

Use of Elliptical Orbits for a Ka-Band Personal Access Satellite System

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ABSTRACT

This paper examines the use of satellites in elliptical orbits for a Ka-band personal communications system application designed to provide voice and data service within the continental U.S. The impact of these orbits on system parameters such as signal carrier-to-noise ratio, roundtrip delay, Doppler shift, and satellite antenna size, is quantized for satellites in two elliptical orbits, the Molniya and the ACE orbits. The number of satellites necessary for continuous CONUS coverage has been determined for the satellites in these orbits. The increased system complexity brought about by the use of satellites at such altitudes is discussed.

INTRODUCTION

JPL is exploring the potential and feasibility of a Personal Access Satellite System (PASS) designed to offer the user freedom of access and mobility via the use of handheld and portable satellite terminals [1,2]. The currently conceived Ka-band system uses a geostationary satellite to support services such as voice, data, and video between a group of service providers, or suppliers, and users. The choice of Ka-band ensures ample spectrum for system growth and will reduce component weight and size thus enabling small user terminal size. Users and suppliers can be located anywhere within the continental U.S. (CONUS), hence the satellite must provide interconnectivity within CONUS. This is accomplished in the preliminary design by employing two CONUS coverage antennas and two multibeam antennas on the satellite. Alternative system designs are being investigated to enhance user capacity and/or reduce the system complexity [3]. The use of circular non-geostationary orbits has been studied and presented in [4]. This paper reports on the impact of using satellites in Elliptical Orbits (EO) on the PASS system design.

Two elliptical orbits, the Apogee at Constant time-of-day Equatorial (ACE) orbit and the Molniya orbit, are characterized in this paper. The selection of these orbits is motivated by the desire for CONUS visibility

from one satellite. Thus signals between geographically separated earth stations within CONUS can be relayed from one satellite. This bypasses the need for intersatellite links. For these orbits, system parameters such as signal carrier-to-noise ratio, roundtrip delay, Doppler shift, and satellite antenna size, are discussed and the number of satellites required to provide continuous CONUS coverage is calculated. The relative advantages and disadvantages arising from their use are discussed as they relate to the PASS application. Finally a comparison between system characteristics obtained with elliptical and previously reported circular orbits is presented.

MOTIVATION FOR NON-GEOSTATIONARY ORBITS

Use of satellites in Non-Geostationary Orbits (NGO) is motivated by the possibility of reducing the EIRP and G/T requirements on the user terminals, lowering signal delay through the satellite, reducing satellite antenna size, supporting a global communication system, and decreasing the fade margin and blockage requirements for mobile vehicle applications [5]. Lastly the use of NGO satellites permits the consideration of a greater range of launch vehicles which may permit lower launch costs due to the use of simpler launch vehicles or the launch of several satellites per vehicle.

While NGOs offer a number of attractive features, other factors must be considered such as: the number of satellites and their control mechanism; the use of tracking antennas on Earth; the existence of large Doppler shifts; and the variations in link characteristics as the satellite moves across the sky. In addition, the design of the NGO satellite will need to cope with radiation effects due to increased radiation exposure from the Van Allen radiation belt as well as support a complex antenna pointing mechanism. Finally questions of possible interference between geostationary and NGO satellites must be resolved (see [6] for details).

To date satellites in non-geostationary circular or-

bits have been proposed to provide a global mobile communications link at L-band [7]; EOs have been proposed to offer primary coverage in Europe for mobile users at L-band [5], to offer global coverage for personal and mobile users at Ku-band [8], and, to offload traffic from GEO satellites at peak traffic hours for fixed users in the U.S. at C- and Ku-bands [6,9].

ORBIT PARAMETERS

The ACE orbit is an elliptical equatorial orbit with five revolutions per day. It is sun-synchronous and highly eccentric (eccentricity = 0.49). The satellite is at the same point in its arc at the same time each day. The apogee and perigee of this orbit are 15,100 km and 1,030 km, respectively. This orbit has been studied extensively by Price et al. [6,9].

