REPORT ITU-R M.2083

Level of unwanted emissions of mobile-satellite service feeder links operating in the bands 1 390-1 392 MHz (Earth-to-space) and 1 430-1 432 MHz (space-to-Earth)

(2006)

Scope

This Report addresses techniques to control unwanted emission levels of mobile-satellite service (MSS) feeder links (Earth-to-space) that may operate in the band 1 390-1 392 MHz and MSS feeder links (space-to-Earth) that may operate in the band 1 430-1 432 MHz.

Introduction

The allocations to the fixed-satellite service (FSS) in the bands 1 390-1 392 MHz (Earth-to-space) and 1 430-1 432 MHz (space-to-Earth) are limited to use by feeder links for non-geostationary-satellite networks in the MSS with service links below 1 GHz. The band 1 400-1 427 MHz is allocated to the Earth exploration-satellite service (EESS) (passive), radio astronomy and space research (passive) services on a primary basis in all Regions and that RR No. 5.340 also applies to the band 1 400-1 427 MHz. Unwanted emissions from FSS links may cause harmful interference to passive services requiring careful design of the transmission sub-system.

The information provided in Annexes 1 to 3 of this Report should be taken into account for the control unwanted emission levels of MSS feeder links operating in the bands 1 390-1 392 MHz and 1 430-1 432 MHz. Baseband processing techniques without a specific post-amplifier filter, as described in Annex 1 for typical combinations of data rates and modulation techniques, should be used to reduce the unwanted emissions from MSS feeder links operating in the bands 1 390-1 392 MHz and 1 430-1 432 MHz into the band 1 400-1 427 MHz to the levels required for the protection of the passive services as defined in Recommendations ITU-R M.1747 and ITU-R M.1748.

An additional post-amplifier filter as described in Annex 3 should be used in cases where the baseband processing techniques are not sufficient to meet the levels required for the protection of the passive services in the band 1 400-1 427 MHz.

Annex 1

Evaluation of unwanted emissions in the 1 400-1 427 MHz band from non-GSO MSS feeder links that may operate in the 1 390-1 392 MHz and 1 430-1 432 MHz bands

1 Introduction

This Annex provides power spectral-density (PSD) data generated via simulation for non-GSO MSS feeder-link transmitters that may operate in the 1 390-1 392 MHz and 1 430-1 432 MHz bands. Modulation techniques considered here include offset quadrature phase shift keying (OQPSK), GMSK and 8-ary PSK (8-PSK) for channel bandwidths of 100 kHz, 300 kHz and 855 kHz. The simulation model used for this study was first validated against hardware measurement data, and then PSD data was generated via simulation for other modulation techniques and channel bandwidths. Two hardware fidelity grades were considered, low and high, in an effort to bound the expected performance of the non-GSO MSS feeder-link transmitters.

2 Technical characteristics of the MSS system

The potential characteristics of non-GSO feeder links that may operate in the 1 390-1 392 MHz and 1 430-1 432 MHz bands are assumed to lie within the ranges given in Table 1. These characteristics are based primarily upon those given in Annex 2 of Recommendation ITU-R M.1184-2.

TABLE 1

Potential technical characteristics of MSS feeder links that may operate in the 1 390-1 392 MHz and 1 430-1 432 MHz bands*

Link	Parameter	Value
Gateway uplink (Earth-to-space)	Band	1 390-1 392 MHz
	Channel bandwidth	30-855 kHz
	Modulation	OQPSK, GMSK, 8-PSK
	Data rate	4.8 kbit/s-3.42 Mbit/s(1)
	Transmit power	1-250 W
Gateway downlink (space-to-Earth)	Band	1 430-1 432 MHz
	Channel bandwidth	30-855 kHz
	Modulation	OQPSK, GMSK, 8PSK
	Data rate	4.8 kbit/s-1.2825 Mbit/s(1)
	Transmit power	1-250 W

* Except where noted, these characteristics are based upon the characteristics given in Annex 2 of Recommendation ITU-R M.1184-2.

(1) Range selected based upon data rates given in Annex 2 of Recommendation ITU-R M.1184-2 and based upon data rates which produce null-to-null bandwidths of 100 kHz, 300 kHz and 855 kHz for the modulation techniques considered in this study.

3 Simulation model

3.1 Approach

Figure 1 provides the transmitter reference architecture assumed for this analysis.

Figure 2 provides the power amplifier power out versus power in curve. The operating points assumed for this study are indicated on the plot.

Figure 3 provides the power amplifier phase change versus power in curve. Again, the operating points are shown.

Figure 4 provides the duplexer filter attenuation characteristics assumed for this study. Also provided in Fig. 4 are the attenuation characteristics of example two-stage resonant cavity filters. The amount of duplexer attenuation was determined by assuming the MSS feeder link receive band will need over 50 dB of protection from the local MSS feeder-link transmission with about 10 dB of this protection coming from isolation introduced by the return loss of the antenna and about 1 dB of loss through the circulator.

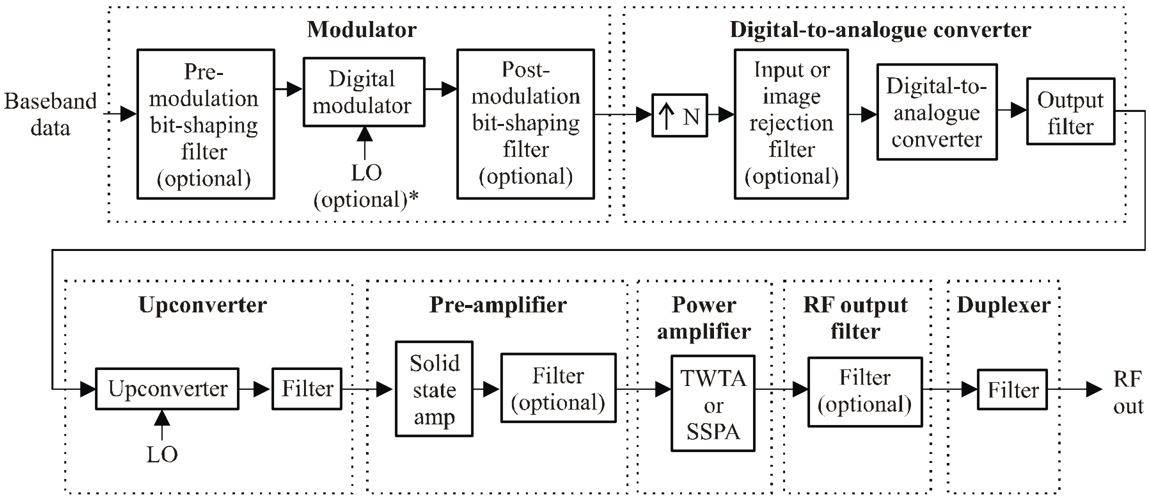
Figure 5 provides a diagram of the duplexer.

Table 2 describes the transmitter architecture characteristics assumed for this analysis. The use of a digital modulator with pre- or post-modulation digital filtering for the simulations is a valid assumption, as the highest modulation symbol rate considered in this study is 427.5 kbit/s (= 855/2 kbit/s), whereas digital modulators can be built to support modulation symbol rates up to at least 100 Mbit/s.

Table 3 provides the transmitter distortion values assumed for this study. It should be noted that this study assumed that the baseband data provided to the modulator was random. If a pattern data is assumed, the results presented in this paper could change slightly. Although in general, pattern data will introduce modulation spurs in the PSD, these will likely be negligible given the large offset in frequencies between the passive service band and the proposed MSS feeder-link bands.

FIGURE 1

Assumed transmitter architecture



Note 1 – Results presented in this Report are applicable to one-stage or two-stage upconversion architecture.

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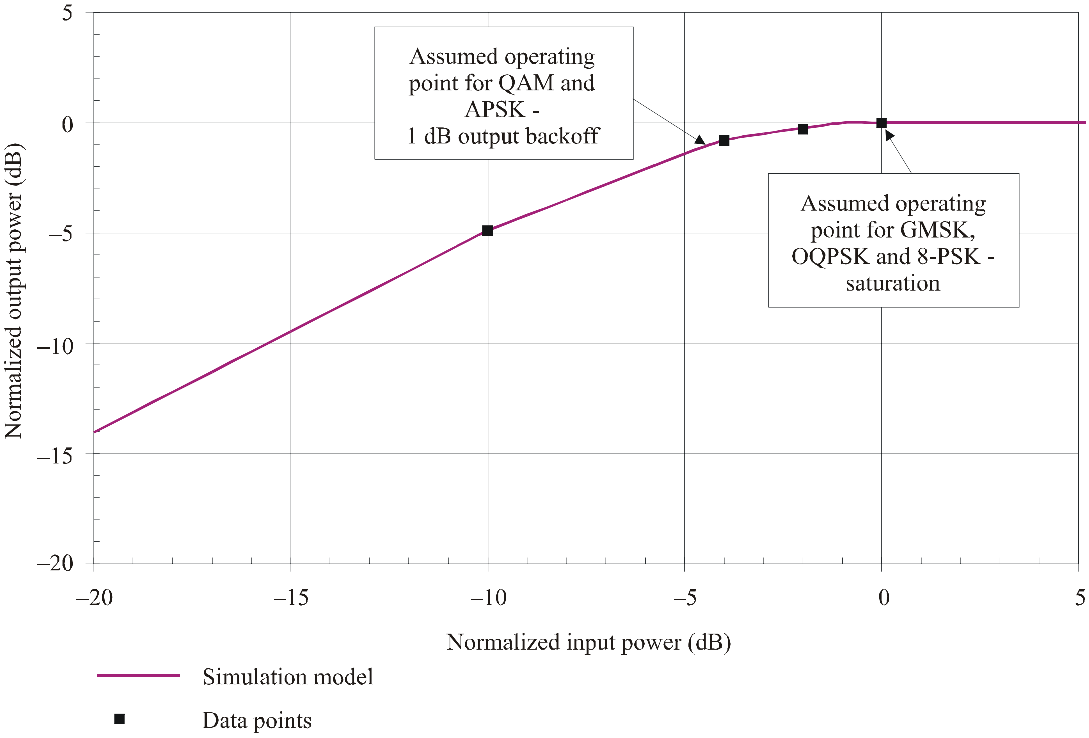
FIGURE 2

Assumed transmitter power amplifier P_{out} versus P_{in} characteristics



Note 1 – Because 8-PSK results collected with power amplifier operating in saturation, 8-PSK results can, at times, be worse than QAM.

