A Low-cost Approach to Small Satellite Control and Data Relay

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Abstract: Using the existing commercial mobile communication system (MCS) for reducing the operation cost of SmallSat has been studied. Through comparing the characteristics of several MCS's, a low-cost approach based on Inmarsat is presented. The system architecture for data relay between the low-earth orbiting Small (scientific) satellites and Inmarsat and its possibility for implementation are detailed. The involved technologies and potential problems, such as Doppler shift compensation, antenna tracking etc., are discussed and some considerations are given. A new concept-TT&C paging is presented for the cost-saving operation of SmallSat. The study shows that the proposed system is available for low and medium orbit SmallSat and the achievable data rate is 64kb/s. Without building Specific ground stations, the presented way can reduce the operation cost.

Introduction

In recent years, A great development has been made for Small satellites whose weight is between tens of kilograms and hundreds of kilograms. They usually operate in near earth orbit and its orbit altitude is from hundreds of kilometers to thousands of kilometers. Small satellite works alone or some of them work together as a constellation for a special purpose, such as land observation, disaster forecasting, etc. Thanks to its lightweight and compact structures, the cost of small satellite is lower than that of ordinary satellite. Therefore, how to reduce the small satellite operation cost has attracted the concerning of ground segment engineers and managers. It may be difficult for reducing manufacture and operation expenditures to build conventional unified microwave system TT&C stations for small satellite's tracking, telecommand, telemetry, and application data receiving. Especially for a constellation composed of small satellites, it needs a large and complicated TT&C system to support its operation. Despite that the number of stations could be cut down by means of arranging satellites to pass through a ground station one by one in fixed period, the small satellite operation expenditure is still high. However, TDRSS (Tracking and data relay satellite system) is more powerful and cheaper than the ground network. But, the number of satellites that could be supported is limited. It is also expensive to build the specific TDRSS system.

In China, experts from the ground segment have been studying on this point and try to find the low-cost methods for small satellite data relay and control. The best way is to adopt the present commercial system. Until now, mobile system such as Inmarsat, Iridium, Globalstar or Odyssey etc. has been build-up or is being constructed. Their performances have been compared in respect of orbit altitude, coverage, radiation energy and provided services etc. Compared with Iridium, Globalstar and Odyssey, Inmarsat is the pioneer in the mobile community and has provided mobile communication service for several years and it operates in geostationary orbit. Since Iridium, Globalstar and Odyssey are operating in low or medium earth orbit, if they are selected to be communication service provider, a small (scientific) satellite (referred to as "SmallSat" hereafter) will travel across too much coverage beams in short time. It results in a high 'hand-over' rate and an interrupt may occur as SmallSat flies across the beams of the adjacent satellites. In order to point the on-board antenna to the mobile communication service (MCS) satellite, it also needs SmallSat to keep contact with the control centers of MCS at all times to know the accurate orbit position of MCS satellites. All of that makes the operation of SmallSat very complex. It is has been proved that it is almost impossible to use LEO or MEO MCS satellites for the control of SamllSat. As the result of the study shows, Inmarsat-Geo MCS satellite is an alternative cost-saving way for the operations of SmallSat. The following sections will demonstrate the technical possibility and the system structure for cost reductions in SmallSat operations.

Inmarsat Mobile System and services

Inmarsat (International Maritime Satellite Organization) begins to provide worldwide satellite communications for the maritime community in 1982. Inmarsat mobile communication system consists of three parts: **Space segment**-geostationary satellites, **Ground segment**-OCC (Operation Control Center) and worldwide LES (land earth station), NCS (network Coordination Station), **User terminals**-mobile or fixed.

Inmarsat geostationary satellites (3rd generation) are located at 178°E, 64°E, 15.5°W and 54°W. They provide global coverage except the polar region through the spot beam and the global beam. The provided communication services include voice, fax, message and data.

Inmarsat has one NCS in each ocean region. NCS is responsible for assigning communication service to the specific LES. LES is the gateway to the PSDN or public telephone network. There are about 30 LES around the world. The OCC located in London monitors, controls and coordinates entire Inmarsat system.

