Global MILSATCOM Augmentation Case Study:
Highly-Inclined Orbital Architectures and Spectrum Reuse

Unclassified

PREPARED FOR

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DFI INTERNATIONAL
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Overview

1. DFI was contracted by the OSD Joint C4ISR Decision Support Center to evaluate Global MILSATCOM Augmentation

2. As part of the effort, DFI examined the relative merits of alternative, non-Geostationary orbits for bandwidth augmentation and spectrum reusability

3. Through its initial analysis, DFI determined that highly-inclined, elliptical orbits offer a variety of strengths deserving further investigation:

- Strong Spectrum Reusability
- Ground Tracking
- Greater Coverage at High Latitudes
- Single Point of Control Opportunities
- Laser Crosslink Opportunities

Study Hypothesis: DoD should explore means to create spatial (equivalently: angular) separation in GEO bands to enable out-of-plane GEO spectrum reuse

Current Spectrum Situation

- **Little or no remaining unencumbered spectrum**
- **GEO spectrum is very scarce**
  - No spare Ku slots over CONUS
- **GEO expansion increasingly requires new bands**
  - More mission-constraining
  - Technically more challenging
- **Spatial isolation enables frequency reuse**
  - Widely used in Cellular/PCS and terrestrial RF licensing
  - Used within the GEO orbit. . And about used up!
  - Not yet exploited in GEO spectrum out of the single GEO orbit plane

To provide a comprehensive analysis of spectrum reuse opportunities, DFI examined a full range of satellite constellation designs

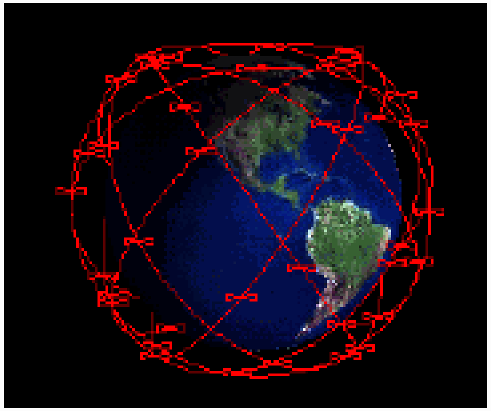
	System	Orbit
LEO MEO	Iridium	LEO near-polar
	Globalstar	LEO inclined
	ICO	Low MEO inclined
	"GPSComm"	High MEO inclined
Near GEO	Inclined Geostationary Two Types	Inclined GSO
	Molniya Two Types	Inclined highly elliptical
	Virtual Geostationary Two Types	Inclined highly elliptical

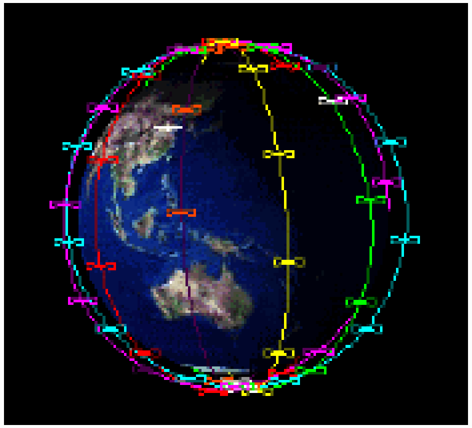
Despite initial popularity for Mobile Satellite Services (MSS), LEOs are very coverage inefficient

LEO and MEO System Characteristics

	Altitude, km	No. sats (operational)	Orbit inclination, °	Satellite weight, kg	Sat DC Power, watts	Visibility time, min	Footprint diameter, km (for 10° elev angle)	Minimum elev angle, °	Area/sat with >20° elev angle, million sq km	Number of Sats needed for 20° min elev angle°
Iridium	780	66	86.4	700	670	11.1	4150	8.75	6.7	160[1]
Globalstar	1,414	48	55	450	1000	16.4	5850	11	15	90[2]
ICO	10,390	12	45	2,750	8,600	115.6	12900	20	88	12
GPS Comm	20,200		55			~330	14,800		116	8

[1] 10 Planes of 16 satellites each following present design approach
[2] 90/10/1 Walker array at same altitude and inclination. Some small pockets below 20° remain.