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FIGURE 3

Assumed transmitter power amplifier θ_{change} versus P_{in} characteristics

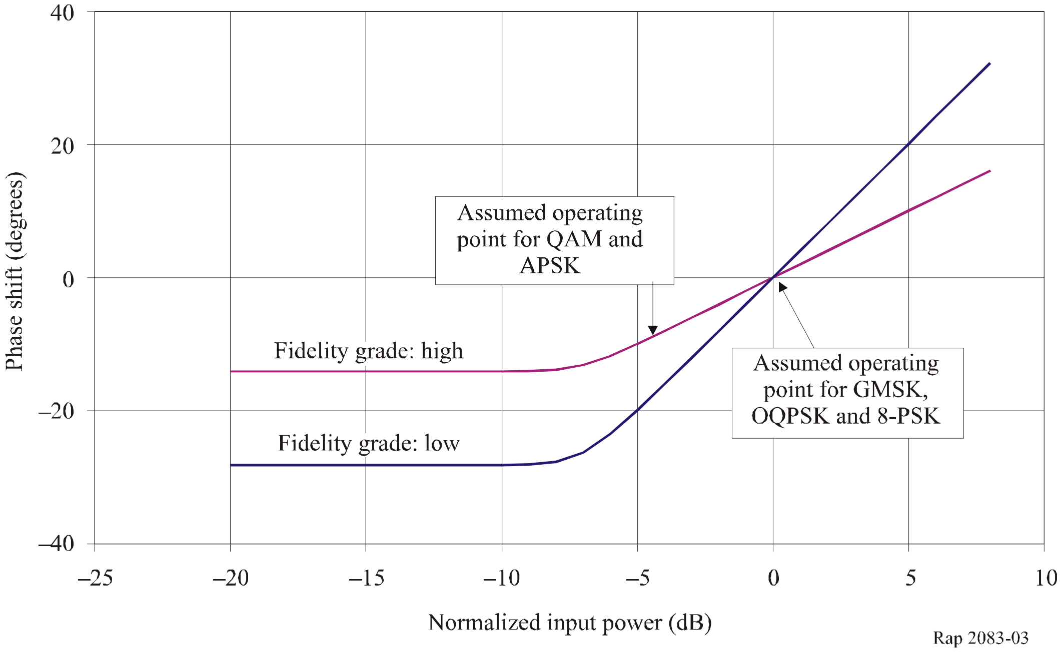

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FIGURE 4

Assumed duplexer attenuation characteristics

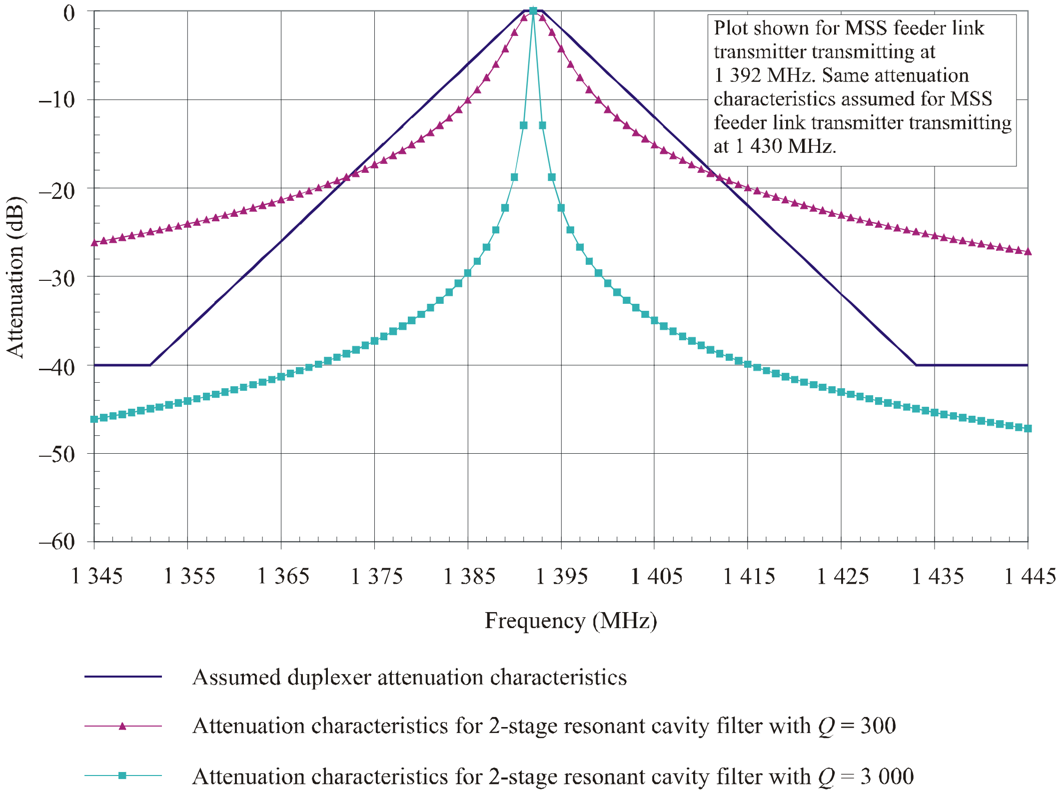


TABLE 2

Assumed transmitter architecture characteristics

Component group	Component	Parameter	Value: Fidelity grade: low	Value: Fidelity grade: high	Comments
Modulator	Pre-modulation bit-shaping filter	Filter type	Gaussian, raised cosine (RC)	Gaussian, RC	– Filter can be optionally bypassed (e.g. for unfiltered case or post-modulation filtered case). – Gaussian filter used for GMSK; RC used for OQPSK; filter bypassed for 8-PSK and QAM which utilize post-modulation filtering
		Filter implementation	64-tap finite impulse response (FIR)	128-tap FIR	– Fewer taps can result in higher Tx output PSD levels – especially beyond the first few side lobes. – Most hardware would likely use 128 taps, however, 64 taps considered here as worst case

TABLE 2 (*continued*)

Component group	Component	Parameter	Value		Comments
			Fidelity grade: low	**Fidelity grade: high**	
Modulator	Pre-modulation bit-shaping filter	Quantization	6-bit(1)	12-bit(1)	– Fewer quantization bits can result in higher Tx output PSD levels – especially beyond the first few side lobes. – Actual hardware would likely use 8-bit or better, however, 6-bit assumed here as worst case
		3 dB bandwidth (one-sided)	50 kHz, 150 kHz, 427.5 kHz	50 kHz, 150 kHz, 427.5 kHz	– Values respectively apply to GMSK $BT_b = 0.5$(2) and OQPSK $BT_s = 1.0$(2) at 100 kbit/s, 300 kbit/s and 855 kbit/s
	Modulator	Clock rate	1.8 MHz to 22.23 MHz	3.6 MHz to 22.23 MHz	– Exact value dependent on data rate and modulation – on the low end 3.6 MHz applies to 100 kbit/s OQPSK, etc. and on the high end 22.23 MHz applies to 855 kbit/s GMSK
		Quantization	6-bit(1)	12-bit(1)	– Fewer quantization bits can result in higher Tx output PSD levels – especially beyond the first few side lobes. – Actual hardware would likely use 8-bit or better, however, 6-bit assumed here as worst case
		LO frequency	Not assumed	Not assumed	– Simulation model uses – equivalent low-pass signal representation (distortions of frequency translation modelled but not the actual frequency translation), therefore, exact definition of LO and IF frequencies not necessary
		Output frequency	Not assumed	Not assumed	
	Post-modulation bit-shaping filter	Filter type	RC	RC	– Filter can be optionally bypassed (e.g. for unfiltered case or pre-modulation filtered case). – RC used for 8-PSK and QAM; filter bypassed for GMSK and OQPSK
		Filter implement-ation	64-tap FIR	128-tap FIR	– Actual hardware would likely use 128 tap or greater, however, 64 tap considered here as worst case. – Fewer taps can result in higher Tx output PSD levels – especially beyond the first few side lobes

TABLE 2 (*continued*)

