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DESIGN AND APPLICATION OF INTER-SATELLITE LINK IN WEATHER OBSERVATION CONSTELLATION

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Key words: satellite constellation, inter-satellite link, weather observation constellation.

ABSTRACT

This paper presents the design and application analysis of the inter-satellite link technique in weather observation satellite constellation. A Walker parameter 18/18/4 satellite constellation with circular orbit at 837 km altitude and 60 degree inclination has been considered. The purposes are to take the weather cloud images of the area from 60 to 180 degree in eastern longitude and 0 to 60 degree in northern latitude, and to transfer the images back to Taiwan ground station as soon as possible. The STK [1] simulation software has been used in analyzing the effects of Doppler phenomenon, azimuth angle, elevation angle and distance between each two satellites. It has been proved that through the use of inter-satellite link technique, the contact time duration between the constellation and ground station has been tremendously increased. Therefore, weather cloud images can be transferred back much more frequently. Analysis results presented in this paper could be the reference for onboard antenna auto-tracking design and power management of the satellite.

I. INTRODUCTION

In this paper, the application of inter-satellite link is for the purpose of transferring a large number of weather images back to Taiwan in real-time. Time is always the most important factor in both the disaster prevention and the rescue after disaster occurrence.

In 1997, Motorola launched the Iridium constellation [3] to the orbit at altitude 780 km with inclination angle 86.4 degree near the polar orbit. It is the earliest low Earth orbit (LEO) satellite constellation with the Ka-band inter-satellite link. Both the intra-orbit and the inter-orbit satellite links are used. Launched in 2001, the ARTEMIS of ESA completed the laser communication experiments between a high orbit satellite (ARTEMIS) and a low orbit satellite (SPOT-4). Then in 2005, Japan successfully launched the optical inter-orbit link Communication Engineering Test Satellite [12] to a 610 km altitude orbit with a high inclination of 97.83 deg (the sun-synchronous orbit). A lot information of great significance about the future of satellite transmission link has been obtained. Taiwan's FORMOSAT-3 Program [9] consists of six LEO micro-satellites to form a constellation. Each satellite weighs 62 kg. The 6 satellites are deployed in six circular orbit at 800 km altitude and 72 deg inclination. They receive the signals from the 24 Global Positioning System (GPS) satellites for the calculation of the atmospheric temperature, pressure, water vapor content, and ionospheric electron density information.

Tamkang University has designed a constellation using 14 low cost microsatellites [6], with CCD imager onboard each satellite for weather observation. The orbital altitude is 800 km and the inclination is 98 degree sun-synchronous. The Walker 14/14/0 satellite constellation can provide one local cloud image of Taiwan per hour [7]. Also designed is a constellation of 18 satellites in 18 orbital planes [11]. The satellites can be deployed in 837 km altitude and 60 deg inclination orbits for weather observation within a region of 60 to 180 deg longitude and 0 to 60 deg latitude.

In this paper, the design of satellite constellations in References [6, 7, 11] is extended to a system includes inter-/intra-links between satellites. The purpose of [11] is to design a weather observation constellation with links to increase the image transmission frequency. Kller *et al*. [5] proposed a formula for calculating the azimuth of satellite links. Pasquale [2] performed the simulation of the links between the geosynchronous satellite and LEO satellites among the Italian Space Center, Keanu, and Fairbanks stations to increase the communication time. Tamkang University team's simulation [4] includes the constellations with Walker parameters 12/12/0,

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10/10/0, 8/8/0, 4/4/0 and 2/2/0, respectively. Satellite links with different inclination angles have been considered: 80 deg, 70 deg, and 60 deg. The team also used STK to obtain the information of the Doppler effect, the relative position, the azimuth angle, the elevation angle, and the relative distance.

This paper presents the design and application analysis of inter-/intra- links for a local weather observation satellite constellation centered at Taiwan. At least one cloud image can be taken and sent back to Taiwan ground station within one hour for the region between 60 deg and 180 deg eastern longitude and 0 deg to 60 deg northern latitude.