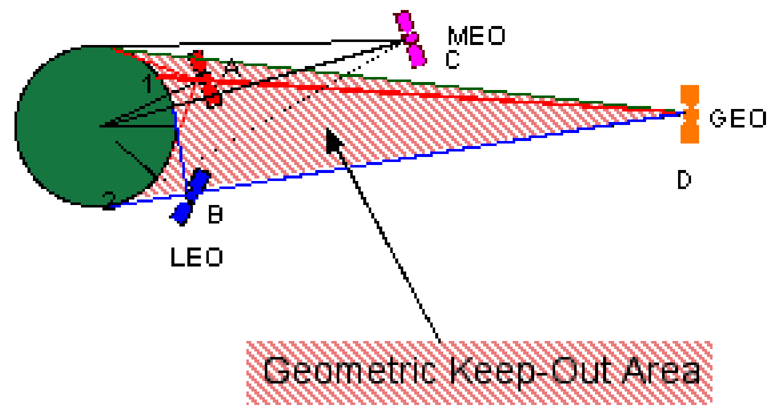


LEOs need *very* large satellite populations to yield good coverage and visibilities

Additionally, lower orbits typically offer poor GEO protection geometries

LEO and MEO Protection of GEOs

	Alt. km	Inclination	Satellite Latitude to which colinear interference with GEO occurs	Min Satellite latitude w/ ? 10° angular separation	Percent of orbit with at least 10° angular separation
Iridium*	780	86.4	54.3	64.3	47
Globalstar*	1,414	55	46.2	56.2	0
ICO**	10,390	45	13.7	23.7	65
GPS Comm**	20,200	55	5.2	15.2	82



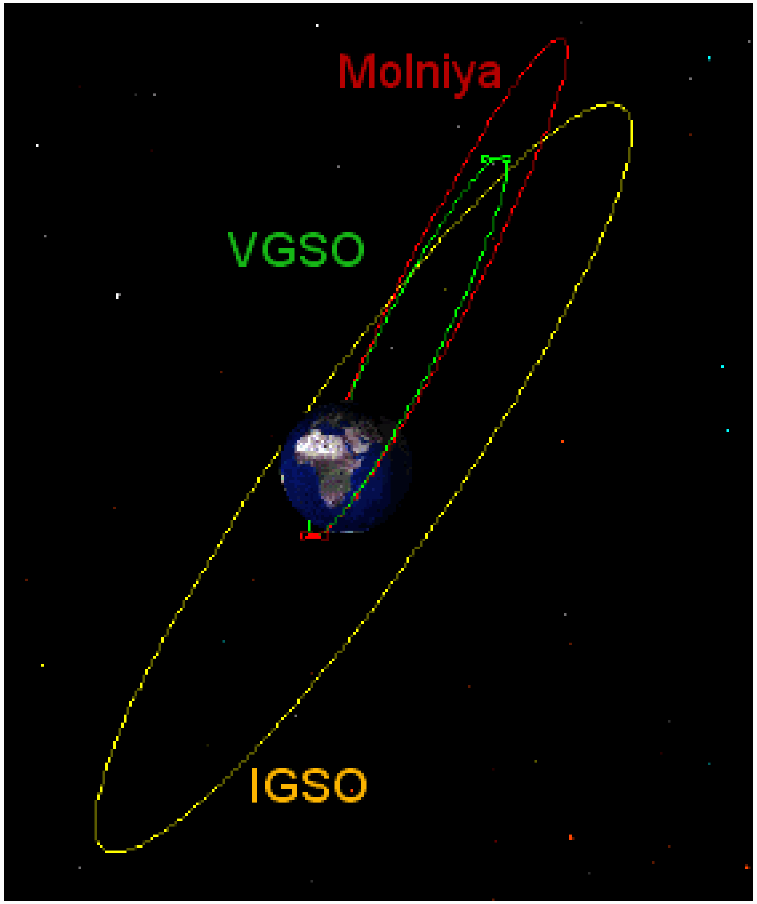
The lower the satellite, the larger the keep-out area