Table 1 Summary of Inmarsat Main Services

	Inmarsat-A	Inmarsat-B	Inmarsat-M	Inmarsat- AERO	Inmarsat-D+
Service start time	1982	1993	1993	1995	1995
services	Voice (9.6Kbps) Fax(9.6K) Data (64K)	Voice 16K F ax 9.6K Data (9.6/56/64K)	Voice 16K F ax 9.6K Data (2.4K	Aero-L: Data (600/1200) Aero-I: Voice, fax (2.4K) Data(4.8K) Aero-H: Voice, fax(4.8K) Data(10.5K)	Voice (4.8K) Fax(2.4K) Data(2.4K)
Terminal weight	25~75Kg	18~25Kg	9~12Kg	15~25Kg	0.5~1Kg
antenna	1m paraboloid	Square 0.6m	Omni	Directional	Omni
Sat. Beam	Global	Global, Spot	Global	Aero-L Global Aero-I Spot Aero-H Global	Global, Spot
Develop -ment trend	Will be out of use	bestseller	Still in use	Widely used by international airlines	Widely used by ships and data collection stations

Inmarsat mobile terminals include airborne, shipborne and portable terminals. Inmarsat has provided various types of services for their users, such as Inmarsat A is the original analogue, Inmarsat-B the digital, Inmarsat-Aero the airborne. The specifications of the services are list in Table 1. The outstanding advantages of them could be summarized: (a) High Security. The data link provided by Inmarsat is 'transparent'. An encryption to the data (such as command sent to SmallSat.) can be easily achieved. (b) Low service cost. No lease fee. The digital service costs about $4 to $6 per minute. (c) High reliability and high put-through-rate.

System architecture based on Inmarsat mobile system for SmallSat

Study of the system possibility

Since the weight and the energy of SmallSat are limited, the equipment on board for data relay should have light weight, low energy consumption and easy to control, If the proposed system doesn't meet these requirements, no matter how good it is, it will be no use. Therefore, the system possibility will be discussed here in respect of the energy budget, orbit coverage and antenna tracking.

(1) Evolution of Link Energy

There are forward and backward links between SmallSat and Inmarsat satellites. Forward link is the link of the MCS satellite to SmallSat. Backward link is the link of SmallSat to the MCS satellite. Telecommand sent from the ground SmallSat Operation Center (SOC) will be transferred to SmallSat through forward link. SmallSat telemetry or payload data is through backward link to SOC.

According to the specifications of Inmarsat satellite, the link budget has been calculated. The required forward data rate for most of Small Satellites is about 2Kb/s. SmallSat backward data rate depends on the type of SamllSat. In general, it is higher than the forward's is. As an example, link budget is calculated on the condition of forward rate 4.8 kb/s and backward rate 9.6kb/s. The results are shown in Table 2. The formulae (highlighted) given in table are available for any data rate.

From the result of Table 2, we know that the on board SmallSat terminal could be light, low energy consumption and etc if the data rate is not high (less than 64Kb/s). Especially, assumes that data rate (duplex) is 9.6kb/s, the diameter of antenna is about 0.13m and transmitting power is about 50W. If SmallSat housekeeping TM is of low or medium rate, through reasonably 'balancing' the antenna gain and transmitting power, the transmitting power should be several Watts or less and the antenna diameter should be tens of centimeters. The requirements like these can be achieved by most of SmallSat. The study also shows that energy "bottle-neck" is in backward link budget.

(2) orbit coverage

SmallSat orbit coverage depends on its orbit altitude and on-board antenna beam width. The result of the calculation for one Inmarsat is shown in Fig.1.It indicates that using Inmarsat to increase orbit coverage is available for the SmallSat. If SmallSat orbit altitude is 300km or 500km, the orbit coverage ratio (the ratio of the orbit arc covered by Inmarsat to the uncovered) should be more than eight-five percent. The maximum is one hundred percent if three Inmarsat satellites are employed. That is almost impossible to be achieved by building worldwide conventional ground stations. Hence, it will greatly reduce the operational cost of SmallSat. However, the orbit coverage ratio will be lower as SmallSat orbit altitude is greater. It means that using Inmarsat is only efficient for LEO or MEO SmallSat.