The Molniya orbit is a highly elliptical orbit at an inclination of 63.4°. With a perigee of 426 km and an apogee of 39,771 km, the satellite spends most of its orbital period ascending to its apogee. The maximum coverage period for CONUS is attained when the orbit's apogee is placed over the center of CONUS.

The following equations relate the period of the satellite's elliptical orbit around the Earth and the satellite velocity to the orbit's geometry. The former, τ_s , is given by:

$$\tau_s = \frac{2\pi a^{\frac{3}{2}}}{\sqrt{G * M}} \quad (1)$$

where

$$\begin{aligned} G &= 6.67 * 10^{-8} \text{ cm}^3/\text{gm sec}^2, \\ M &= 5.976 * 10^{27} \text{ gm}, \end{aligned}$$

and a is the major semiaxis of the ellipse, defined to be one half of the sum of apogee and perigee. The satellite velocity, v_s , can be expressed as:

$$v_s = \left[2G * M \left(\frac{1}{r_E + h} - \frac{1}{2a} \right) \right]^{\frac{1}{2}} \quad (2)$$

where r_E is the radius of the Earth, 6379.5 km, and h is the height of the satellite above the Earth. Table 1 gives the period, velocity and roundtrip signal delay (τ_d) when satellites in the ACE and Molniya orbits are at their apogees.

LINK CHARACTERISTICS

Doppler Shift

The Doppler shift of the signal is proportional to the velocity vector of the satellite relative to the Earth's motion. Specifically it is proportional to the component of this relative velocity vector which lies in the

direction of the receiving earth station, $v_{rel,in}$. The Doppler shift, $f_{Doppler}$, can be written as:

$$f_{Doppler} = \pm \left(\frac{v_{rel,in}}{c} f_c \right) \quad (3)$$

where c is the speed of light and f_c is the signal frequency. To determine the Doppler shift, $v_{rel,in}$ must be found from the velocity of the satellite, the inclination angle of the satellite's orbit with respect to the Equator, and the angle between the satellite and the user terminal on Earth.

The velocities and locations of a satellite and an earth station can each be decomposed in terms of their three orthogonal components in the geocentric equatorial coordinate system. The origin of this coordinate system is the center of the Earth, its x -axis points towards the Sun and the z -axis coincides with the Earth's axis of rotation. The velocity vector, \vec{v}_E , of an earth station at location \vec{P}_E is:

$$\begin{aligned} \vec{v}_E &= r_E [\sin(\omega t) + \cos(\omega t + \beta)] \cos \theta_i \hat{i} \\ &+ r_E [\cos(\omega t) - \cos(\omega t + \beta)] \cos \theta_i \hat{j} \\ &+ 0 \hat{k} \end{aligned} \quad (4)$$

where ωt denotes the angular distance moved in period t (ω being the angular velocity of the Earth), β is the angle from the x -axis at $t = 0$, and θ_i is the latitude of the earth station. The position (\vec{P}_s) and the velocity (\vec{v}_s) of a satellite can be written similarly. They are omitted from the text due to length of their expressions but can be found in [10].

The relative velocity between the earth station and the earth station and the satellite can be written as:

$$\vec{v}_{rel} = \vec{v}_s - \vec{v}_E. \quad (5)$$

The vector between the earth station and the satellite is known as P_{ES} . The component of \vec{v}_{rel} along the unit vector in the direction of P_{ES} sets the Doppler velocity, i.e.