In conclusion, lower LEO/MEO orbits are unsuited for spectrum sharing with GEOs

- Large areas on the ground with colinear geometries
- Poor angular separation from GEO arc
- LEOs require too many satellite for good elevation angle performance
- LEO/MEOs do not offer low tracking rates
- Do not offer stationary features

DFI examined six Near-Geostationary concepts for relative performance and reuse capabilities

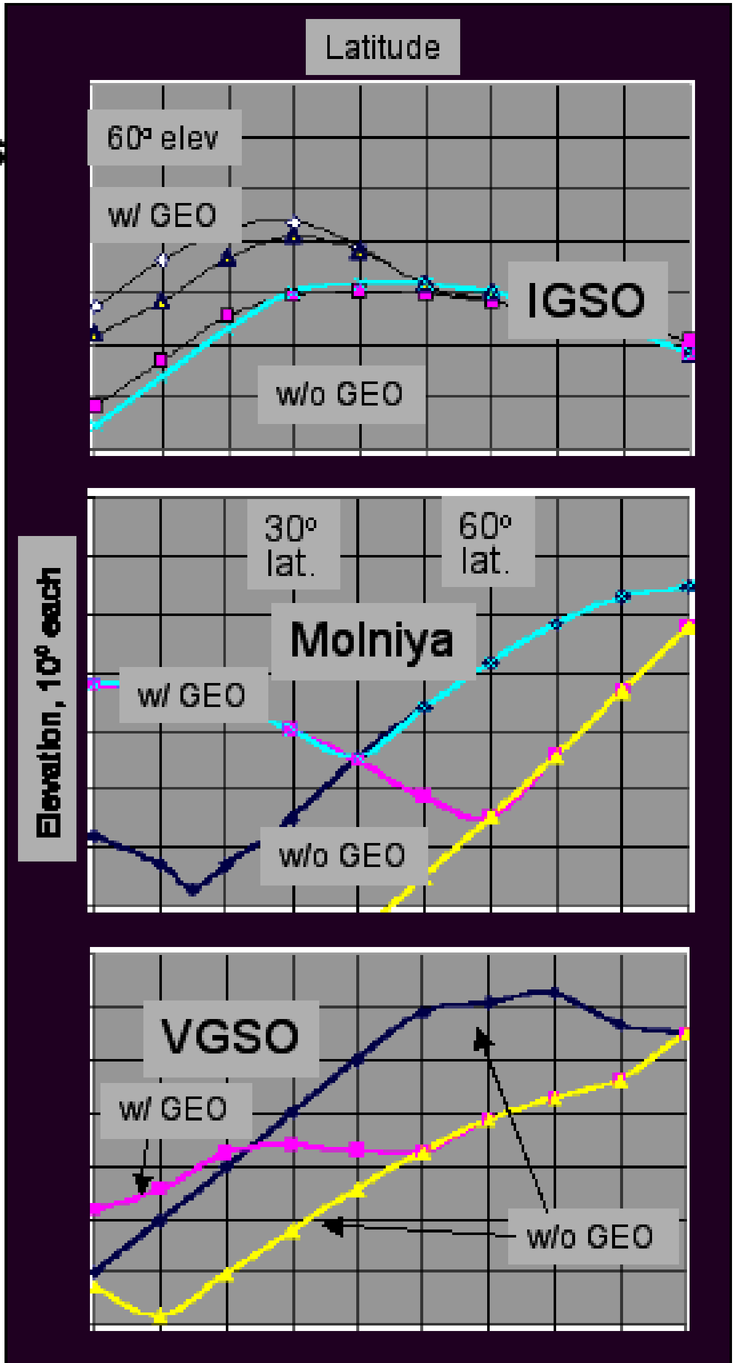
	Near-Geostationary Concepts Under Examination
Inclined Geostationary (IGSO) (55°)	3 in each of 3 figure-8 tracks plus 3 GEOs, total 12
IGSO (63.4°)	3 in each of 3 figure-8 tracks plus 3 GEOs, total 12
Molniya 3/track (63.4°)	3 in each of 2 tracks (1 North, 1 South) plus 4 GEOs, total 10
Molniya 2/track (63.4°)	2 in each of 2 tracks (1 North, 1 South) plus 4 GEOs, total 8
Virtual Geostationary (VGSO) 3-track (63.4°)	5 in each of 3 tracks (2 North, 1 South), total 15
VGSO 2track (63.4°)	5 in each of 2 tracks (1 North, 1 South),plus 3 GEOs, total 13



