TRI-BAND GROUND STATION ANTENNA FOR EARTH OBSERVATION SATELLITES

B. Baggett[1], S. Parekh[1], D. Sinyard[1], B. Chandler[1], R. Morris[1]
[1]ViaSat Inc., Duluth, Georgia, USA

ABSTRACT

The need for increased downlink data rates and bandwidth for Earth Observation (EO) missions is driving mission planners to consider Ka-Band (25.5 to 27.0 GHz) downlinks to replace or augment the existing X-Band (8.025 to 8.400 GHz) services. Future ground stations will be required to support both bands as well as S-Band (2.0-2.3) GHz telemetry and command functions.
This paper discusses the inherent tradeoffs in such a design, and proposes an implementation which permits simultaneous data reception in X-Band and Ka-Band, while providing TT&C functionality at S-Band. Analytical and measured data for the implementation are provided.

KEY WORDS
Ka-Band, Tri-Band, Earth Observation, Dichroic, Subreflector,

INTRODUCTION

The last decade has seen an explosion of commercial and scientific EO satellites in low earth orbit. Since the early days of Landsat-4, the great majority of these satellites provide their high rate downlink in the 8025 to 8400 MHz EO band. Typically the same ground antenna employed for the high rate downlink is used to provide simultaneous telemetry and command at S-Band. The limitations of the bandwidth available in the current X-Band spectrum allocation is forcing systems designers to consider the provision of wideband downlinks in the 25,500 to 27,000 MHz band.

From a theoretical standpoint movement from X-Band to Ka-Band downlinks would seem to be a straight-forward design challenge. However, a number of heritage and technical issues complicate the design of these ground stations:

1) There is a significant installed base of X-Band ground stations. Many of these were recently built to support WorldView-1/2/3, Pleiades-1A/1B, and Landsat-8. Reuse of these new capital assets is of great interest.
2) The stations deployed for "mid-latitude" coverage are principally 7.3-m S-/X-Band stations that are lightly loaded ; typically observing less than ten passes per day. There is significant reluctance to adding additional antennas at these sites. The current owner/operators are motivated to achieve a relatively simple upgrade to add Ka-Band capability the existing systems.
3) The ever increasing need for bandwidth is likely to drive systems designers to include simultaneous X-Band and Ka-Band downlinks on future satellites.
4) Tracking at Ka-Band, where half-power beamwidths will approach 0.1 degrees poses satellite acquisition difficulties. The antenna now becomes much more

sensitive to ephemeris and station alignment. To ameliorate this problem, the antenna needs to have autotracking acquisition capability in all three bands.

REQUIREMENTS

As discussed in the paragraph above, the tri-band antenna system must support legacy X-Band high rate downlinks (for constellations like DigitalGlobe's WorldView and the Astrium Spot/Pleiades) and S-Band TT&C as well as the future Ka-Band wideband requirements. The legacy requirements are easily derived from existing missions. Ka-Band requirements are somewhat more speculative, but some preliminary work on these future systems is given in [1], [2] and [3]. A summary of these specifications is given in the table below:

Tab. 1. Summary of System Requirements

Requirement	Ka-Band Receive	X-Band Receive	S-Band Receive	S-Band Transmit
Frequency Range (GHz)	25.5 to 27.0	7.985 to 8.4	2.2 to 2.3	2.025-2.120
G/T (dB/K)	35.0	31.0	19.0	N/A
EIRP (dBW)	N/A	N/A	N/A	54.7
Autotrack Capability	Yes	Yes	Yes	N/A
Polarization	Simultaneous RHCP/LHCP	Simultaneous RHCP/LHCP	Simultaneous RHCP/LHCP	Selectable RHCP/LHCP
Axial Ratio (dB)	1.5	0.5	1.5	1.5

OPTIONS

There are many potential configurations to provide an S/X/Ka-band solution, each offering advantages and disadvantages. Tab. 1 below summarizes the approaches considered. Taking all the performance parameters into account, Approach 4 appears to offer the best solution. Fig. 1. shows the basic geometry of this approach. The selected optics provide high aperture efficiency and good autotracking performance at all three bands as well.