Table 1: Characteristics of the ACE and Molniya Orbits

Orbit	Altitude km	Period hrs	v_s km/hr	τ_d msec
GEO	35,784	23.93	11069	239
ACE	15,100	4.8	11152	252
Molniya	39,771	12	5590	100

$$v_{rel,in} = \frac{\vec{v}_s \cdot \vec{P}_{ES}}{|\vec{P}_{ES}|} - \frac{\vec{v}_E \cdot \vec{P}_{ES}}{|\vec{P}_{ES}|} \quad (6)$$

The Doppler shift of the carrier frequency, f_c , can be obtained by finding the velocity and position vectors of the satellite and the earth station. The Doppler shift is zero when both \vec{v}_s and \vec{v}_E are perpendicular to \vec{P}_{ES} . For both the ACE and the Molniya orbits, this occurs when the satellite is at its apogee for those earth stations at the same longitude as the satellite. Alternatively, the Doppler shift will be maximized for earth stations directly under the satellite as the satellite ascending to its apogee or descending from it. The maximum Doppler shift at 30 GHz is approximately 300 KHz and 600 KHz for satellites in the ACE and Molniya orbits, respectively.

These large Doppler shifts require a compensation mechanism or a modulation scheme capable of tolerating wide deviations. Doppler compensation techniques would be straightforward if all the communications were done by a central station. The central station would use a set algorithm to change the pilot frequencies going to the user terminals and the down-link frequencies to the supplier stations. However in PASS, where users for a given supplier can be located in different beams, frequency tracking and compensation would put a big burden on the Network Management Center (NMC). The NMC would have to keep track of the position (beam number) of all the users and change the inbound and outbound frequencies accordingly. This would require large guardbands and a real time frequency calculation for all of the active users and suppliers of the system. The implication of the Doppler shift on the complexity of the channel assignment routine is detailed in Appendix A.

Propagation Loss

The use of elliptical orbits leads to a changing path range between the satellite and the users. Pt. A in Fig. 1 depicts the moment at which all of CONUS is visible from the EO satellite. At this point the range from the earth station (at the closest edge of coverage) to the satellite, d_{min} , sets the minimum propagation loss. Pt. B depicts the satellite at its apogee; at this point the range from the earth station (at the farthest edge of coverage) to the satellite, d_{max} , sets the maximum propagation loss. Pt. C depicts the satellite at the last moment at which all of CONUS is visible. The propagation loss, L_P , can be calculated according to:

$$L_P = \left(\frac{4 \pi d}{\lambda_c} \right)^2 \quad (7)$$

where λ_c is the wavelength corresponding to the carrier frequency f_c and d varies from d_{min} to d_{max} . The

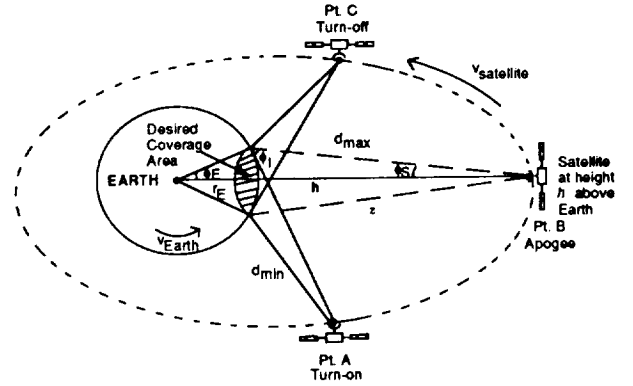


Figure 1: Earth station and satellite geometry.

Table 2: Variation of Propagation Loss

Orbit	Pt. A*		Pt. B†	
	30 GHz	ΔL_P ‡	30 GHz	ΔL_P
GEO:	213.1dB	0dB	213.1dB	0dB
ACE:	192.5dB	20.6dB	205.5dB	7.6dB
Molniya:	186.0dB	27.1dB	214dB	-0.9dB

* 20° elevation, at turn-on, for earth stations at the farthest edge of coverage.

† 20° elevation, at apogee, for earth stations at the center of coverage.

‡ $\Delta L_P = L_{PGEO} - L_{PNGO}$.

propagation loss along with its variation compared to GEO is shown in Table 2. For the ACE orbit, the improvement in the path loss ranges from 7.6 dB to 20.6 dB. For the Molniya orbit, propagation loss increases relative to GEO by 0.9 dB at orbit apogee.