II. DESIGN OF SATELLITE CONSTELLATION WITH INTER-/INTRA- LINK

1. Inter-Satellite Link Mission Objectives

As mentioned above, it is intended to design a local satellite constellation with Taiwan's ground station as the receiving center for weather observation image. The coverage area is 60 deg to 180 deg eastern longitude and 0 deg to 60 deg northern latitude. In order to understand the weather change within the designated area in almost real time, it is required to transfer back the cloud image taken in one hour. Walker's notation [8] T/P/F shall be used where T is the total number of satellites, P is the the number of orbital planes, and F is the relative spacing between satellites in adjacent planes. By using the Walker notation, it is understood that all satellites are deployed in the same altitude with the same inclination angle. The only difference is the longitudinal angle of the ascending node of each orbital plane.

2. Design of Satellite Constellation

If the ground track repeat time T, since the Earth rotation rate ω_e, orbital regression rate $\dot{\Omega}$, then

$$\begin{aligned} &T(\omega_e - \dot{\Omega}) = 2\pi \\ &\Rightarrow \omega_e - \dot{\Omega} = \frac{2\pi}{T} = \frac{2\pi}{N \times P} = \frac{n}{N} \end{aligned} \tag{1}$$

where N is the number of revolutions required, P is the orbital period, and n is the average rate obtained from the following equation:

$$n = \sqrt{\frac{\mu}{a^3}} \tag{2}$$

and $\dot{\Omega}$ is the gravitational perturbation J_2 on the orbital longitude of the ascending node:

$$\dot{\Omega} = -\frac{3}{2}\frac{J_2 R^2}{a^2(1-e^2)^2} n \cos i \tag{3}$$

According to Reference [8], the Earth's gravitational perturbation coefficient $J_2 = 108263 \times 10^{-8}$, the gravitational constant 3.986005×10^5 km^3/s^2, the Earth's radius 6378.14 km. By substituting (2) and (3) into (1), we have the following simplified equation:

$$\frac{N \times w_e}{\sqrt{\mu}} a^{3/2} + \frac{3}{2} N \frac{J_2 R^2}{a^2} \cos i - 1 = 0 \tag{4}$$

In Eq. (4) the coefficient needs to be specified is N. If N is 15, 14, or 13 and the orbital inclination is between 0 deg and 90 deg, Table 1 shows the relation between inclination and altitude for the ground track to repeat.

Table 1. Relationship of Orbit altitude (km) and the orbital inclination (degrees).

Inclination *i*	N = 15	N = 14	N = 13
10	476.7	813.2	1190.1
20	479.2	814.9	1191.5
30	482.8	818.1	1194.1
40	488.4	822.6	1197.7
50	495.9	829.1	1203.1
60	506	837.4	1210
70	517.9	847.9	1219.1
80	531.9	860.3	1229.9
90	547.9	874.5	1242.4

III. SATELLITE INTER-LINK COMMUNICATION CHARACTERISTICS

1. Effect of Doppler Frequency Shift

In the process of satellite communications for satellite inter-links, the Doppler frequency shift effect cannot be ignored. The Doppler frequency shift equation is

$$f_{Dop} = f_c \times \frac{v_D}{c} \tag{5}$$

where f_c is the radio frequency, V_D is the relative speed between the satellites, and c is the speed of light with the value $c = 3 \times 10^8$ m/s. Since the satellites' velocity vectors change with time, the calculation of satellites link Doppler frequency shift is to calculate the relative velocity vector V_D between the satellites. Basically, V_D depends on the distance between the satellites change rate [10]. Fig. 1 shows the satellite Doppler frequency shift for the Walker 18/18/4 satellite constellation with inclination of 60 deg. The Doppler frequency shift range of -460~460 (kHz) between the inter- link satellites must be considered.