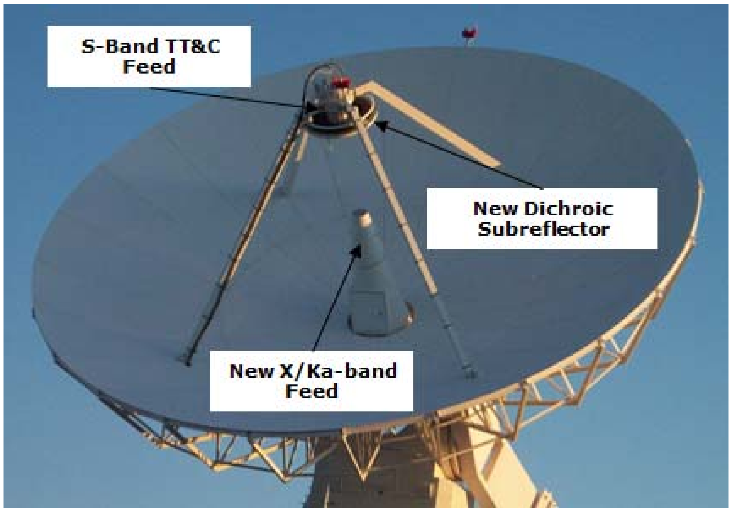


Fig. 1. Selected Antenna Geometry.

The 7.3-meter reflector used in the design has an F/D ratio of 0.4, which supports high accuracy autotracking at S-Band.

The surface accuracy of the reflector can be adjusted to a value of better than 0.36 mm RMS using photogrammetric alignment. With this level of accuracy the attendant losses at Ka-Band are held to approximately 0.53 dB.

:

Tab. 2. Summary of Tri-Band Antenna Architectural Approaches

Parameter	Approach			
	1	2	3	4
Description	Prime S/Ka	Splash Plate	Coaxial X/Ka	Turnstile X/Ka
S-Band Feed Optics	Prime Focus	Prime Focus	Prime Focus	Prime Focus
X-Band Feed Optics	Cassegrain	Cassegrain	Cassegrain	Cassegrain
Ka-Band Feed Optics	Prime Focus	Offset	Cassegrain	Cassegrain
Efficiency	Unacceptable at Ka-band	Acceptable	S-band: Standard X-band: 60% Ka-band: 35%	S-band: Standard X-band: 78% Ka-band: 86%
Tracking	Difficult to package Ka-band tracking coupler	Difficult to package Ka-band tracking coupler	S-band: 5 element X-band: 5 element Ka-band: TE21	S-band: 5 element X-band: 5 element Ka-band: TE21
Subreflector	Most complex configuration	Two frequency selective surface designs required: splash-plate and subreflector	Incorporate features from existing S/X-band and S/Ka-band subreflectors	Incorporate features from existing S/X-band and S/Ka-band subreflectors
Ease of Retro-fit	Simple swap of prime focus feed	Unacceptable mechanical complexity, challenging alignment	Simple swap of vertex mounted feed	Simple swap of vertex mounted feed
G/T	S-band: Low X-band: Compliant Ka-band: Low	S-band: Compliant X-band: Compliant Ka-band: Compliant	S-band: Compliant X-band: Low Ka-band: Marginal	S-band: Compliant X-band: Compliant Ka-band: Exceeds

Fig. 2 is a schematic of the optical design showing the critical dimensions in inches.