CONUS Coverage Antenna

The preliminary PASS system design utilizes two CONUS beam antennas on the satellite for all communication between the supplier and the satellite. The size of the receive antenna is 0.1m and that of the transmit antenna is 0.15m; both have a gain of 26.9 dBi. In order to determine the effect of operating with EO satellites, the gain of a CONUS covering antenna is calculated for satellites at the apogee of their orbits. The satellite is assumed to have a tracking antenna which is trained on CONUS whenever the latter is visible. This scheme is illustrated in Fig. 1. As the satellite moves from Pt. A through Pt. B to Pt. C, the antenna tracks CONUS (shown by the hatched area). Antenna gain is calculated when the satellite is over the middle of the U.S., i.e. Pt. B in Fig. 1.¹

¹ Antenna gain for an equatorial orbit could be slightly larger as the beamwidth required to see CONUS from the Equator is

Antenna gain can be written as:

$$G_{ant} = \rho \frac{4\pi h^2}{2\pi h^2(1 - \cos \phi_S)}, \quad (8)$$

where the numerator represents the surface area of a sphere of radius h and the denominator is the surface area into which the radiated power is directed and ρ is the aperture efficiency. For CONUS coverage, ϕ_S , ϕ_I , and ϕ_E in Fig. 1 are denoted by ϕ_{S_C} , ϕ_{I_C} , and ϕ_{E_C} , respectively. ϕ_{I_C} is then the minimum elevation angle required for CONUS coverage.

ϕ_{S_C} can be expressed in terms of the minimum elevation angle on Earth to the satellite from:

$$\phi_{S_C} = 90^\circ - \cos^{-1} \left(\frac{r_E \cos \phi_{I_C}}{r_E + h} \right). \quad (9)$$

To find the minimum elevation angle necessary to see a satellite from CONUS, seven points on the perimeter of CONUS are defined. They are listed in Table 3. The elevation angle, ϕ_I , is calculated for each location by determining the angle between that location and the satellite. Calculation of ϕ_I and θ_{ES} for any point and a satellite at any position is given in [4].

Here we calculate the gain of a CONUS antenna specifically for the case of a satellite in an inclined orbit such that it passes over the center of the US, i.e. its latitude is 40° N and its longitude is 95° W. Satellites in the inclined orbits under consideration will have optimal CONUS coverage at this point. Satellites in equatorial orbits will, of course, never pass over a latitude of 40° N but will have optimal coverage when their longitude is 95° W; the gain of their CONUS antennas will at that point be slightly greater than that of their inclined orbit counterpart as the antenna beamwidth will be slightly narrower.

Once the elevation angles are calculated for each of the locations in Table 3, then ϕ_{I_C} , or the minimum value of ϕ_I , can be found. ϕ_{S_C} can then be calculated from Eq. 9 and the gain of a CONUS antenna can be found from Eq. 8.

ϕ_{I_C} , ϕ_{S_C} and CONUS antenna gain G_C (for $\rho = 0.5$) are given in Table 4; ϕ_{E_C} is not given as it does not vary with the satellite's height. The minimum CONUS elevation angle, ϕ_{I_C} , for a satellite at 35,784 km (equivalent to the height of a geostationary satellite) can be seen from Table 4 to be 64° .

In Table 4 the 0-3 dB power beamwidth of the CONUS antenna, ϕ_{S_C} , increases from 3.8° to 6.7° for the ACE orbit and decreases to 3.6° for the Molniya orbit. Thus, the gain of the CONUS antenna falls from 26.6 dB to 19.1 dB for the ACE orbit and increases to 27.5 dB for the Molniya orbit. The change

less than that required when the satellite is directly over the center of CONUS.