Component group	**Component**	**Parameter**	**Value**		**Comments**
			Fidelity grade: low	**Fidelity grade: high**	
Modulator	Post-modulation bit-shaping filter	Quantization	6-bit(1)	12-bit(1)	– Fewer quantization bits can result in higher Tx output PSD levels – especially beyond the first few side lobes. – Actual hardware would likely use 8-bit or better, however, 6-bit assumed here as worst case
		3 dB bandwidth (at IF)	100 kHz, 300 kHz, 855 kHz	100 kHz, 300 kHz, 855 kHz	– Values respectively apply to 8-PSK 150 kbit/s, 450 kbit/s and 1.2825 Mbit/s. – Values selected to produce $BT_s = 1.0$(2)
Digital-to-analogue converter (DAC)	Input filter or image rejection filter	Filter type	Generic	Generic	
		Filter implement-ation	64-tap FIR	128-tap FIR	– Fewer taps can result in a slower filter roll-off and, therefore, a higher Tx output PSD envelope
		Quantization	12-bit(1)	16-bit(1)	– Actual hardware would likely use 12- or 16-bit
		3 dB bandwidth	500 kHz to 4.275 MHz	500 kHz to 4.275 MHz	– Exact values dependent on data rate, modulation, modulator clock rate and DAC clock rate. – Introduces modest filtering. – Useful for limiting out-of-band emissions with little to no impact to BER
		Roll-off	0.020 dB/kHz to 0.022 dB/kHz	0.020 dB/kHz to 0.022 dB/kHz	
	Digital-to-analogue converter	Clock rate	21.6 MHz to 44.46 MHz	21.6 MHz to 44.46 MHz	– Exact values dependent on modulation and data rate
		Quantization	12-bit(1)	16-bit(1)	– Actual hardware would likely use 12-bit or better. – While the PSD envelope/floor can be driven by quantization in the DAC, DAC output filter generally precludes this from occurring
	Output smoothing filter	3 dB bandwidth	~2 MHz	~2 MHz	– Based upon comments by MSS feeder-link hardware developers
		Roll-off	25 dB/MHz	25 dB/MHz	– 8th order Butterworth filter was used

TABLE 2 (*continued*)

Component group	Component	Parameter	Value		Comments
			Fidelity grade: low	**Fidelity grade: high**	
Up-converter	Up-converter	IF input frequency	Not assumed	Not assumed	– Simulation model uses – equivalent lowpass signal representation (distortions of frequency translation modelled but not the actual frequency translation), therefore, exact definition of LO and IF frequencies not necessary
		LO frequency	Not assumed	Not assumed	
		RF output frequency	1 390-1 392 MHz 1 430-1 432 MHz	1 390-1 392 MHz 1 430-1 432 MHz	– Defined by frequency bands considered for allocation to non-GSO MSS feeder links
	Filter	3 dB bandwidth	Bypassed	Bypassed	– Filter bypassed to ensure conservative results. – Up-converter model does not produce unwanted image because baseband equivalent signal representation used, therefore, filter not required in simulation model
		Roll-off	Bypassed	Bypassed	
Pre-amplifier	Amplifier	Type	TWTA	TWTA	– Noise figure discussed in Table 3
	Filter	3 dB bandwidth	Bypassed	Bypassed	– Filter bypassed to ensure conservative results. – Transmitter designers must weigh the benefits of spectral containment against the insertion loss
		Roll-off	Bypassed	Bypassed	
Power - amplifier	Amplifier	Type	Solid-state amplifier	Solid-state amplifier	– Modelled after 50 W TWTA. – Noise figure discussed in Table 3
	Filter	3 dB bandwidth	Bypassed	Bypassed	– Filter bypassed to ensure conservative results. – Transmitter designers must weigh the benefits of spectral containment against the insertion loss
		Roll-off	Bypassed	Bypassed	
RF output filter		Type	Resonant cavity	Resonant cavity	– Filter bypassed to ensure conservative results. – Transmitter designers must weigh the benefits of spectral containment against the insertion loss
		3 dB bandwidth	Bypassed	Bypassed	
		Roll-off	Bypassed	Bypassed	

TABLE 2 (*end*)

Component group	Component	Parameter	Value		Comments
			Fidelity grade: low	Fidelity grade: high	
Duplexer (transmit path)		Type	Resonant cavity	Resonant cavity	– Duplexer required to protect the feeder-link receive band from the feeder-link transmit band. – See Fig. 4 for plot of assumed duplexer attenuation characteristics. – Duplexer attenuation characteristics determined by assuming the MSS feeder-link receive band will need over 50 dB of protection from the local MSS feeder-link transmission with about 11 dB of this protection coming from isolation introduced by the antenna and circulator components and the rest required to come from the duplexer. – Duplexer can have a large impact on the Tx PSD envelope/floor
		3 dB bandwidth	2 MHz	2 MHz	
		Roll-off	1 dB/ MHz	1 dB/ MHz	

(1) Clip levels set near optimally. Similar PSDs will result if more quantization bits are used but clip levels not set optimally.

(2) Where B is the one-sided bandwidth of the filter, T_b is the bit duration when data is in a single data stream and T_s is the modulation symbol duration.

TABLE 3

Assumed transmitter distortions(1)

Parameter	Value		Comments
	Low fidelity	High fidelity	
Data asymmetry	1%	0%	– Data asymmetry is present when one data bit polarity state is longer in duration than the other data bit polarity state – it is effectively the fixed error component of data bit jitter. – Data asymmetry introduces spikes in the Tx output PSD. – Digital modulators typically have no data asymmetry, however, 1% is considered here as a worst-case amount. – This study assumed data asymmetry was not applicable to GMSK and 8-PSK

TABLE 3 (*continued*)

Parameter	Value		Comments
	Low fidelity	High fidelity	
I/Q data skew	1%	0%	– I/Q data skew is the variation from the ideal time delay between the I channel data transitions and the Q channel data transitions. – I/Q data skew makes PSD more susceptible to spectral regrowth following a nonlinearity (such as the PA) – as compared to ideal OQPSK. – This study assumed I/Q data skew was not applicable to GMSK and 8-PSK
Modulator gain imbalance, peak	~ 0.6 dB	~ 0.6 dB	– Gain imbalance is present when one or more of the modulation vector magnitudes differ from the ideal value. – Value dependent on modulation, bit-shaping, quantization and quantization clip level setting
Modulator phase imbalance, peak	~ 6.0°	~ 5.3°	– Phase imbalance is present when one or more of the modulation vector phases differ from the ideal value. – Value dependent on modulation, bit-shaping, quantization and quantization clip level setting
Gain flatness, peak-to-peak	1.0 dB	0.6 dB	– Assumed values based upon available hardware
Gain slope, peak	0.1 dB/kHz	0.1 dB/kHz	– Assumed values based upon available hardware
Phase non-linearity, peak-to-peak	8°	6°	– Assumed values based upon available hardware
AM/AM conversion	0.0 dB/dB to 0.6 dB/dB	0.0 dB/dB to 0.6 dB/dB	– See Fig. 2 – saturation assumed for GMSK, OQPSK and 8-PSK. – AM/AM introduces spectral regrowth in non-constant envelope signals
AM/PM conversion	4°/dB at operating point	2°/dB at operating point	– See Fig. 3. – AM/PM does not have as large of an impact on the out-of-band emissions as AM/AM
Frequency instability, peak over lifetime	1 ppm	0.1 ppm	– Assumed values based upon available hardware. – Based upon this value, it can be determined that a transmitter centred at 1 430 MHz can drift no more than 1.43 kHz – this amount of drift is insignificant relative to the data rates and band separation amounts considered in this study – a drift of this amount toward the passive service band will change the interference power negligibly

TABLE 3 (*continued*)

Parameter	Value		Comments
	Low fidelity	**High fidelity**	
Phase noise @ 1 430 MHz RF	≥1 MHz offset frequency: ≤ –151 dBc/Hz	≥1 MHz offset frequency: ≤ –157 dBc/Hz	– Values based upon available hardware – most 5 MHz reference oscillators have a phase noise floor of –150 dBc/Hz or better – scaling up to 1 430 MHz yields a phase noise PSD floor of –101 dBc/Hz – methods exist for cleaning up the reference far from the carrier – it is assumed here those methods will yield a phase noise floor far from the carrier no greater than –151 dBc/Hz. – Based upon this floor, it can be concluded that phase noise will have no appreciable impact on the PSD envelope – it should be noted, however, if h/w design not sound and component selection poor, phase noise can ultimately drive the PSD floor. – This analysis did not simulate phase noise as it will have no impact on the PSDs – DAC quantization is driving PSD floor
Antenna(2) and/or PA-induced AM	5%	1%	– Assumed values based upon available hardware
Spurious PM @ 1 430 MHz RF	≥1 MHz offset frequency: ≤ –150 dBc/Hz	≥1 MHz offset frequency: ≤ –156 dBc/Hz	– Similar discussion/derivation as provided for phase noise. – Most reference oscillators and upconverter oscillators have very little discernible spurious PM. – This analysis did not simulate spurious PM, however, if it did, it would be below the PSD envelope for all modulations and data rates
Spurious outputs	> 1 MHz: < –150 dBc	> 1 MHz: < –156 dBc	– Spurs will likely be introduced by up-converter, however, they will likely be below PSD floor or filter following upconverter will likely render them insignificant – This analysis did not simulate spurious outputs, however, if they were simulated, they would be below the PSD envelope for all modulations and data rates
Data rate inaccuracy	0.0%	0.0%	– Assumed hardware exactly achieves desired data rate
I/Q power ratio inaccuracy	0.0 dB	0.0 dB	– Assumed hardware exactly achieves desired I/Q power ratio. – I/Q power ratio inaccuracy likely has no impact on Tx output PSD
Data bit jitter	1%	0.1%	– It is expected that data bit jitter will have a moderate impact on the PSD near the mainlobe and the first few side lobes, however, minimal impact beyond that. – This analysis could not simulate data bit jitter as this distortion does not lend itself well to being simulated

TABLE 3 (*end*)

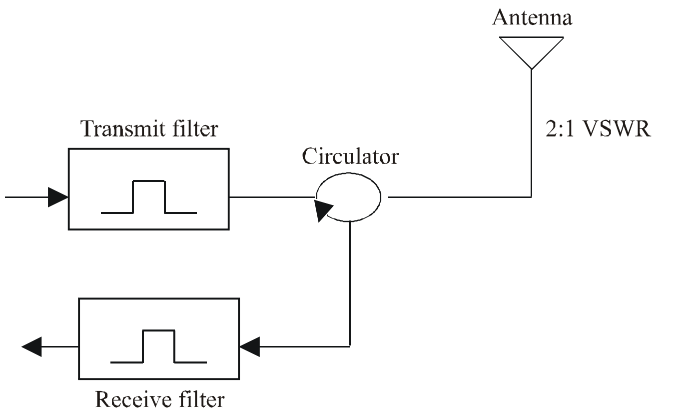
Parameter	**Value**		**Comments**
	Low fidelity	**High fidelity**	
System noise figure	40.5 dB	18.5 dB	– Noise figure can and generally does drive PSD floor. – Noise figure will introduce a PSD floor according to the following equation: PSD Floor = (Noise Factor – 1) × 290 × Boltzmann's Constant, W/Hz where Noise Factor = 10^(Noise Figure/10) – Output duplexer will shape this floor far from the Tx centre frequency

(1) Distortion amounts are total amounts for the entire transmitter.