2. Free Space Propagation Loss

Free space transmission loss can be obtained from the following equation:

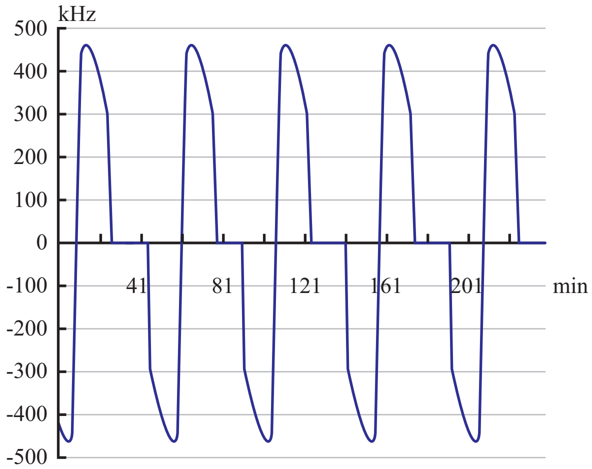

Fig. 1. Doppler frequency shift of Walker 18/18/4 constellation with 60 degree inclination angle.

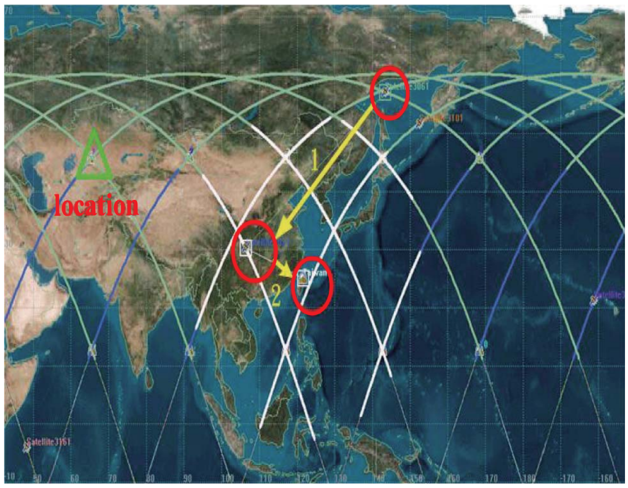

Fig. 2. Schematic diagram of cloud image transmission.

$$L_f = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2 \quad (6)$$

In Eq. (6), d is the signal propagation distance, f is the transmission frequency, and c is the speed of light. Loss in decibels (dB) is expressed as:

$$L_f = 92.44 + 20 \log d + 20 \log f \quad (7)$$

$$L_f = 32.44 + 20 \log d + 20 \log f \quad (8)$$

where the unit of d is km, the unit of f is GHz in Eq. (7), and the unit of f is MHz in Eq. (8).

IV. INTER-SATELLITE LINK DESIGN AND ANALYSIS

1. Inter-Satellite Link (ISL)

In the inter-satellite link design, it is not enough to consider only the static parameters of the constellation. Using the static parameters, only the design at a specific time for a communication system of satellite constellation can be done. In the LEO satellite constellation, the relative position of the two inter-linked satellites is changing. Both the relative distance and the relative position between the two inter-linked satellites (azimuth, elevation) become more complex. Therefore, the following dynamic parameters for the inter-satellite links must be taken into account: (1) the range-rate of satellite, (2) the change rate of satellite azimuth, and (3) the change rate of satellite elevation.

2. Application of Simulated ISL

An example of inter-satellite link for cloud image transmission is shown in Fig. 2. The cloud image is captured by one of the satellites at point (1) marked by a green triangle. When that satellite travels to the point circled by a red ellipse, it transmits the image to another satellite within the coverage of Taiwan's ground station through the yellow path 1. The image can then be transmitted to the Taiwan's ground station through the yellow path 2. This completes part of the weather observation mission of the constellation.

The total time schedule for cloud image taking at point (1) along with the time required for image transmission to Taiwan's ground station is presented in Table 2. Similar analysis can be done for any other locations within the specified region.