Table 3: Cities Considered to Bound CONUS

City	Latitude	Longitude
Bay of Fundy, Maine	47.2°	-68.0°
Key Largo, Florida	25.0°	-80.5°
Brownsville, Texas	26.0°	-97.0°
San Diego, California	32.5°	-117.0°
Seattle, Washington	49.0°	-123.3°
Bottineau, North Dakota	49.0°	-100.0°
Center of USA	40.0°	-95.0°

Table 4: Satellite CONUS Antenna Characteristics

Altitude	CONUS Satellite Antenna			
	ϕ_{I_C}	ϕ_{S_C}	$G_C _{\rho=0.5}$	$\Delta G_C \dagger$
35,784 km (GEO)	64°	3.8°	26.6 dB	0 dB
15,100 km (ACE)	57°	9.3°	19.1 dB	-7.5 dB
39,771 km (Molniya)	65°	3.4°	27.5 dB	+0.6 dB

$$\dagger \Delta G_C = G_{C_{NGO}} - G_{C_{GEO}}.$$

in CONUS antenna gain relative to a geostationary satellite, ΔG_C , is given in the table.

Antenna diameter can be calculated from the standard gain equation ($\sqrt{\frac{G_{ant}}{\rho}} \cdot \frac{\lambda_c}{\pi}$) and the ensuing size reduction compared to GEO operation can be found. The results are given in Table 5.

Multibeam Antenna Gain

As currently envisaged, the PASS satellite uses two multibeam antennas (MBAs) for communication between the user terminals and the satellite. Each MBA has a beamwidth of 0.35° and uses an 142 beam feed network to cover CONUS. In the preliminary PASS design, the gain of both the transmit and receive MBAs is 52.5 dBi and their efficiencies are both taken to be 0.45, corresponding to a reflector diameter of 2m at 30GHz and 3m at 20GHz. As the satellite orbit height decreases, the spot beams must continue to cover the same area in CONUS. Therefore the required MBA beamwidth will increase from 0.35° and the gain of the MBA will decrease with decreasing satellite altitude.

In reference [4] the gain of a multibeam antenna, $G_{MBA_{NGO}}$, used in a NGO satellite is derived in terms of the gain of the multibeam antenna of a GEO satellite, $G_{MBA_{GEO}}$ and the ratio of the satellite heights. It can be written as:

$$G_{MBA_{NGO}} = \left(\frac{h_{NGO}}{h_{GEO}} \right)^2 G_{MBA_{GEO}} \quad (10)$$

Antenna diameter and the ensuing size reduction compared to GEO operation are given in Table 5 when the satellites are at the apogees of their orbits for $G_{MBA_{GEO}} = 52.2$ dBi and $\rho = 0.45$.

Impact on Link Equations

The PASS system is asymmetrical: the user terminal equipment, designed to be handheld and portable, is less powerful than the supplier station, a fixed earth station with a 4m antenna. In both the link from the supplier to the user and the link from the user to the supplier, the channel between the user terminal and the satellite determines the overall carrier to noise of the received signal.

The change in downlink C/N and uplink C/N are given in [4]. They can be written as (in dB):

$$\Delta \frac{C}{N}_{down} = \left(G_{MBA_{t_{NGO}}} - G_{MBA_{t_{GEO}}} \right) + \left(L_{P_{down_{GEO}}} - L_{P_{down_{NGO}}} \right) \quad (11)$$

and

$$\Delta \frac{C}{N}_{up} = \left(G_{MBA_{r_{NGO}}} - G_{MBA_{r_{GEO}}} \right) + \left(L_{P_{up_{GEO}}} - L_{P_{up_{NGO}}} \right) \quad (12)$$

where the subscripts t and r refer to the transmit and receive gain of the MBA. Substituting Eqs. 7 and 10 into Eqs. 11 and 12, the latter can be shown to reduce a common expression, d being the range to the satellite:

$$\Delta \frac{C}{N} = \frac{h_{NGO}^2}{h_{GEO}^2} \frac{d_{GEO}^2}{d_{NGO}^2} \quad (13)$$

NUMBER OF SATELLITES REQUIRED

ACE orbit

Approximately eight satellites are required to provide continuous CONUS coverage from this orbit. The total coverage period and thus the number of satellites can be calculated from finding the turn-on and turn-off points of the satellite assuming that the satellite antennas have their boresights directed towards the center of CONUS during the coverage period. As depicted in Fig. 2 satellites in the ACE orbit can be phased in order to give a 24hr CONUS coverage. These satellites, with their orbit apogees at 0° latitude and -95° longitude, would turn their transponders on at the first