(2) Although the results of this Report are referenced at the MSS feeder-link antenna interface, this antenna distortion is included in the simulation model. This AM is in addition to that introduced by pre-modulation filtering, post-modulation filtering and PA AM/AM conversion.

FIGURE 5

Duplexer and antenna isolation overview



Notes:
1. 20 dB isolation across circulator.
2. 2:1 VSWR means 9.5% of transmit power reflected into receive path.
3. 1 dB loss through circulator.

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3.2 Verification

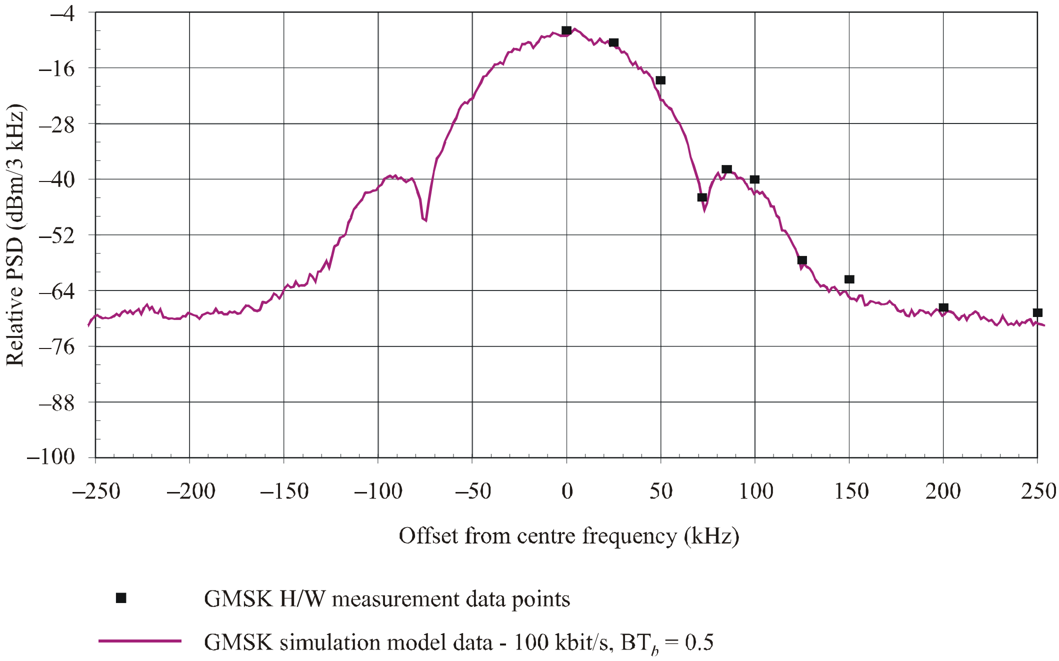
To validate the simulation model, 100 kbit/s GMSK PSD data generated via the simulation were compared to the 100 kbit/s GMSK PSD data collected during hardware testing. Figure 6 compares the two PSDs near the mainlobe and first side lobe. Figure 7 compares the two PSDs over a very wide frequency range. The very close correlation between the simulation data and the hardware measurement data demonstrates that the simulation model can be used to accurately predict the PSD performance of real hardware.

4 Results

Table 4 provides a summary of the worst-case expected MSS feeder-link power in the 1 400-1 427 MHz band assuming a 1 W MSS feeder-link transmitter power and a reference point at the MSS feeder-link antenna interface. These results are based upon the transmitter architecture, architecture characteristics and distortions described below.

FIGURE 6

Comparison of GMSK 100 kbit/s PSD – simulation and hardware testing – near mainlobe



Note 1 – PSD generated based upon the low fidelity grade settings described in § 3.1 with the exception that 10-bit quantization with non-optimal clip levels was used. Additionally, no output diplexer was used.

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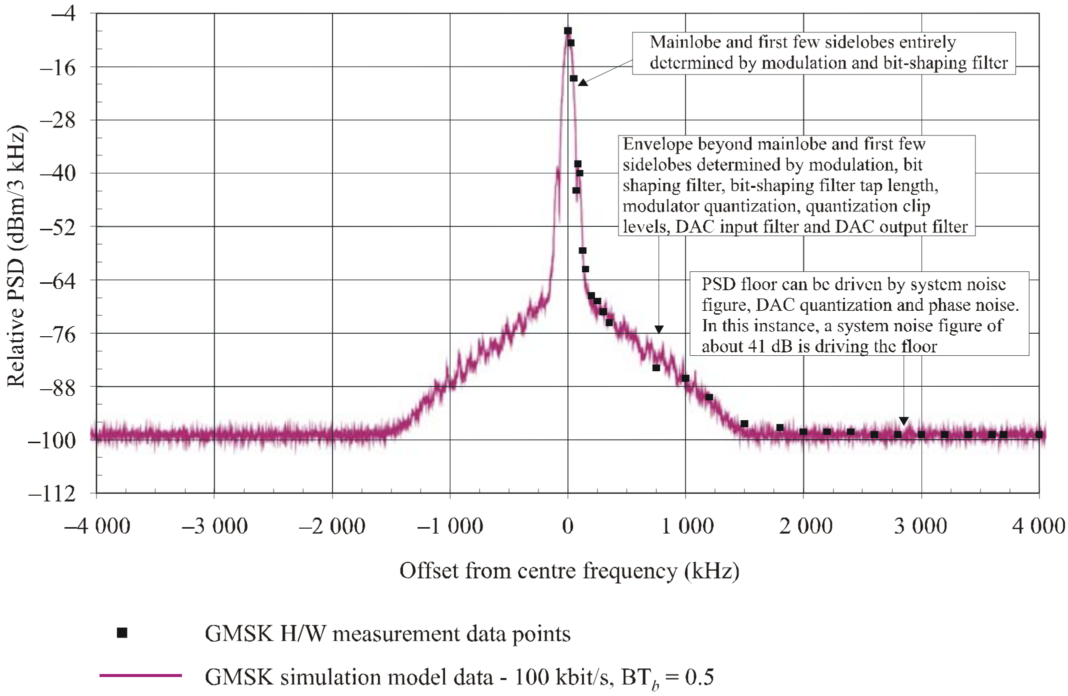
FIGURE 7

Comparison of GMSK 100 kbit/s PSD – simulation and hardware testing – wide spectrum



Note 1 – PSD generated based upon the low fidelity grade settings described in § 3.1 with the exception that 10-bit quantization with non-optimal clip levels was used. Additionally, no output diplexer was used.

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TABLE 4

MSS feeder-link power in the 1 400-1 427 MHz band assuming a 1 W transmitter power

Feeder-link description					Results(1), (2)					
Channel BW(3)	**Modulation**	**Data rate**	**Bit-shaping filter**	**Feeder-link centre frequency (MHz)**	**Maximum feeder-link PSD level in the 1 400-1 427 MHz band (dBm/4 kHz)(4)**		**Feeder-link total power in the 1 400- 427 MHz band(4) (dBW)**		**99% bandwidth (kHz)**	
					Fidelity grade: low	**Fidelity grade: high**	**Fidelity grade: low**	**Fidelity grade: high**	**Fidelity grade: low**	**Fidelity grade: high**
100 kHz	GMSK	100 kbit/s	Gaussian, BT$_b$ = 0.5	1 391.95	–78.9	–100.9	–75.04	–97.03	100	100
				1 430.05	–72.8	–94.56	–71.52	–93.53		
				1 430.05	–72.8	–94.56	–71.52	–93.53		
	OQPSK/ IQ(5)	100 kbit/s	RC, BT$_s$ = 1.0	1 391.95	–79.33	–101.37	–74.30	–96.27	84	84
				1 430.05	–72.92	–94.57	–71.76	–93.66		
	OQPSK/ PM(6)	100 kbit/s	RC, BT$_s$ = 1.0	1 391.95	–79.32	–101.41	–74.30	–96.35	84	84
				1 430.05	–72.94	–94.86	–71.76	–93.75		
	8-PSK	150 kbit/s	RC, BT$_s$ = 1.0	1 391.95	–79.37	–100.55	–74.38	–95.68	141(7)	132(7)
				1 430.05	–72.62	–91.76	–71.83	–89.72		
				1 430.05	–73.23	–91.63	–72.03	–93.63		

TABLE 4 (*end*)