V. APPLICATION OF INTER-SATELLITE LINK SIMULATION RESULTS

Each individual satellite in a constellation is moving on its respective orbit, the relative distance, speed, azimuth, and elevation of any two satellites in ISL are time varying. In order to understand the variations of these parameters as functions of time, the STK platform is used to do the simulation.

1. Analysis of the Relative Parameters of Two ISL Satellites during Descending Phase

For the constellation proposed in this paper, the repeat number of ground coverage for all satellites to a designated location within the specified region is 36. Among the 36 passes of each satellite, 18 are ascending passes (from south to north, in even number) and 18 are descending passes (from north to south, in odd number). To look the satellite #2 from the satellite #6 during the descending phase, the variations of the relative azimuth angle, the relative elevation angle, and the relative distance are presented in Figs. 3, 4, and 5, respectively. The (maximum, minimum) pairs for the azimuth, elevation, and distance are (291.967 deg, 68.033 deg), (-2.29 deg, -27.97 deg), and (6768.12 km, 577.36 km), respectively. On the contrary, to look the satellite #6 from the satellite #2 during the descending phase, the variations of the relative azimuth angle, the relative elevation angle, and the relative distance are

Table 2. Location (1) schedule of shooting time with inter-satellite links.

Shooting time	Shooting satellite	Link satellite	ISLs start time	ISLs stop time	Link time
0:04:20	6	2	0:13:40	0:24:40	660
0:35:15	1	9	0:29:00	0:41:25	370
1:23:35	7	3	1:32:45	1:43:40	655
1:54:15	2	10	1:48:05	2:00:25	370
2:42:35	8	4	2:51:50	3:02:45	655
3:13:20	3	11	3:07:10	3:19:30	370
4:01:20	9	5	4:10:55	4:21:50	655
4:32:20	4	12	4:26:15	4:38:35	375
5:20:40	10	6	5:30:30	5:40:55	655
5:51:20	5	13	5:45:20	5:57:40	380
6:39:40	11	7	6:49:05	7:00:00	655
7:10:30	6	14	7:04:25	7:16:45	375
7:59:00	12	8	8:08:10	8:19:05	655
8:29:40	7	15	8:23:25	8:35:50	370
9:17:40	13	9	9:27:10	9:38:10	660
9:48:40	8	16	9:42:30	9:54:50	370
10:37:00	14	10	10:46:15	10:57:10	655
11:07:40	9	17	11:01:35	11:13:55	370
11:56:00	15	11	12:05:20	12:16:15	655
12:26:50	10	18	12:20:40	12:33:00	370
13:15:00	16	12	13:24:25	13:35:20	655
13:46:00	11	1	13:39:45	13:52:05	370
14:34:00	17	13	14:43:30	14:54:25	655
15:05:00	12	2	14:58:50	15:11:10	370
15:53:10	18	14	16:02:35	16:13:30	655
16:24:00	13	3	16:17:55	16:30:15	375
17:12:00	1	15	17:21:40	17:32:35	655
17:43:10	14	4	17:36:55	17:49:20	370
18:31:20	2	16	18:40:40	18:51:40	660
19:02:10	15	5	18:56:00	19:08:20	370
19:50:30	3	17	19:59:45	20:10:40	655
20:21:15	16	6	20:15:05	20:27:35	380
21:09:32	4	18	21:18:50	21:29:45	655
21:40:22	17	7	21:34:10	21:46:30	370
22:28:42	5	1	22:37:55	22:48:50	655
22:59:32	18	8	22:53:15	23:05:35	370
Average			513		
Total			5:07:41		

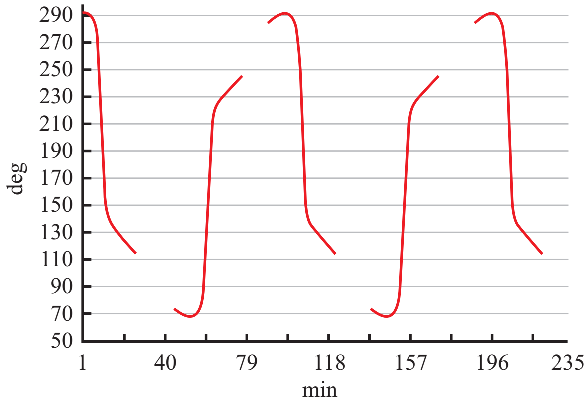

Fig. 3. Variation of relative azimuth angle look from #6 to #2, descending phase.