Notes:

- IGSOs are circular, the rest are elliptical
- Many mixes include GEOs, given that GEOs would play a role in an overall DOD capability

In general, ellipticals provide better coverage at higher latitudes than circulars, and offer greater visibility times compared to LEOs and MEOs



Near-GSO System Characteristics

	Inclined GSO (55º)	Inclined GSO (63.4º)	Molniya	VGSO 3-Track	VGSO 2-Track
Maximum Altitude, km	35,800	35,800	39,300	26,633	26,633
Min opnl Altitude, km	35,800	35,800	23,700	17,500	17,500
Latitude at Handover	24.2	26.6	45.5	44	44
Orbit Inclination	55	63.4	63.4	63.4	63.4
Number of Inclined	9	9	6	15	10
Number of GEOs	3	3	4	0	3
Visibility Time, min	480	480	480	288	288

Visibility time is proportional to max altitude

Ellipticals also maintain better separation from the GEO arc than circulars, enabling cleaner frequency reuse

System Characteristics for Near-GSOs

	Inclined GSO (55°)	Inclined GSO (63.4°)	Molniya	VGSO 3-Track	VGSO 2-Track
Footprint Diameter, 20° elev angle, km	15,900	15,900	Max 16,050	Max 15,400	Max 15,400
			Min 15,100	Min 14,400	Min 14,400
One-way delay, overhead, msec	119.3	119.3	Max 131.0	Max 88.8	Max 88.8
			Min 79.0	Min 58.3	Min 58.3
One-way delay, edge of coverage, msec	135.3	135.3	Max 147.1	Max 104.3	Max 104.3
			Min 94.4	Min 73.1	Min 73.1
Maximum Doppler, Hz	1,200 (poles)	1,300 (poles)	9,000	9,150	9,150
Maximum Tracking Slew-rate, °/sec	<0.009	<0.01	<0.005	<0.009	<0.009
Minimum NGSO angular sep from GEO arc	28°	32°	46°	41°	41°

Ellipticals hang at the higher latitudes longer than circulars

Initial cost estimates for a given mission profile display potential savings of elliptical systems

Relative Near-GSO Costs
(% of GEO Satellite of Same Capability)

	GEO	IGSO	Molniya-3	Molniya-2	VGSO
Antenna Cost	100	100	111	112	78
Payload Cost	100	100	88	116	69
Power Cost	100	100	97	104	91
Structure Cost	100	100	107	127	102
Attitude Determination and Control Cost	100	100	99	114	85
TT&C Cost	100	100	100	100	100
AKM Cost	100	75	0	0	0
Total Unit Satellite Cost	**100**	**99**	**92**	**108**	**78**
Unit Satellite + Launch Cost	**100**	**93**	**71**	**86**	**59**

Elliptical configurations cost less per satellite: mostly from launch and payload savings

Source: earlier tables, Wong, "Cost Modeling", Chapter 20 Space Mission Analysis and Design Larson and Wertz

In a measure of overall performance, robustness, and cost-effectiveness, VGSO 3 and Molniya-3 dominated

		IGSO	Molniya-3	Molniya-2	VGSO-3Track	VGSO-2Track
Constellation Cost		11.4	8.26	7.42	8.78	8.86
Separation from GEO arc		28/32	46	57.5	41	41
NGSO Modularity		3	2	1	3	2
NGSO satellite loss impact		0.33	0.33	0.5	0.2	0.2
Robustness		2	2	2	3	3
Min lat of Full NGSO visibility		79.3	61.8	50.2	64.8	64.8
Max NGSO Latency, msec		135	147	147	104	104
High latitude min elev angles	50N	30	34	19	59	32
	70N	27	48	26	62	47
NGSO Cost effectiveness		0.713	0.939	0.585	1.025	1.025
FCC Licensed (commercial)		No	No	No	Imminent*	No