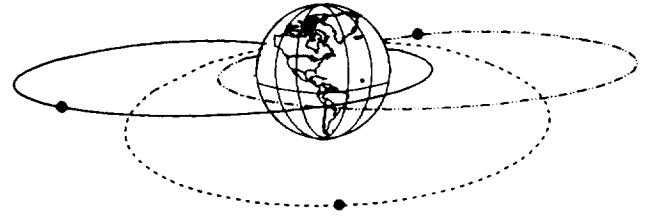


Figure 2: Satellite location for three satellites in three ACE orbits.

point that $\phi_{l_{min}} = 20^\circ$ and turn them off at the next $\phi_{l_{min}} = 20^\circ$.

Molniya orbit

The satellites in the Molniya orbit are phased in the same fashion as the ACE satellites. Approximately three satellites, with their apogee at 37° latitude and -95° longitude, are required to provide continuous CONUS coverage from this orbit.

ADVANTAGES AND DISADVANTAGES

The relative advantages and disadvantages to using NGO satellites for the PASS application can be measured in terms of the parameters mentioned in the introduction. These parameters are given in Table 5 for the three NGO satellite altitudes studied in [4] at which CONUS coverage from one satellite is possible and for the two elliptical orbits considered. The propagation loss listed, L_{P_1} , represents the variation in propagation loss from the time when the satellite first becomes visible at $\phi_{l_{min}}$ to the time when the satellite is overhead, $\phi_{l_{max}}$. The link margin is calculated from Eq. 13 for satellites at their apogees for earth stations with $\phi_l = \phi_{l_{min}}$.

As can be seen from Table 5, the gain in signal power brought about by the reduced propagation loss when NGO satellites are used is outweighed by the loss in satellite antenna gain. For the PASS design, the degradation in uplink C/N means that both suppliers and users will have to transmit higher EIRPs; the degradation in downlink C/N will require both suppliers and users to increase their receive G/T . This most certainly means that the size of the user antenna could not be reduced: directional antennas will still be necessary as in the preliminary design. Moreover the user and supplier antennas will require satellite tracking mechanisms for both circular or elliptical orbits. Both user and supplier transceivers will need to implement techniques to compensate for the varying Doppler shift of the signal which at 20 GHz and 30 GHz is substantial, up to 344 KHz for satellite altitudes of 5,143 km. Lastly the variation in the link will necessitate some modification to the present rain fade

Table 5: GEO and NGO Satellite Parameter Comparison ($\phi_{l_{min}} = 20^\circ$).

Orbit	Incl. Angle Ψ	Prop. Loss $\Delta L_{P_1} \dagger$	Link Margin	N_{sat}	Roundtrip Delay (Overhead)	Max. Doppler Shift at 30 GHz	Satellite Antenna \dagger at 20 GHz	
							CONUS	MBA
Circular Orbits								
GEO	0°	0	0	1	239 msec	0.0 KHz	14.4cm	3m
20,182 km	45°	1.4 dB	-0.6 dB	8	135 msec	131 KHz	8.2 cm (43%)	1.7 m (44%)
10,353 km	45°	2.3 dB	-1.5 dB	18	69 msec	216 KHz	4.35 cm (70%)	0.87 m (71%)
5,143 km	45°	3.5 dB	-2.7 dB	48	34 msec	344 KHz	2.3 cm (83%)	0.43 m (86%)
Elliptical Orbits								
ACE	0°	6 dB	-1.7 dB	8	252 msec	300 KHz	6.1 cm (58%)	1.3m (58%)
Molniya ($\phi_{l_{min}} = 41^\circ$)	63.4°	5 dB	-0.4 dB	3	100 msec	600 KHz	16.0 cm (-11%)	3.3m (-11%)

† Reduction in antenna size compared to GEO is given in parenthesis.

control scheme wherein both users and suppliers utilize the signal strength of the pilot to determine the rain fade condition in their uplink and downlink.