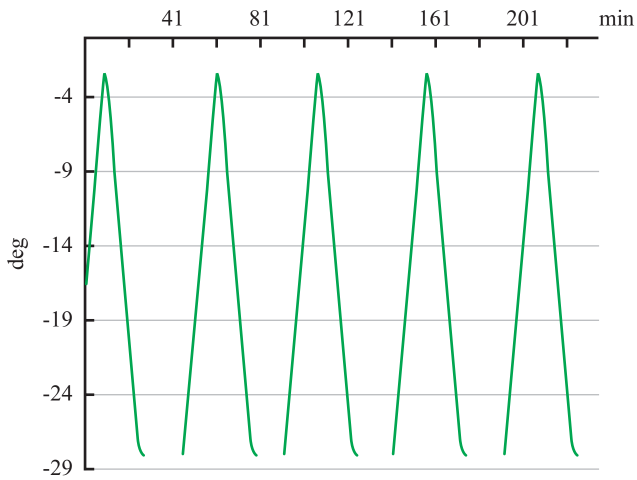

Fig. 4. Variation of relative elevation angle look from #6 to #2, descending phase.

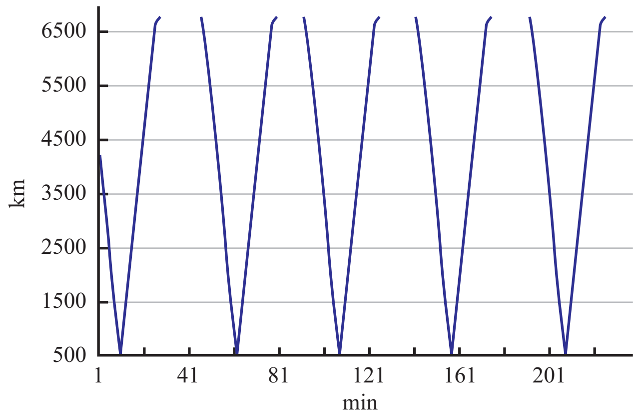

Fig. 5. Variation of relative distance look from #6 to #2, descending phase.

presented in Figs. 6, 7, and 8, respectively. The (maximum, minimum) pairs for the azimuth, elevation, and distance are (349.89 deg, 27.96 deg), (-2.29 deg, -27.97 deg), (6768.12 km, 577.36 km), respectively.

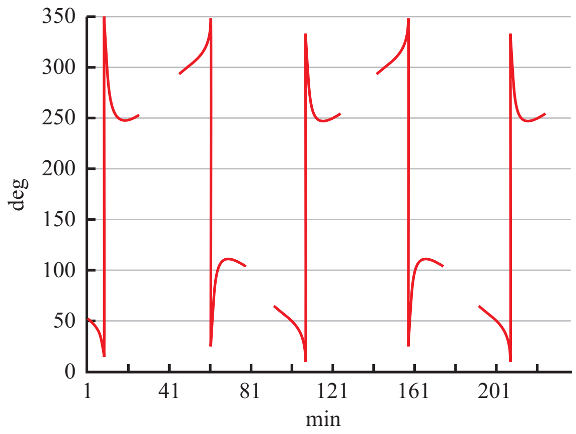

Fig. 6. Variation of relative azimuth angle look from #2 to #6, descending phase.