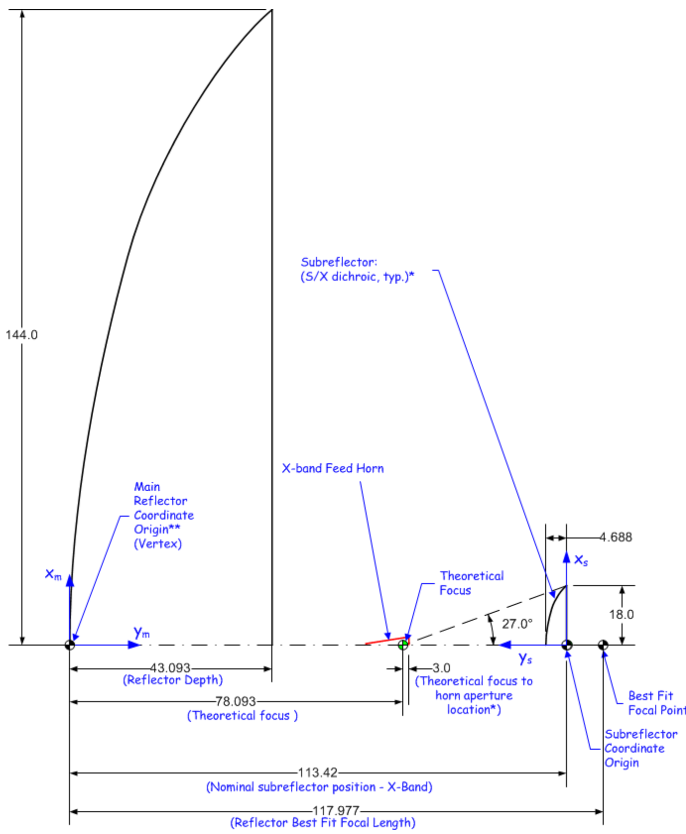


Fig. 2 Schematic of Antenna Optical Design (inches)

DICHROIC SUBREFLECTOR DESIGN

The dichroic subreflector is required to act as a near perfect reflector for the Cassegrain optics at X and Ka-Band, while approaching transparency for the prime focus mounted S-Band radiators. The added constraints of this tri-band operation required a significant departure from the more customary single-layer design.

A new optimized subreflector employs multiple layers of circuitry and dielectric material in order to achieve the desired frequency response across all three bands of interest. It was designed and optimized using a dual circuit approach that allows the simultaneous reflection of X and Ka-Band signals, while allowing S-band signals to pass through. The double square loop (DSL) elements were chosen because their resonant frequencies are fairly stable with respect to changes in incident angle. Also, the grid geometry is symmetrical in both the x and y directions, making the double square loop is a good choice for circular polarization applications. Fig. 3 shows the designed circuitry layer.

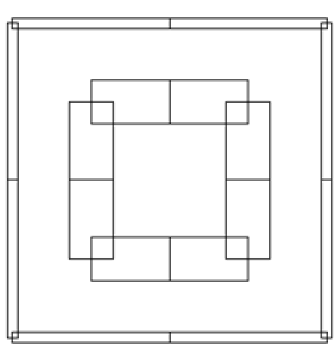


Fig. 3. Subreflector circuit design

The optimized design includes multiple circuit layers separated by an air gap. This air gap was added in order to achieve the desired frequency response at S-band. In this design, X-Band and Ka-Band signals share the same physical reflection layer. This is important to note as this prevents any de-focusing issues between X and Ka-Band in the main reflector optics.

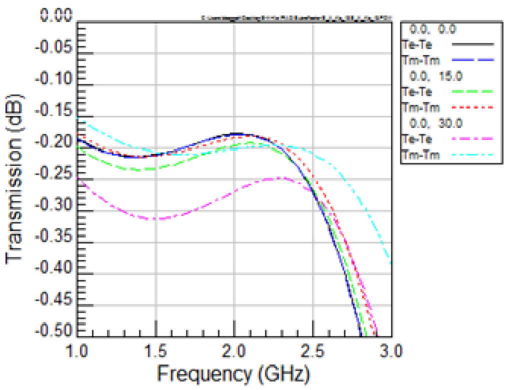


Fig. 4. S-Band Transmission Loss vs. Freq.

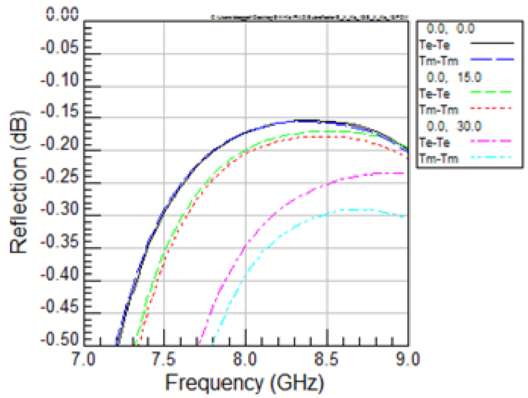
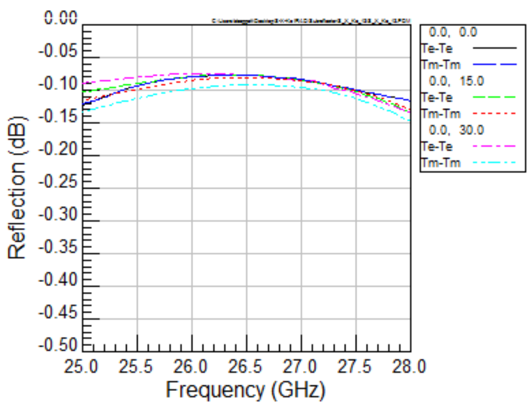


Fig.5. X-Band reflection Loss vs. Freq.