A comparison of the orbits under consideration shows that the fewest number of satellites required for continual CONUS coverage is the Molniya orbit which requires only three. However this orbit has the highest maximum Doppler shift, the widest range in path loss, and requires one dB more margin compared to the geostationary orbit. The 20,182 km circular orbit has far less Doppler shift and negligible path loss change with less link margin degradation but requires 8 satellites. Lower orbits require greater numbers of satellites, have greater degradation in the link margin, possess higher variations in the path loss, and are characterized by high Doppler shifts; however they have greater advantages in terms of signal delay and reduction in satellite antenna size.

CONCLUSION

This paper has studied the effects on the link characteristics of satellites in two elliptical orbits. The number of satellites necessary for continuous CONUS coverage has been determined for these orbits. The relative advantages and disadvantages of using EO satellites for the PASS application are measured in terms of the following parameters: the impact on the signal uplink and downlink, the roundtrip signal delay, Doppler shift, reduction in the size of satellite antennas, and the number of satellites required to cover CONUS contin-

ually.

The advantages of using satellites in the studied orbits do not appear to outweigh the increased system complexity especially for the Personal Communication Satellite System application considered here.

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APPENDIX A. IMPLICATION OF DOPPLER SHIFT ON THE COMPLEXITY OF THE CHANNEL ASSIGNMENT ROUTINE

To a stationary observer, the frequency of a moving transmitter varies with the transmitter's velocity. If a stationary transmitter's frequency is at f_T , the received frequency f_R is higher than f_T when the transmitter is moving toward the receiver and lower than f_T when the transmitter is moving away from the receiver. This change in frequency, or Doppler shift, is quite pronounced for low orbiting satellites and compensating for it requires intense frequency assignment and tracking.

For a non-geosynchronous satellite system linking supplier stations to users scattered around CONUS, direct supervision of the frequency assignment by a network management routine is required. The man-

agement routine has to ensure that no two signals in any link overlap, that is for any two signals centered at f_n and f_m in a given link,

$$|f_n - f_m| > BW, \quad (14)$$

where BW is the required data bandwidth.

For the PASS forward link specified in the preliminary design [1,2], all the suppliers will have to compensate for the Doppler shift by tracking the incoming pilot from the satellite thus ensuring that the same nominal frequency is received by the satellite from all suppliers transmitting via a TDM/TDMA channel to a particular beam.

Denoting the signal destined to beam b by $F_{up}(b)$, onboard the satellite the signal is frequency shifted using a constant frequency $F_{for}(b)$ and is transmitted using beam b . This signal $F_{down}(b)$ received by user n , U_n , is in the form of:

$$F_{down}(b, U_n) = F_{up}(b) + F_{for}(b) + \text{Doppler}(U_n) \quad (15)$$

where $\text{Doppler}(U_n)$ is the Doppler shift due to the motion of the satellite as observed by the n^{th} user. The Doppler shift varies from one user to the other as a function of their positions. Following the channel assignment of Eq. 14 the network controller has to ensure that in an area where frequency reuse is not implemented, for any beam number p and q ($p \neq q$), and and i and j ($i \neq j$),

$$|F_{down}(p, U_i) - F_{down}(q, U_j)| > BW_{forward}, \quad (16)$$

thus requiring wide guard bands or a constant changing of the TDMA channels center frequencies based on the location of the users in communication.

In the return direction where SCPC channels are assigned to users for transmission, the assignment procedure includes selection of an even greater number of center frequencies. In this link, assuming that Doppler correction is done on the inbound channel, means should be taken to correct the transmit frequency so that overlap at the satellite are avoided. That is at the satellite for any k and l ($k \neq l$) in a region without frequency reuse:

$$|F_{user_k} - F_{user_l}| > BW_{return}. \quad (17)$$

Furthermore, the downlink from the satellite to the suppliers will require frequency correction based on the received pilot by the suppliers.

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