Feeder-link description					Results(1), (2)					
Channel BW(3)	Modulation	Data rate	Bit-shaping filter	Feeder-link centre frequency (MHz)	Maximum feeder-link PSD level in the 1 400-1 427 MHz band (dBm/4 kHz)(4)		Feeder-link total power in the 1 400- 427 MHz band(4) (dBW)		99% bandwidth (kHz)	
					Fidelity grade: low	Fidelity grade: high	Fidelity grade: low	Fidelity grade: high	Fidelity grade: low	Fidelity grade: high
300 kHz	GMSK	300 kbit/s	Gaussian, $BT_b = 0.5$	1 391.85	–79.51	–101.51	–74.12	–96.15	309	309
				1 430.15	–74.10	–95.77	–72.15	–94.16		
				1 430.15	–74.14	–95.44	–72.15	–94.16		
	OQPSK/ IQ(5)	300 kbit/s	RC, $BT_s = 1.0$	1 391.85	–78.75	–100.78	–73.48	–95.41	264	249
				1 430.15	–72.73	–94.55	–70.99	–92.74		
	OQPSK/ PM(6)	300 kbit/s	RC, $BT_s = 1.0$	1 391.85	–78.74	–100.81	–73.47	–95.55	264	264
				1 430.15	–72.67	–94.83	–71.0	–93.00		
	8-PSK	450 kbit/s	RC, $BT_s = 1.0$	1 391.85	–78.30(7)	–89.21(7)	–73.57(7)	–91.50(7)	436(7)	400(7)
				1 430.15	–70.02(7)	–78.67(7)	–71.23(7)	–78.29(7)		
				1 430.15	–69.72	–73.12	–71.61	–80.61		
855 kHz	GMSK	855 kbit/s	Gaussian, $BT_b = 0.5$	1 391.5725	–79.89	–102.05	–74.97	–96.93	881	881
				1 430.4275	–75.46	–96.87	–71.33	–93.37		
				1 430.4275	–71.54	–75.75	–71.33	–89.93		
	OQPSK/ IQ(5)	855 kbit/s	RC, $BT_s = 1.0$	1 391.5725	–79.19	–101.52	–75.10	–96.84	744	718
				1 430.4275	–71.07	–80.20	–70.75	–88.20		
	OQPSK/ PM(6)	855 kbit/s	RC, $BT_s = 1.0$	1 391.5725	–79.19	–101.22	–75.11	–97.18	744	744
				1 430.4275	–73.65	–95.54	–70.92	–92.75		
	8-PSK	1.284 Mbit/s	RC, $BT_s = 1.0$	1 391.5725	–76.22(7)	–77.06(7)	–73.10(7)	–79.55(7)	1 244(7)	1 193(7)
				1 430.4275	–52.58(7)	–54.45(7)	–59.05(7)	–60.54(7)		
				1 430.4275	–56.67	–57.63	–63.80	–65.30		

(1) All PSD results based upon the transmitter distortion scenarios described in section 3 including the PA operating in saturation for OQPSK, GMSK and 8-PSK.

(2) Interference power referenced at the MSS feeder-link antenna interface.

(3) With the exception of GMSK, channel bandwidth is defined here as the null-to-null bandwidth. For GMSK, channel bandwidth is defined as the 99% bandwidth (approximately).

(4) For 100 kHz and some 300 kHz channel bandwidth configurations, interference power is driven entirely by PSD floor introduced by system noise figure and is independent of modulation technique.

(5) Offset QPSK with a linear I/Q modulator (OQPSK/IQ) is the most simple OQPSK implementation, however, it is non-constant envelope which makes it susceptible to spectral regrowth.

(6) Offset QPSK with a linear phase modulator (OQPSK/PM) requires a more complex implementation than OQPSK/IQ, however, it is constant envelope which makes it less susceptible to spectral regrowth. OQPSK/PM outperforms GMSK from a BER point of view and a spectral point of view, however, GMSK is more readily available in commercial hardware.

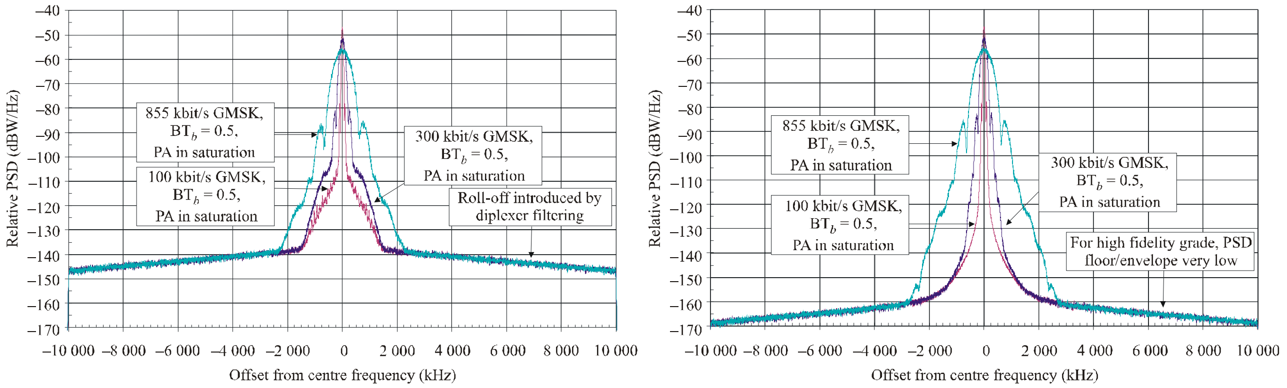
(7) 8-PSK results collected assuming the PA operating in saturation, whereas, PA assumed to be operating 1 dB output backed off for all other higher order modulation techniques. This generally results in very conservative results for 8-PSK. If a 1 dB Output Backoff (OBO) is considered for 8-PSK, the interference power amounts presented in this analysis can be lower by as much as 5.5 dB for the 855 kHz channel bandwidth case and 2.0 dB for the 300 kHz channel bandwidth case.

Figures 8 and 9 provide GMSK PSD data generated via simulation assuming, respectively, the hardware low- and high-fidelity grade settings.

FIGURES 8 and 9

Output PSD assuming GMSK BT_b = 0.5 modulation and a normalized output power of 1 W

low grade hardware fidelity **high grade hardware fidelity**



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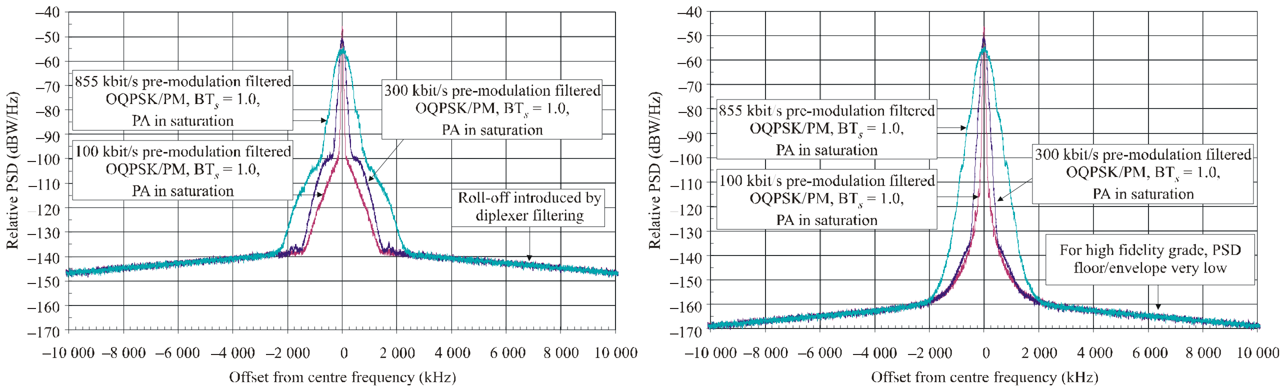
Figures 10 and 11 provide OQPSK/PM PSD data generated via simulation assuming, respectively, the hardware low- and high-fidelity grade settings.

FIGURES 10 and 11

Output PSD assuming OQPSK/PM modulation and a normalized output power of 1 W

low grade hardware fidelity **high grade hardware fidelity**



Note 1 – Constant envelope aspect of OQPSK/PM yields a very spectrally-efficient PSD after PA.

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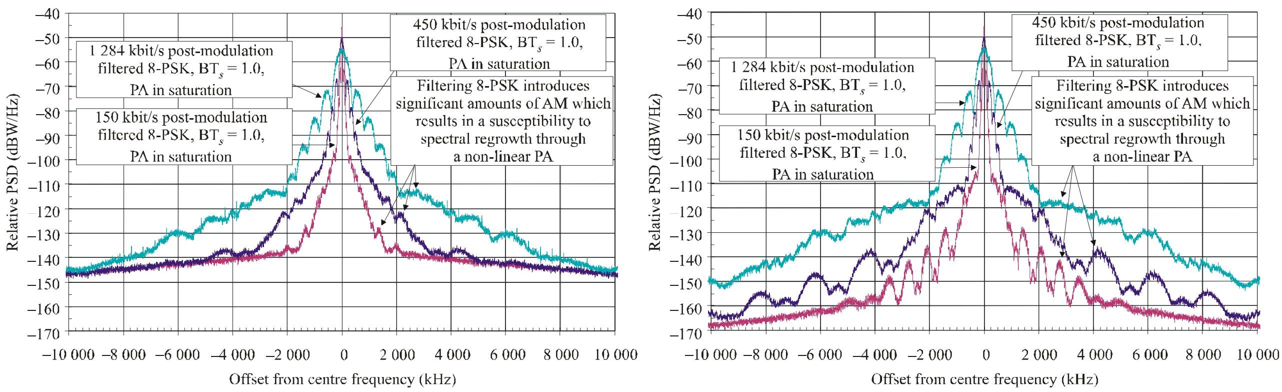
Figures 12 and 13 provide 8-PSK PSD data generated via simulation assuming, respectively, the hardware low- and high-fidelity grade settings.

FIGURES 12 and 13

Output PSD assuming 8PSK modulation and a normalized output power of 1 W

low grade hardware fidelity **high grade hardware fidelity**



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Annex 2

Results of tests and measurements pertaining to containment of unwanted emissions

This Annex contains the results of test and measurements pertaining to the containment of unwanted emission from non-GSO FSS feeder links, with mobile services below 1 GHz, operating in the bands 1 390-1 392 MHz, Earth-to-space, and 1 430-1 432 MHz, space-to-Earth.