Best (blue) / 2nd Best (yellow)

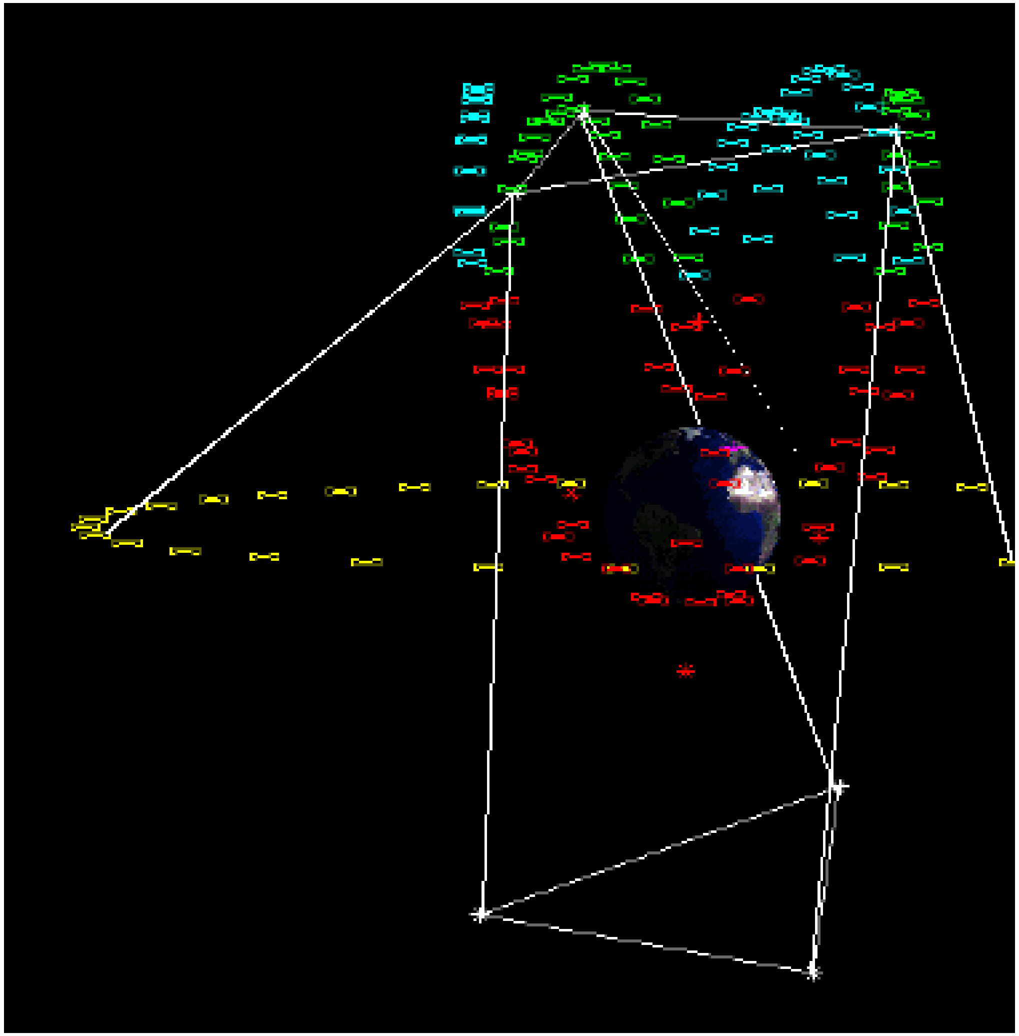
Best values: Molniya-2 (Constellation Cost 7.42, Separation from GEO arc 57.5, Min lat of Full NGSO visibility 50.2); IGSO (NGSO Modularity 3); VGSO-3Track (NGSO Modularity 3, NGSO satellite loss impact 0.2, Robustness 3, Max NGSO Latency 104, 50N 59, 70N 62, NGSO Cost effectiveness 1.025, FCC Licensed Imminent*); VGSO-2Track (NGSO satellite loss impact 0.2, Robustness 3, Max NGSO Latency 104, NGSO Cost effectiveness 1.025).