The results of the design are shown in Figs. 7-10 below. The subreflector produces transmission losses at S-Band which are held to under 0.30 dB across the band.

Reflection losses at X-Band are held at under 0.40 dB across the band. Ka-band losses are held under 0.15 dB across the band.

Fig. 6. Ka-Band Reflection Loss vs. Freq.

DUAL BAND HORN

The dual-band Cassegrain feed horn network must provide high gain at both X-band and Ka-band, while simultaneously providing similar illumination of the subreflector at both bands. The feed must also meet axial ratio requirements at X-band of ≤0.5dB to support simultaneous polarization downlinks.

A. Common Horn

The dual-band radiating feed assembly is designed to provide simultaneous operation in both X-band and Ka-band for both tracking and data collection in a circular polarization (CP) mode. The radiating element consists of a single horn which propagates both frequencies. The horn is a simple lightweight design and is specially optimized to provide similar radiating amplitude and phase patterns in both X-band and Ka-band. Figs. 7 and 8 show the computed far-field amplitude patterns of the horn at 8.2 GHz and 26.2 GHz.

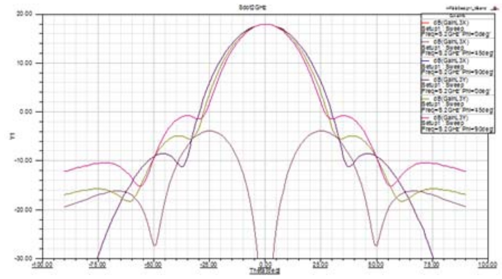


Fig. 7. Horn Amplitude Patterns at 8.2 GHz

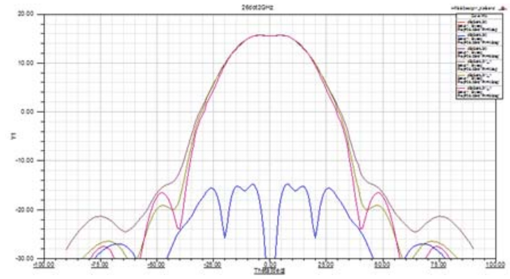


Fig. 8. Horn Amplitude Patterns at 26.2 GHz

The two frequency bands have the same phase-center location within the horn aperture. Combined with the optimized low-loss design of the dichroic subreflector, this common horn approach yields high efficiency operation in both frequency bands while also providing for simultaneous receive capability and mechanical simplicity.

B. Ka-band Network

The common horn provides a single Ka-band interface, located at the horn throat. It is at this point that the Ka-band receive and tracking network is attached. A TE21 mode coupler provides tracking signal outputs at both RHC and LHC polarizations. At the output of the coupler, a single device acts as both the polarizer and orthomode transducer (OMT). At the output of the OMT, both RHC and LHC data signals are provided to low noise amplifiers (LNAs). A low axial ratio is maintained throughout the Ka-band network in order to support dual polarization downlinks. The ground station reception capability is further aided by the cross polarization cancellation techniques of available advanced earth observation modems.

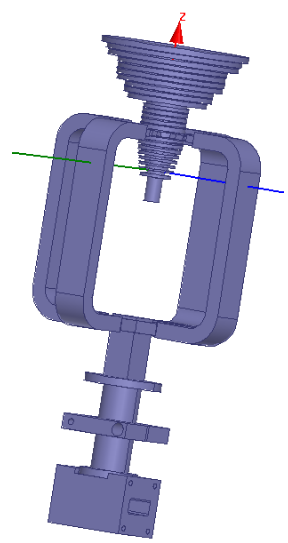


Fig. 9. X-band Network

C. X-band Network

The horn also couples to an X-band receive network via its integrated turnstile junction which provides the X-band signal at four symmetrically-displaced side openings. These four separate signals are then carried around the Ka-band mode coupler and into a recombination network. This consists of an X-band combiner, a polarizer, and an OMT. At the output of the OMT, separate RHC and LHC signals are made available to the LNA input.

