the satellite communication link budget as well.

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Table 3. Link budgets for example cases

	D = 110 cm , ds = 302 km				D = 90 cm, ds = 369 km				D = 60 cm, ds = 553 km			
Ex.	Site#1	Site#2	ρ	dr	Site#1	Site#2	ρ	dr	Site#1	Site#2	ρ	dr
I	ds<dt			n/a	AR:20.9	TN:22.6	-0.0147	20.8	AR:17.3	TN:19.00	-0. 0147	112.8
II	BG:24.8	KR:21.4	-0.0091	7.3	AR:20.9	BG:23.1	-0.0152	40.8	AR:17.5	BG:19.6	-0.0152	132.8
III	AR:22.9	MS:25.8	-0.0113	23.7	AR:20.9	BG:23.1	-0.0152	57.2	AR:17.5	BG:19.6	-0.0152	149.2
IV	AR:22.9	MS:25.8	-0.0113	36.4	AR:20.9	BG:23.1	-0.0152	69.9	AR:17.5	BG:19.6	-0.0152	161.9
V	AT:19.2	KR:21.4	-0.0135	93.7	AR:20.9	BG:23.1	-0.0152	127.2	AR:17.5	BG:19.6	-0.0152	219.2
VI	AR:22.3	RZ:13.0	-0.0132	65.1	AR:20.9	BG:23.1	-0.0152	98.65	AR:17.5	BG:19.6	-0.0152	190.6

Fig.5. Possible ground station locations and Example I scenario (D=90cm)
AR: Ardahan, AT: Artvin, BG: Bingol, KR: Kars, MS: Mus, RZ: Rize, TN: Tunceli

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