The tests and measurements are showing that for a non-GSO MSS transmitter operating in the band 1 430-1 432 MHz (space-to-Earth) the practicable levels of attenuation of out-of-band emissions exceed the value of 73 dB that ITU-R studies have shown would provide acceptable interference power into EESS (passive) and RAS systems operating in the frequency band 1 400-1 427 MHz. Studies performed with the tests have shown that additional attenuation of 10 to 30 dB is achievable through the use of post-transmitter filters on the satellites.

On the basis of those tests and studies of transmitters in the band 1 430-1 432 MHz, it is concluded that for non-GSO MSS feeder links in the band 1 390-1 392 MHz with earth station transmitters similar to the transmitters tested (similar in power levels, up to 50 W, and at nearly the same frequency), the achievable out-of-band emission levels and additional post-transmitter filtering of 30 dB can practicably result in attenuation levels of unwanted emissions greater than the approximately 119 dB required to produce acceptable interference levels into EESS (passive) systems operating in the frequency band 1 400-1 427 MHz.

1 Transmitter architecture

Figure 14 shows the feeder-link transmitter architecture based on a single conversion transmitter using a direct up-conversion quadrature modulator. The local oscillator is at carrier frequency. Figure 15 shows the architecture of the GMSK baseband modulator. Figure 16 shows the architecture of the local oscillator.

FIGURE 14

Transmitter architecture

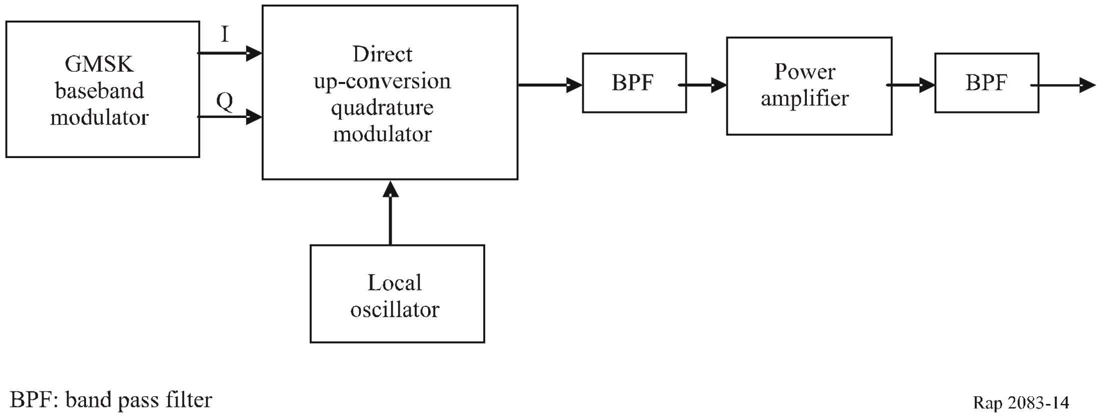


FIGURE 15

GMSK baseband modulator

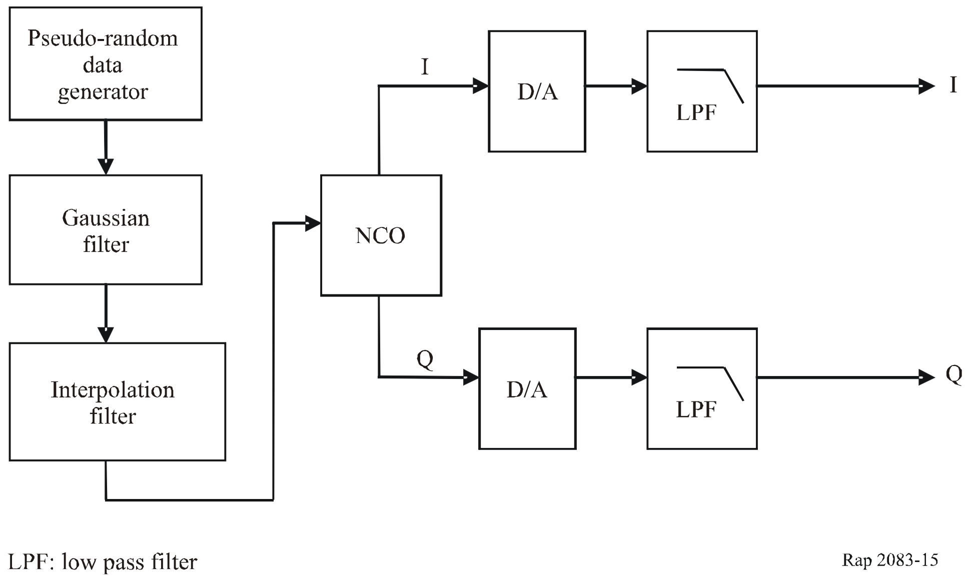
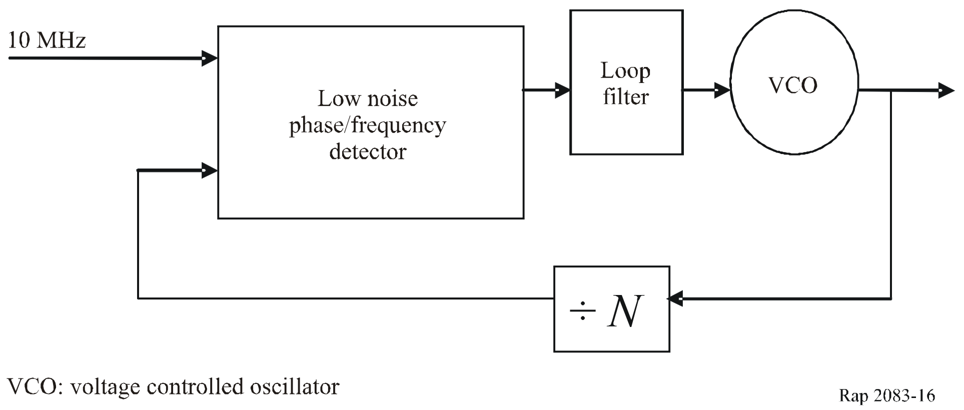


FIGURE 16

Local oscillator

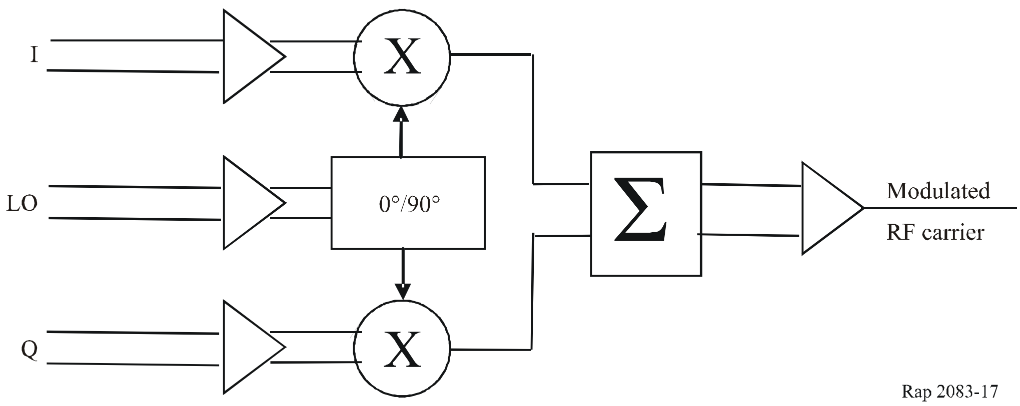


The modulator generates baseband GMSK using a field programmable gate array (FPGA). First a pseudo-random data sequence is generated and then filtered using a Gaussian filter with a filter constant of $BT = 0.5$. The filter is implemented as a FIR with 17 taps and 12-bit coefficients. The result is then interpolated 64:1 using a 3-stage cascaded integrator comb. The result is input to a numerically controlled oscillator, which then generates the resulting inphase and quadrature (I&Q) outputs. The NCO has a 32-bit phase accumulator, and has a 512-deep lookup table for sine and cosine functions. Clock rates are 100 kHz for PN generation, 800 kHz for the Gaussian filter and 512 kHz for the GMSK NCO. The intent is for the spurious content of the digitally created GMSK baseband signal to be below the spurious free dynamic range of the *D*/*A* convertors in order to minimize the amount of analogue filtering required.

The local oscillator uses a PLL that accepts a 10 MHz frequency reference from the spacecraft bus and multiplies this frequency to the RF carrier frequency. The 10 MHz frequency reference is phase locked to the spacecraft bus GPS receiver and thus has no long term drift. Figure 17 shows the architecture of the direct up-conversion quadrature modulator. The local oscillator (LO) frequency is at carrier frequency.

FIGURE 17

Direct up-conversion quadrature modulator



2 Evaluation of unwanted emissions

Output spectral plots taken on various combinations of evaluation hardware show that it is feasible to implement a GMSK transmitter which will meet the requirements regarding unwanted emissions (i.e. when transmitting in the band 1 430-1 432 MHz, no emissions allowed above 86 dBsd in the adjacent 1 400-1 427 MHz band).

TABLE 5

Hardware combinations tested

Configuration	GMSK data source	RF up-converter	Power amplifier
1	Agilent 8648D	N/A	Hughes 50-W TWTA
2	FACS breadboard	FACS breadboard	Hughes 50-W TWTA or WJ 0.1-W SSPA

TWTA: travelling wave tube amplifier

No extraordinary methods beyond standard good RF practice were required to achieve these measured results. An Agilent PSA series spectrum analyser (Model E4440A) was used to make the measurements. Auto-coupling of the analyser settings was overridden to maximize measurement range. The signal-free noise floor of the analyser was measured at least 6 dB below the measured minimum signal, verifying adequate dynamic range for the measurements.