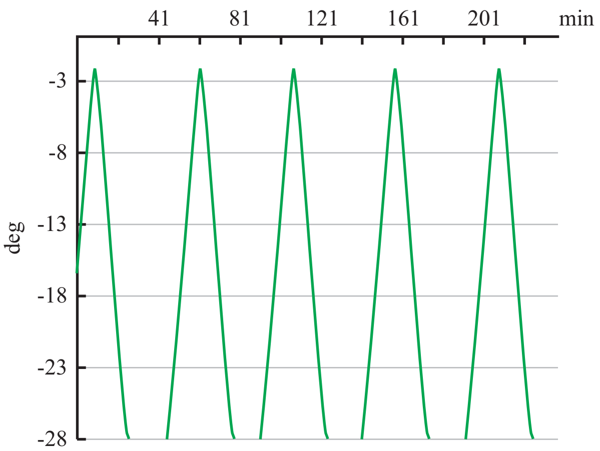

Fig. 7. Variation of relative elevation angle look from #2 to #6, descending phase.

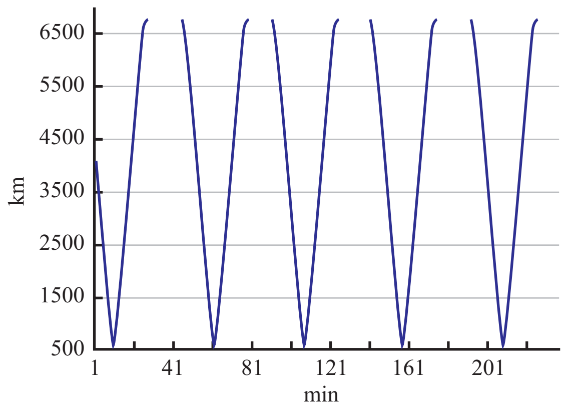

Fig. 8. Variation of relative distance look from #2 to #6, descending phase.

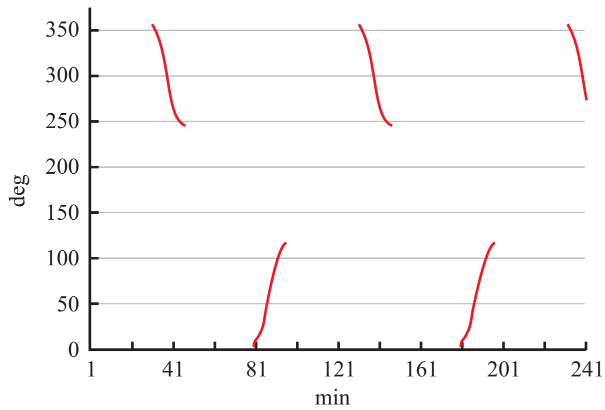

Fig. 9. Variation of relative azimuth angle look from #1 to #9, ascending phase.

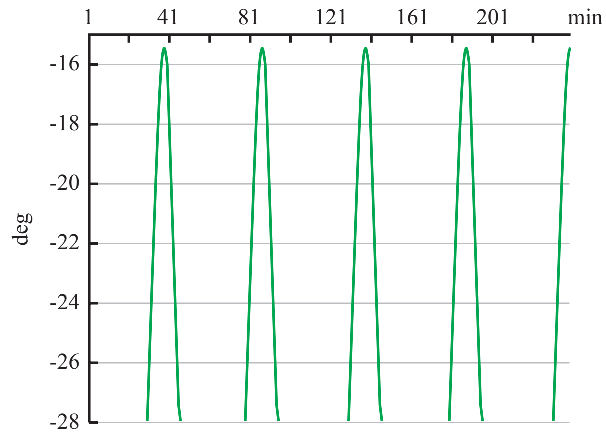

Fig. 10. Variation of relative elevation angle look from #1 to #9, ascending phase.