Another conclusion obtained from Fig.1 is that:

Table 2 Budget of Forward and Backward Links Between INMARSAT and SmallSat

Link	Parameters	Unit	Value	Notes
FORWARD-LINK	Inmarsat EIRP	dBW	39.0	global Beam
	SamllSat Rx Frequency	MHz	1550	L band
	Data rate	Kb/s	4.8	
	Modulation		O-QPSK	
	R-S and evolution code	dB	6	Code gain
	Code Error Rate(ERR)		$1*10^{-5}$	
	Path loss	dB	188.7	42000Km (max.)
	Pol. pointing loss	dB	1	
	Safety merit	dB	3	
	$S/\Phi(P_e=1*10^{-5})$	dBHz	48.2	E/N_0=11.4 dB
	Required G/T of SmallSat	$dB/^oK$	≥-32.2	**-32.2 +10log(R_b/4.8)(Kb/s)** (formula for general case)
	SmallSat RCVR Noise Temp. (estimated)	^oK	200	Normal case
	Required SmallSat ANT. Gain	dB_i	-7.2	Data rate: 4.8kb/s (circuit loss 2dB is concerned)
BACKWARD-LINK	Inmarsat G/T	$dB/^oK$	-11.5	Global beam
	SamllSat TX Frequency	MHz	1650	L band
	Data rate	Kb/s	9.6	
	Modulation		O-QPSK	
	R-S and evolution code	dB	6	Code gain
	Code Error Rate(ERR)		1×10^{-5}	
	Path loss	dB	189.2	42000Km (max.)
	Pol. pointing loss	dB	1	
	Safety merit	dB	3	
	$S/\Phi(P_e=1\times10^{-5})$	dBHz	51.2	E/N_0=11.4 dB
	Required EIRP of SmallSat	dBW	≥21.3	**21.3 +10log(R_b/9.6)(Kb/s)** (formula for general case)
	SmallSat TX path loss	dB	2	estimated
	SmallSat TX power	dBW	17 (50W)	estimated
	Required antenna Gain	dB_i	≥6.3	Data rate: 9.6kb/s
	Antenna aperture	m	0.13	ANT efficiency 80% is concerned
	ANT beam width($2\theta_{0.5}$)	deg	≤95	D/4f=0.8

Every different orbit altitude has a maximum antenna beam width (antenna is fixed and faces to geostationary orbit). That is to say, if SmallSat on-board equivalent antenna beam width has reached the defined maximum value, the orbit coverage will be the maximum. The orbit coverage will be the same (maximum) for that the antennas whose beam width is greater than the defined maximum.

(3) Antenna Tracking

The link energy budget tells us that SmallSat should employ high gain and narrow beam antenna in order to decrease transmitting power. But Fig.1 illustrates that the narrow beam will reduce the orbit coverage. Therefore, a tracking or pointing servo system should be adopted by narrow beam antenna in order to track Inmarsat satellites all the time. In this way, the link can be maintained continuously. It is evident that the antenna tracking strategy is not permitted to be complex for SmallSat. In order to simplify servo system, program tracking technology and multi-antenna switchover technology can be used on SmallSat. (a) Program Tracking. The ephemeris of SmallSat and Inmarsat satellites are installed in the on board computer preliminarily. The antenna should be controlled to track by the installed ephemeris. As there will be a great change in the orbit parameters, SmallSat operation center should inject and new ephemeris data to SmallSat It has been testified that the tracking accuracy of it is enough for keeping the link. (b) Multi-antenna Switchover Technology. If servo system can't be employed on board, multi-antenna switchover method will be the best choice. A few narrow beam antennae should be installed and are switched on one by one. So long as the synthesized beam width meets the value defined in Fig.1, the maximum orbit coverage should be achieved. GPS can be used to replace the ephemeris sent by SOC to determine its position by SmallSat itself.