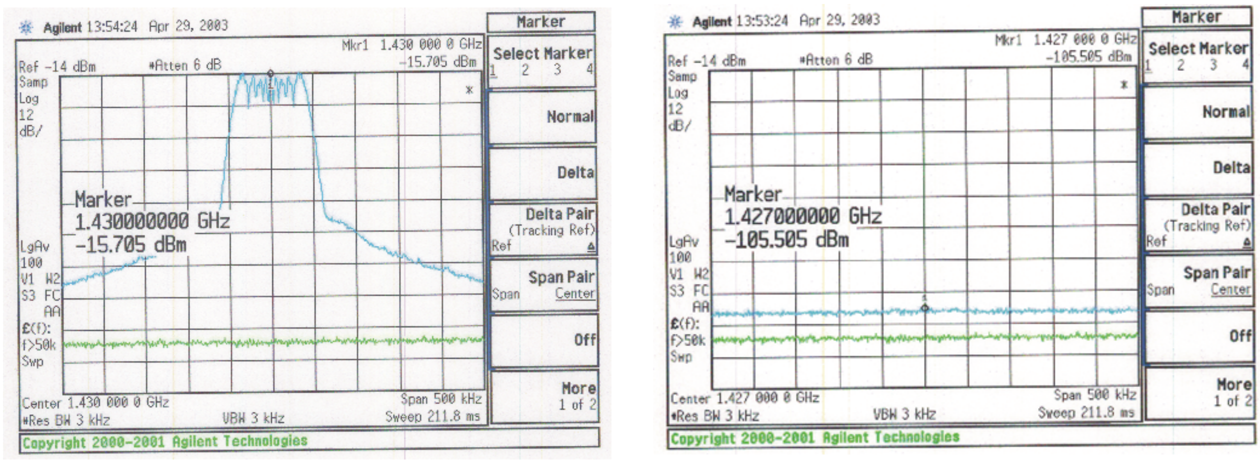
Minor modulator filtering (pre-TWTA) in the flight hardware may be needed to attain the 86 dBsd requirement over the entire 1 420-1 427 MHz band. In the FACS modulator, two in-band spurious images were observed, however an additional 2-3 dB of bandstop filtering would be sufficient to meet ITU requirements and increase margin. Spectral degradation of the GMSK signal floor was less than 1 dB through the solid state power amplifier (SSPA) or TWTA.

2.1 Configuration 1

A commercial Agilent signal generator (8648D) was configured to produce a shaped, phase modulated carrier at 1 430 MHz, with a data bandwidth of approximately 100 kbit/s. Figures 18 and 19 show the modulated spectrum at the carrier frequency (1 430 MHz) and residual modulation at 1 427 MHz as measured on an Agilent E4440A spectrum analyser. The spectral attenuation at the output of the generator was ~90 dBsd at 1 427 MHz (–15.7 dBm at 1 430 MHz) – (–105.5 dBm at 1 427 MHz). The measured generator spectral floor of –105.5 dBm was 9.5 dB higher than the signal-free floor of the spectrum analyser at –115.0 dBm, implying a measurement error of less than 0.5 dB.

FIGURES 18 and 19

Agilent modulator at 1 430 MHz and 1 427 MHz



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A Hughes 50 W TWTA (Model 1277H) was used to amplify the phase-modulated carrier. Little degradation was observed in the spectral attenuation when passed through the Hughes TWTA. Measurements were taken at saturation (SAT), SAT-2 dB, SAT-4 dB and SAT-10 dB (input back off), and spectral attenuation at 1 427 MHz ranged from 92 to 94 dBsd. Spectral attenuation results are summarized in Table 6.

TABLE 6

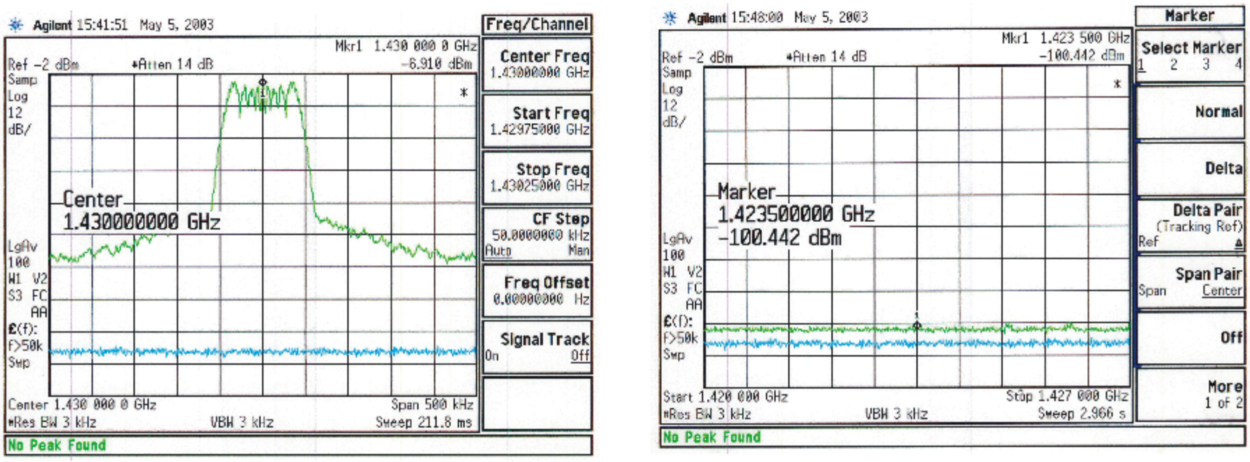
Spectral attenuation vs. TWTA input backoff (Agilent modulator)

Input back off from SAT (dB)	Relative output power (dBm)	Density at 1 430 MHz (dBm/3 kHz)	Density at 1 427 MHz (dBm/3 kHz)	Spectral attenuation (dBsd)
0	17.3	–9.0	–102.3	93.3
2	17.1	–9.2	–102.1	92.9
4	16.6	–9.6	–103.3	93.7
10	12.9	–9.4	–101.6	92.2

Figures 20 and 21 show compliance of the Agilent modulator-TWTA configuration against the ITU 86 dBsd requirement in the 1 420-1 427 MHz band. The peak spectral-density at 1 430 MHz was measured at –6.9 dBm in a 3 kHz BW. Measured spectral attenuation against this peak ranged from 90 to 94 dBsd across the restricted band, and no spurious tones were observed.

FIGURES 20 and 21

Peak spectral-density at 1 430 MHz and spectral-density from 1 420-1 427 MHz



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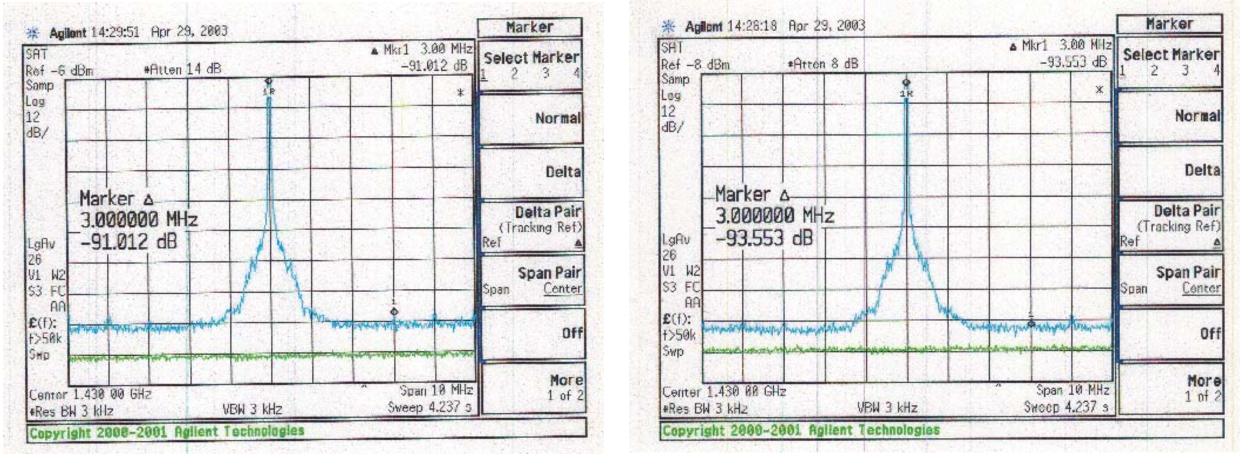
Figures 22 and 23 show medium span (10 MHz) views of the power spectral-density after going through the Hughes 50-W TWTA at SAT and SAT-10 dB (10 dB input backoff). Since the modulation waveform was not precisely constant amplitude, spectral regrowth was noticeable at the output of the TWTA. However, the regrowth was not significant enough to violate the 86 dBsd interference requirement at 1 427 MHz, or anywhere in the 1 420-1 427 MHz band.