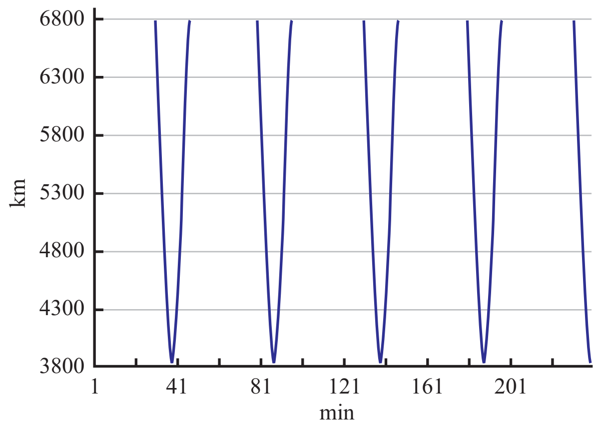

Fig. 11. Variation of relative distance look from #1 to #9, ascending phase.

2. Analysis of the Relative Parameters of Two ISL Satellites during Ascending Phase

For the relative motions in the ascending phase, to look the satellite #9 from the satellite #1 during, the variations of the relative azimuth angle, the relative elevation angle, and the relative distance are presented in Figs. 9, 10, and 11, respectively. The (maximum, minimum) pairs for the azimuth, elevation, and distance are (356.22 deg, 3.78 deg), (-15.44 deg,

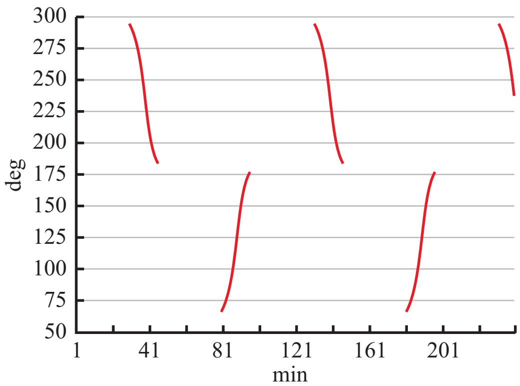

Fig. 12. Variation of relative azimuth angle look from #9 to #1, ascending phase.

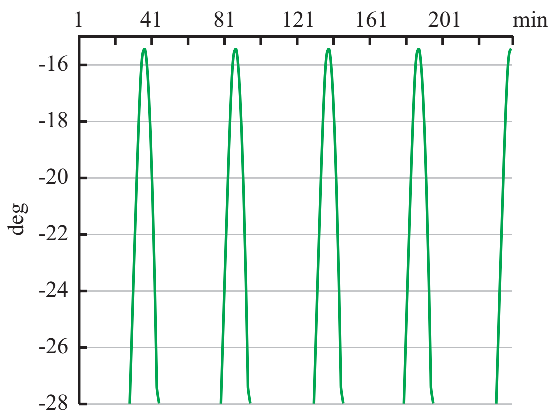

Fig. 13. Variation of relative elevation angle look from #9 to #1, ascending phase.

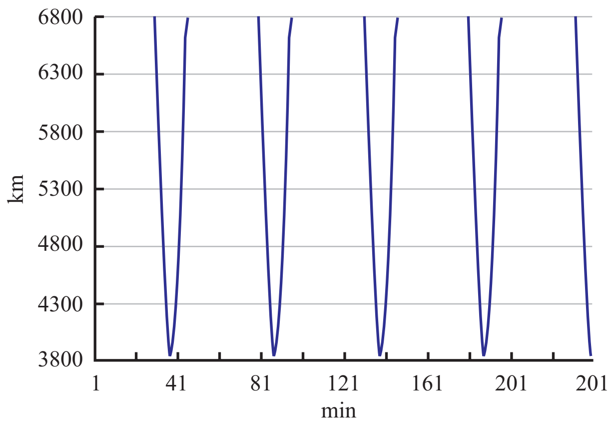

Fig. 14. Variation of relative distance look from #9 to #1, ascending phase.