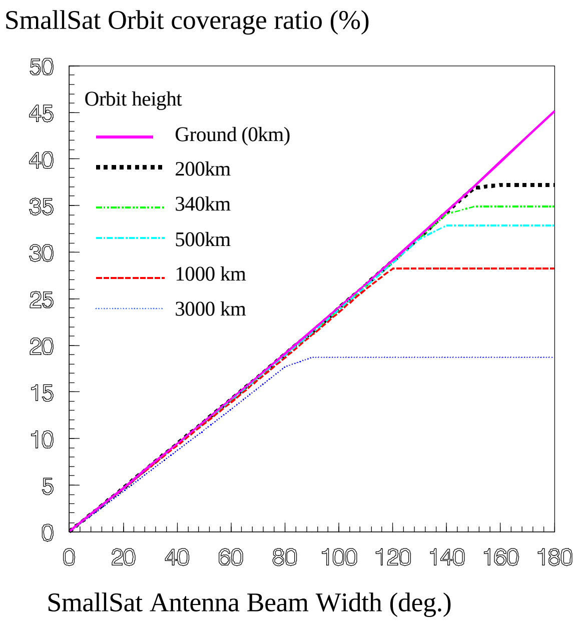

Fig. 1 the impacts of SmallSat antenna beam on orbit coverage rate (for one Geo. Satellite)

The proposed system architecture for data relay between SmallSat and Inmarsat is shown in Fig. 2. The work principle of it is as the follows:

SmallSat is registered as a mobile user in the Inmarsat system. SmallSat Operation Center (SOC) can access Inmarsat LES through local PSDN. If SOC is inaccessible to PSDN, it can employ an Inmarsat ground (fixed or mobile) user terminal to access Inmarsat system. Firstly, the link should be built before data transfer. SmallSat searches the Inmarsat navigation signal and locks on it. Then, keep its antenna pointing to the Inmarsat. Then, dial the user number of the SOC on the communication frequency assigned by NCS.

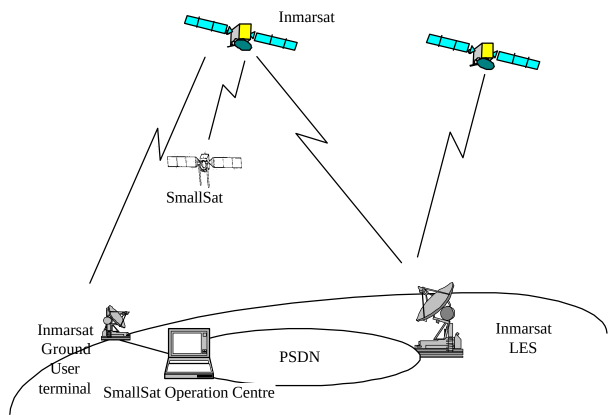

Fig. 2 The proposed system architecture for SmallSat Data Relay and Control

When SOC answers the calling, the link is up. After that, SmallSat transmits telemetry to Inmarsat. Through Inmarsat system, the TM is transferred to SOC and SOC can monitors the status of SmallSat. After link is up, SOC can send telecommand to SmallSat through Inmarsat system. For the SOC, the only operation is to get the Inmarsat ephemeris and send it to SmallSat. Inmarsat will supervise and operate the whole system.

Since the requirement of the equipment that will be on SmallSat is much different to that on the ground, the user terminal on SmallSat will be specially manufactured according to Inmarsat system specifications. Comparing and analyzing the services provided by Inmarsat, Inmarsat-B, Inmarsat-M and Inmarsat D+ can be used for SmallSat. If high data rate is expected, Inmarsat-B serviced should be used as the maximum achievable data rate of it is 64kb/s. If the data rate is low, Inmarsat-M will be better since the user terminal on SmallSat can be light and energy-saving. If weight and energy is very concerned and SmallSat has a great degree of automation, Inmarsat-D+ may be the best choice. The Inmarsat D+ user terminal is not bigger than a personal CD player and its weight is less than 1Kg. If Inmarsat-M or Inmarsat-B service is adopted, the operation of SmallSat is similar to conventional way and has been discussed in the last paragraph. The operation of high automation SmallSat through Inmarsat-D+ will be detailed in the following paragraph.