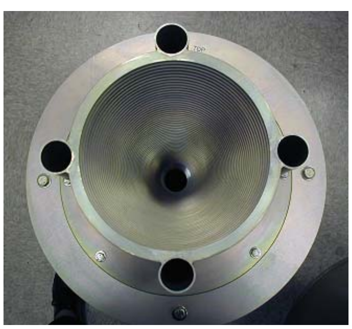


Fig. 10. X-band Tracking Layout

Four small horns surround the main horn radiating aperture to provide a five-horn monopulse tracking operation in X-band. These horns are carefully mechanically integrated around the rest of the X-band network. These signals are recombined with the data channel signals to form a traditional single channel monopulse tracking signal.

SYSTEM PERFORMANCE

The overall systems performance meets or exceeded the basic system performance parameters, as shown in Tab. 3. Another benefit of the design is that the feed designs can be used in a 9.14-m aperture with the same F/D without modification to achieve a gain increase of approximately 2.0 dB.

Tab. 3. Performance of Tri-Band Antenna Design

Parameters	S-Band	X-Band	Ka-Band
Aperture Efficiency (Illumination, Spillover, Subreflector Loss and Reflector Surface Tolerance Loss)	68%	85%	35%
Dichroic Loss (dB)	-0.3	-0.6	-0.3
Noies Temp Contribution due to Dichroic Surface (K)	9.0	6.0	4.0
Predicted G/T (including dichroic losses) (dB/K)	19.0	31.5	35.88

Tab. 4 and 5 below show the how the allocated losses and efficiencies effect the system net gain and G/T performance at Ka-Band.

Tab. 4 Ka-Band Gain Budget

Antenna Gain Budget

7.3M Ka-band w/Dichroic Subreflector

Rev 1 Date: 14-Jun-13

Budget Term		Receive 25.5 GHz Power Ratio	Receive 25.5 GHz dB	Comment
Antenna Diameter	24.0 ft			
Optics Type		Cassegrain		
Best Fit f/D ratio	0.4096			f/D used for surface tol loss
100% Efficient Aperture	7.32 M	1.000	65.82 dBi	
Directivity Contributors				
Illumination, Spillover, Central Blockage		0.440	-3.57 dB	GRASP Analsys
Spar Blockage		0.955	-0.20 dB	Quadrapod
Reflector Surface Tolerance	0.014 in	0.884	-0.53 dB	rms, normal to surface
Tri-band Sub		0.966	-0.15 dB	
Other directivity contributor		1.000	0.00 dB	
Design Margin		1.000	0.00 dB	
Impedance Mismatch Loss	1.30:1	0.983	-0.07 dB	Feed interface
Resultant Directivity		0.353	61.30 dBi	
Loss Contributors				
X/Ka Smooth Wall Aperture Loss		0.977	-0.10 dB	Approximated from HFSS
Tracking Coupler		0.944	-0.25 dB	Tracking Coupler Data
H-plane Bend		0.977	-0.10 dB	
Dielectric Loaded Circular Waveguide Loss		0.933	-0.30 dB	
		1.000	0.00 dB	
		1.000	0.00 dB	
		1.000	0.00 dB	
		1.000	0.00 dB	
		1.000	0.00 dB	
		1.000	0.00 dB	
Total Feed Losses			-0.75 dB	
Resultant Antenna Gain		0.297	**60.55 dBi**	Feed interface at back of polarizer
Required Gain			No spec	
Gain Margin			---	

Tab. 5 Ka-Band G/T analysis

System G/T Analysis

7.3M Ka-band w/Dichroic Subreflector

Version	Date	Frequency	Elevation Angle	Ambient Temperature	Vapor	Humidity	Precipitation
Rev 1	14-Jun-13	25.500 GHz	10.0 degrees	23 °C	7.5 g/m^3	36.5% RH	Clear sky