-28.04 deg), and (6783.96 km, 3832.71 km), respectively. On the contrary, to look the satellite #1 from the satellite #9 during the ascending phase, the variations of the relative azimuth angle, the relative elevation angle, and the relative distance are presented in Figs. 12, 13, and 14, respectively. The (maximum, minimum) pairs for the azimuth, elevation, and distance are (294.98 deg, 65.02 deg), (-15.44 deg, -28.04 deg), and (6783.96 km, 3832.71 km), respectively.

VI. CONCLUSIONS

A Walker 18/18/4 constellation with inter-satellite link (ISL) capability has been designed for weather cloud image observation and transmission to the Taiwan ground station. It is proposed to be a constellation for local application purposes for a specified region within (longitude, latitude) = (60 deg to 180 deg East, 0 deg to 60 deg North). The inclination angle of the orbital planes is 60 deg. The constellation can take weather cloud images for a mosaic to cover the whole specified area. Furthermore, the mosaic can be updated 36 times per day. Also analyzed are the Doppler frequency shift, the relative azimuth angle, the relative elevation angle, and the relative speed of the two ISL related satellites. For future studies and investigations, we need to consider the concept design of the satellites, the communication capability for ISL, the launch cost consideration, the mission operations issues, etc.

REFERENCES

1. American Analytical Graphics Company, Satellite Tool Kit (STK), Version 5, May (2003).
2. De Carlo, P. M., Roberto, L., Marano, G., and De Luca, G. F., “Inter-satellite link for earth observation satellites constellation,” SPACEOPS, Roma, Italy, pp. 19-23 (2006).
3. Hatlelid, J. E. and Casey, L., “The Iridium system personal communications anytime, anyplace,” *Proceeding of the Third International Mobile Satellite Conference*, pp. 285-290 (1993).
4. Hong, Z. C., Chuang, C. M., and Chien, T. L., “Microsatellite constellation design for weather observation with Inter-Satellite Links,” AASRC/CCAS Joint Conference, 27-05, pp. 1-9 (2008).
5. Keller, H., Salzwedel, H., Freund, U., and Schorcht, G., “Examination of the circular polar orbit constellation for the use of inter-satellite links,” *Proceeding of 1997 IEEE International Conference on Personal Wireless Communications*, pp. 283-287 (1997).
6. Lin, C. H. and Hong, Z. C., “Mission and constellation design for low-cost weather observation satellites,” *Journal of Spacecraft and Rockets*, Vol. 42, No. 1, pp. 118-123 (2005).
7. Lin, C. H., Hong, Z. C., and Shieh, C. J., “The Constellation design of weather observation mission for Gravity-Gradient Stabilized Microsatellites,” *Journal of Mechanics*, Vol. 20, No. 3, pp. 241-248 (2004).
8. Ma, D. M. and Shu, W. J., “Micro-satellite constellation cover design,” *Instrument Today*, Vol. 23, No. 1, pp. 60-74 (2001).
9. Rocken, C., Kuo, Y. H., Sokolovskiy, S., and Anthes, R. A., “The ROCSAT-3/COSMIC mission and applications of GPS radio occultation data to weather and climate,” *Proceedings of SPIE - The International Society for Optical Engineering, Remote Sensing Applications of the Global Positioning System*, Vol. 5661, pp. 1-12 (2004).
10. Wang, K. F., He, X. Y., and Zhao, H. L., “The simulation of Doppler shift in inter-satellite links,” *Radio Engineering of China*, Vol. 37, No. 03, pp. 36-38 (2007).
11. Wen, Y. C., Chuang, C. M., and Hong, Z. C., “Design of Microsatellite constellation for weather observation and communication mission,” AASRC/CCAS Joint Conference, A25-03 pp. 2-10 (2007).
12. Yuuichi, F., Masaaki, M., Takashi, J., Toshihiko, Y., Katsuyoshi, A., Morio, T., Hiroo, K., Sodnik, Z., Bird, A., and Demelenne, B., “Optical inter-orbit communication engineering test satellite,” *AIAA 57th International Astronautical Congress Proceedings*, Vol. 4, pp. 2741-2749 (2006).