2nd Best values: Molniya-3 (Constellation Cost 8.26, Separation from GEO arc 46, NGSO Modularity 2, NGSO satellite loss impact 0.33, Robustness 2, Max NGSO Latency 147, 50N 34, 70N 48, NGSO Cost effectiveness 0.939); IGSO (NGSO satellite loss impact 0.33, Robustness 2, Max NGSO Latency 135); Molniya-2 (Robustness 2); VGSO-2Track (NGSO Modularity 2).

* FCC Report and Order issued, facilitates licensing additional systems

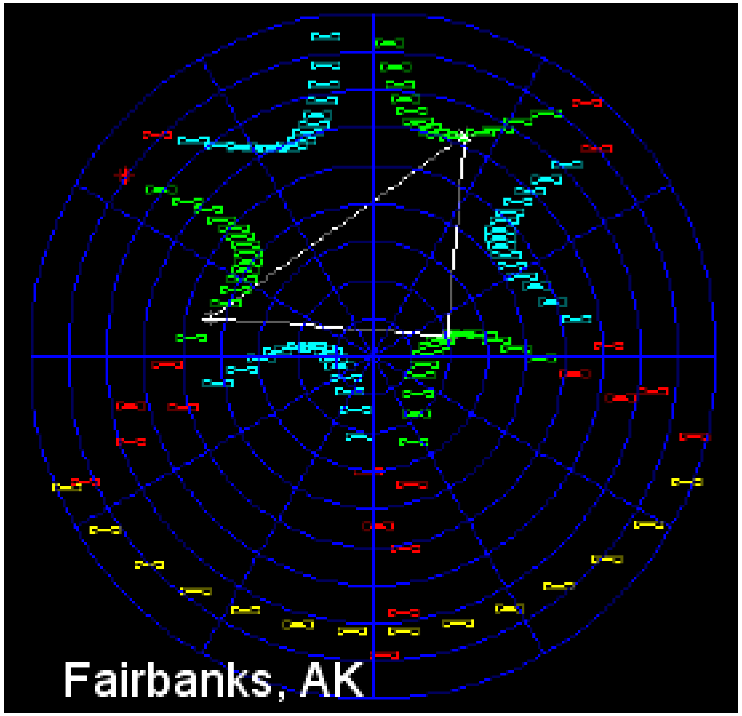
Moreover, utilization of optical crosslinks offers additional advantages to Near-GSO systems

- **Near-GSOs in active arcs can be fully mesh-interconnected**
  - GEOs cannot do this
- **Satellites networked to East-West and North-South neighbors by optical crosslinks**
- **Crosslinks**
  - Permit secure global content delivery
  - Expand control capabilities
  - Enable secure Gateway operations
- **GEO Optical crosslink developments directly applicable to Near-GSO active arcs**
  - Ranges
  - Tracking rates
- **Constellation design permits visibility of all Northern or all Southern Active arcs from one location each**



Finally, VGSO offers a variety of additional operational and financial benefits

- **Distributed Investment and Risk**
  - A single shared pool (track) of satellites serves 3 regions
  - No region depends on only one satellite
  - 80 percent service remains after a complete satellite loss (excluding diversity)
  - Diversity among multiple visible active arcs eliminates outages due to single satellite failures
  - Economic 1-for-5 sparing possible in lieu of expensive GEO 1-for-1 sparing
- **Single terrestrial points of control available in high Northern and Southern latitudes**
- **A single ground track begins full time service**
  - Incremental
- **Each Northern active satellite sees all other active Northern satellites all the time**
  - Ditto for Southern active satellites
  - Enables more robust mesh inter-satellite networking
- **Reduced Tracking Burden**
  - Only one track through sky for any active arc



Next Steps

1. Pursue an in-depth trades analysis for Near-GSO deployment
2. Based on trades analysis results, explore a Near-GSO design to expand GEO spectrum availability
3. If required, develop all-services, world-wide migration path to Near-GSO mission support