	Inputs				Outputs			
Contributors	Gain/Loss	Noise Figure	Device Input Noise Temp	ΔTemp Relative to Ambient	Cumulative Gain	Device Input Noise Temp	Device Noise Temp at LNA Input	System Noise Contribution
Not Used								
Not Used								
7.32 Meter Antenna	**61.30 dBi**		**115.0 K**		**61.30 dB**	**115.0 K**	**96.8 K**	**33.0%**
Feed Loss	-0.75 dB			0.0 °C	60.55 dB	55.8 K	46.97 K	16.0%
	0.00 dB			0.0 °C	60.55 dB	0.0 K	0.00 K	0.0%
				0.0 °C	60.55 dB	0.0 K	0.00 K	0.0%
				0.0 °C	60.55 dB	0.0 K	0.00 K	0.0%
				0.0 °C	60.55 dB	0.0 K	0.00 K	0.0%
Low Noise Amplifier	**50.00 dB**	**1.8 dB**	**149.0 K**		**110.55 dB**	**149.0 K**	**149.0 K**	**50.9%**
Post LNA and WG Loss	-3.06 dB			0.0 °C	107.49 dB	303.0 K	0.00 K	0.0%
	0.0 dB			0.0 °C	107.49 dB	0.0 K	0.00 K	0.0%
Data D/C	28.00 dB	16.0 dB	11255.1 K		135.49 dB	11255.1 K	0.23 K	0.1%
Cable	-2.20 dB			0.0 °C	133.29 dB	195.3 K	0.00 K	0.0%
	0.0 dB			0.0 °C	133.29 dB	0.0 K	0.00 K	0.0%
	0.00 dB	0.0 dB	0.0 K		133.29 dB	0.0 K	0.00 K	0.0%
IFL (100m of LDF4)	-6.10 dB			0.0 °C	127.19 dB	910.3 K	0.00 K	0.0%
	0.0 dB			0.0 °C	127.19 dB	0.0 K	0.00 K	0.0%
	0.00 dB	0.0 dB	0.0 K		127.19 dB	0.0 K	0.00 K	0.0%
	0.00 dB			0.0 °C	127.19 dB	0.0 K	0.00 K	0.0%
Receiver		13.0 dB	5496.3 K		127.19 dB	5496.3 K	0.00 K	0.0%
							293.0 K	100.0%

Pre-LNA System Noise:	143.73 K	49.1%	Required G/T:	35.00 dB/K
LNA System Noise:	149.00 K	50.9%		
Post-LNA System Noise:	0.23 K	0.1%	Computed G/T:	35.88 dB/K at 10.0° Elevation Angle
Total System Noise at LNA Input:	293.0 K	100.0%		
System Gain at LNA Input:	60.55 dB		Margin:	0.88 dB/K

It must be noted that none of the analysis include the losses and system noise temperature increases that would result from placing the antenna under a radome. Those losses may exceed 1.0 dB in practice.

CONCLUSION

The requirements for future Tri-Band earth observation satellite ground stations have been analysed. Following a trade study of candidate configurations for an antenna capable of meeting this requirement an architecture was selected, the key components (dichroic subreflector and dual-band horn) were designed and used to determine the system performance.

REFERENCES

[1] Klaus-Dieter Günthner, Ulrich Petruschke, Clemens Kalde, Robert Purvinskis, Jörg Lange, David A. Smith, Martin Smith, "Ka-Band Downlink End-to-End Communication System for Earth Exploration Satellites," *5th ESA International Workshop on Tracking, Telemetry and Command Systems for Space Applications*

[2] J. Roselló, A. Martellucci, R. Acosta, J. Nessel, L.E. Bråten, C. Riva "26 GHz Data Downlink for LEO Satellites," *5th ESA International Workshop on Tracking, Telemetry and Command Systems for Space Applications*

[3] Mario Cossu, Michelangelo L'Abbate, Rita Roscigno, Carlo Svara, Josep Rosello, "Ka-Band Architecture and Performance for EO Satellites," *5th ESA International Workshop on Tracking, Telemetry and Command Systems for Space Applications*

[4] Christophe Granet, et. al., “A Deployable Simultaneous X/Ka-Band Satcom Antenna to Support WGS,” *MILC2008, Canberra, 18-20 November 2008*