In order to reduce the cost of SmallSat, a new concept-**TT&C PAGING** is raised. The **TT&C PAGING** means: only when a failure or symptom occurs on small satellite, will it call ground operators and inform what happened. The operator analyzes the received message and gives a support. The system based on Inmarsat-D+ is as the following:

An Inmarsat-D+ terminal (its weight is less than 1Kg) should be mounted on SmallSat. In normal case, there is no link between SmallSat and Inmarsat. The alarm and warn limits are set for status parameters on SmallSat. When the value of the monitored status exceeds the defined limit, SmallSat will power on the D+ terminal and send these alarm parameters and collection time to Inmarsat. At the same time, SmallSat should go to the safe mode and wait to be repaired. Since the Omni antenna is used by D+ and its frequency is protected by international law, the search and point of antenna is not complex and the data transfer is reliable. When Inmarsat system receives these parameters (message), the message will be labeled "high priority" and transferred to SOC. After SOC receives and processes it, the telecommand can be generated and sent to SmallSat through D+ backward link (the data rate is about tens of bits per second) or through the common conventional ground station (as SmallSat comes into its sight). When the operation is over, the link can be shut down. If the conventional ground station is used for telecommand, it can be used for other satellite after the 'repair' operation is successfully completed. In order to know the SmallSat position as an alarm occurs, GPS receiver can be used and the position parameters should be involved in the alarm message. By this way, the SOC stuff can be released from the heavy operation burden. The communication and operation cost can be reduced.

The potential problems and key technologies

(1) Doppler shift compensation

The Inmarsat mobile communication services are mainly to meet the requirements of airborne, shipborne and land mobile user. The frequency Doppler shift is caused by their motion is slow and is permitted by Inmarsat system. The Doppler shift is caused by SmallSat can reach 40KHz and is a few times than that caused by the ordinary land mobile user terminals. Hence, SmallSat has to compensate as receiving and transmitting data. There are two potential ways for compensating Doppler shift. The one is using Inmarsat NCSC frequency (navigation frequency).

A wide-scan -range receiver can be used to search and lock the Inmarsat navigation frequency (NCSC). When SmallSat receiver has locked on it, the Doppler shift can be obtained. When transmitting data, the transmitting frequency can be compensated through transforming from the received frequency. The second way is using ephemeris. The Doppler shift can be obtained in real time through calculating the relative velocity. In order to let SmallSat know its precise position, GPS should be used on it.

(2) Advanced coding Technology

The coding technologies such as Redeem-Solomon and evolution coding have contributed almost 6-dB gain to the communication link. If advanced coding technologies that have higher gain can used be on SmallSat, the antenna size and transmitting power can more reduced. The Turbo coding recommended by CCSDS should be concerned.

(3) The design of Antenna

The weight and steering of the on board antenna have a direct effect on the data rate. Interference for neighboring Inmarsat Satellites could be caused by the SmallSat that radiates with Omni radiation characteristics when it is moving in the region covered by more than one Inmarsat satellite. The SmallSat antenna thus has to be steerable and directional. The high gain antenna with lightweight and simple servo system should be studied for the implement of system.

Conclusion

The data relay and control for small, scientific satellites using existing commercial mobile satellite service has been studied. Since omitting the conventional stations and the only cost is to pay the lease link fee, it is efficient for cost reductions operating SmallSat without building dedicated ground stations. Compared with other low earth orbit MCS system, using Inmarsat for the SmallSat operation is relatively simple and easy-to implementation. The system based on Inmarsat presented here is available for Low-orbit or medium-orbit SmallSat telemetry and telecommand. The on-board communication terminal is not complex and achievable. The maximum data transfer rate can be 64Kb/s. The steerable and directional antenna should be used on SmallSat to avoid interfering neighbor Inmarsat satellites. The global beam of Inmarsat except spot beam should be employed to increase the orbit coverage and reduce hand-over rate. For light SmallSat that is less than tens of kilograms and of high automation, TT&C paging will be the best way for reducing operation cost. Before the system presented here is to be implemented, Some potential problems such as interference, antenna tracking should be more studied.

References

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