FIGURES 22 and 23

Agilent modulator, TWTA at saturation and 10 dB back-off



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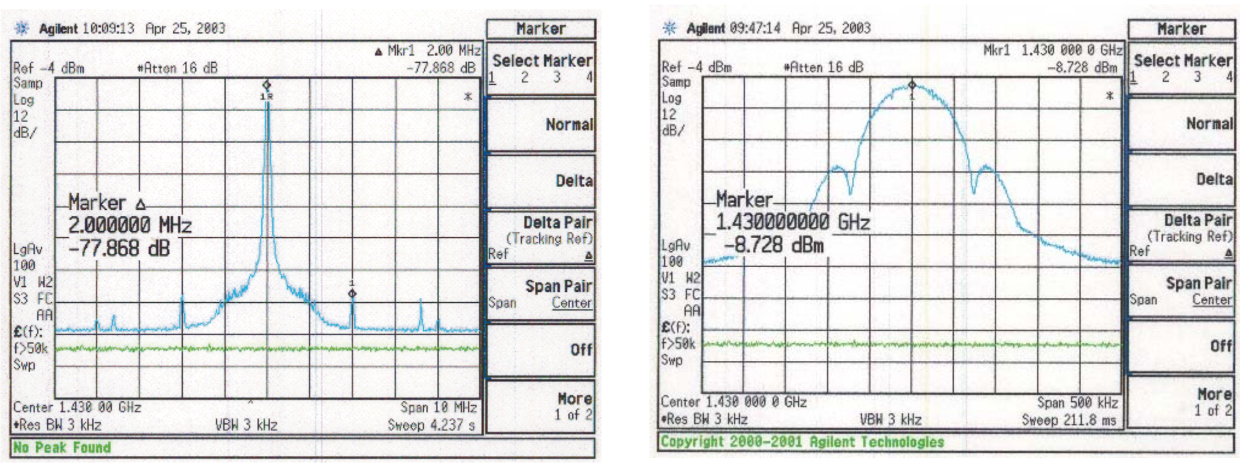
2.2 Configuration 2

A FACS modulator breadboard (*S*/*N* 002) was connected first to a WJ medium-power (100 mW) SSPA, and then to the Hughes 50-W TWTA. The FACS breadboard generated a GMSK modulated L-band carrier (at 1 430 MHz). Some spectral energy was observed at a spacing of 2 MHz and 3.6 MHz away from 1 430 MHz (Fig. 24). At close inspection, this energy appeared to be spurious images of the main modulated signal as opposed to discrete clock or frequency lines.

Measured spectral attenuation at the output of the FACS breadboard was approximately 90 dBsd at 1 427 MHz (relative to spectral-density at 1 430 MHz). The measured GMSK spectral floor of –98.8 dBm was 6.4 dB higher than the signal-free floor of the spectrum analyser at –105.2 dBm, implying a measurement error of less than 0.9 dB. Figure 25 shows the spectral output of FACS modulator 2 prior to external amplification.

FIGURES 24 and 25

FACS modulator 2 before signal amplification by HPA



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Little degradation was observed in the spectral attenuation when passed through the Hughes TWTA. Measurements were taken at SAT, SAT-2 dB, SAT-4 dB and SAT-10 dB (input back off), and spectral attenuation at 1 427 MHz was still approximately 90 dBsd in all cases. Spectral attenuation results are summarized in Table 7.

TABLE 7

Spectral attenuation vs. TWTA input backoff (FACS modulator)

Input back off from SAT (dB)	Relative output power (dBm)	Density at 1 430 MHz (dBm/3 kHz)	Density at 1 427 MHz (dBm/3 kHz)	Spectral attenuation (dBsd)
0	17.3	–7.9	–99.5	91.6
2	17.0	–7.9	–99.2	91.3
4	16.5	–9.1	–99.5	90.4
10	12.4	–7.8	–97.0	89.2

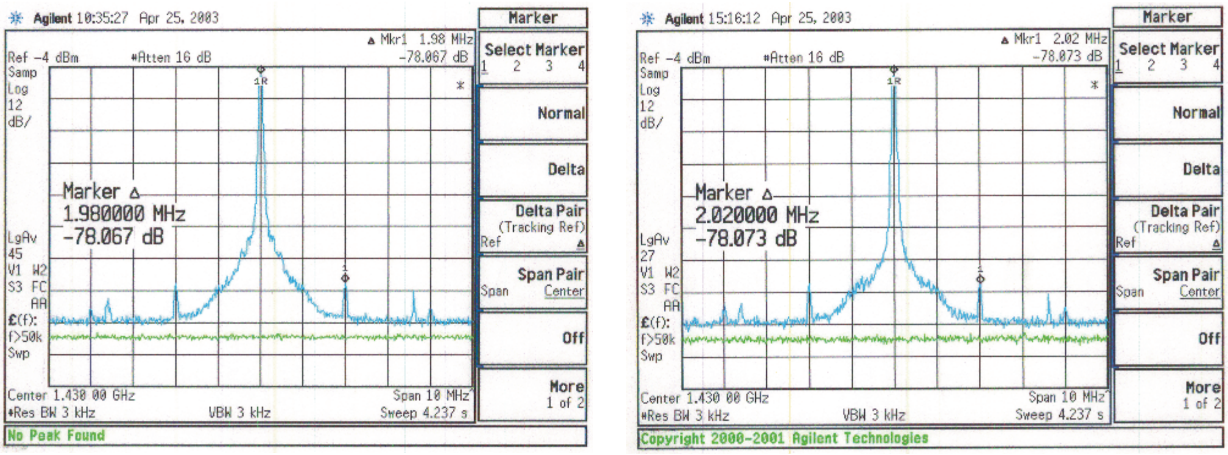
Figure 26 shows the spectrum after the TWTA operating at SAT. There is no noticeable spectral regrowth, indicating that the FACS modulation is constant amplitude, as would be expected with properly implemented GMSK.

Similarly, little degradation was observed in spectral attenuation when passed through a medium power (100 mW) Watkins-Johnson Versa-amp SSPA. The amplifier was operated at 1 dB output compression, and spectral attenuation was 92.2 dBsd at 1 427 MHz, relative to spectral-density at 1 430 MHz.

Figure 27 shows spectral output after the SSPA. This output signal appears very similar to the TWTA amplified signal (SAT) in Fig. 1.2.3, providing additional test evidence that spectral degradation through a properly operating power amplifier is minimal and does not appear to be a limiting factor in meeting ITU-R protection requirements in the 1 420-1 427 MHz band.

FIGURES 26 and 27

FACS modulator 2, TWTA at SAT and SSPA at 1 dB compression



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3 Flight hardware implementation considerations

A summary of path-to-flight issues (Table 8) addresses potential beginning-of-life (BOL) performance issues as the modulator-transmitter design evolves into space-qualified hardware from the breadboards measured on this task.

A small number of building block components can be assumed to have the potential to contribute to degradation of spectral-density attenuation of a GMSK modulator-transmitter as a flight hardware configuration evolves from the breadboard designs tested at our facility.

TABLE 8

Summary of path-to-flight issues

Building block	Comments	Projected performance delta
L.O. carrier	Breadboards use either lab test equipment synthesizer or RFIC source; flight equivalent likely would use crystal oscillator with multiplier chain	No expected degradation
Digital modulation	Company breadboard uses 16-bit dual DACs; FACS board uses 10-bit DACs, which are available as flight qualified	No expected degradation
RF up-converter/modulator	Breadboard uses RFIC or RF mixers and hybrids; flight equivalent would use similar technology	No expected degradation
Output power amplifier	Breadboard uses 50 W TWTA; flight equivalent would use smaller TWTA or SSPA	No expected degradation
Pre- and post-amplifier filter	None used in breadboard measurements; high-power flight filters from other satellite programs show availability if necessary	Additional 30 dB of positive margin towards ITU-R spectral-density interference specification

3.1 L.O. carrier

Tested hardware configuration 1 used Agilent test equipment synthesizers to generate the L-band carriers. Agilent synthesizers typically have excellent carrier phase noise performance, above what would be expected in a flight LO. However the FACS breadboards (configuration 2) use a commercial quality RFIC synthesizer, and the measured GMSK spectral performance did not appear to be limited by the performance of that LO source (synchronized against a laboratory 10 MHz standard), as spectral attenuation performance was very similar in all configurations measured at our facility. In the flight hardware configuration, the RFIC would be synchronized against a received GPS (atomic clock) reference, which would have better long-term stability than a lab standard. Specified and measured performance of space quality oscillators indicate that at a distance of 3 MHz from the centre frequency, the phase noise of a multiplied crystal oscillator should typically be better than –140 dBc, which would provide greater than 40 dB of margin over what is needed to avoid contributing to degradation of the GMSK spectrum.

3.2 Digital modulation

The projected 100 kbit/s data rate is well within the range of available space-qualified digital ICs in bipolar or CMOS technologies, thus the translation of the digital designs used in the GMSK breadboards to flight qualified implementations is straightforward, with the exception of the 16-bit dual D-to-A converters used in the output stage of our company's testbed digital modulator.

The AD9731 12-bit high-speed DACs used in the FACS breadboard modulator are available as space-qualified devices for use in the flight modulator design, thus no degradation of the performance of the digital subsection is expected as compared to the tested FACS breadboard.

3.3 RF up-converter

The Agilent signal generator and FACS breadboard both utilize RFIC modulators. In the case of the FACS RFIC modulator (AD8346) a path to flight is expected to be available through the specific vendor's space qualified fabrication process. In the worst case, this component may require individual qualification if no equivalent heritage part built in the same fabrication process is located before the design is fixed.

3.4 Output power amplifier

The Hughes 50 W TWTA used in the testing of all modulator breadboards has extensive flight heritage from the Boeing EDD (formerly Hughes) organization. FACS transmitter requirements are understood to be significantly lower (1 W space, 10 W ground) than the tested TWTA, however the measured performance of the spectral interference pre- and post-TWTA shows that there is insignificant performance degradation of the GMSK waveform in this major component, even at the higher (50 W) power level.

1 W or 10 W 1.5 GHz (L-band) solid-state amplifiers were not readily available to support these tests; however no significant difference in degradation is expected if SSPAs were selected for use over TWTAs. The 100 mW SSPA that was tested with the FACS breadboard had slightly less spectral interference degradation as compared against the performance seen with the 50 W TWTA.

3.5 Pre- and post-amplifier filter

No tests were performed with post-amplifier, high power filters, as all tested configurations met the 86 dBsd spectral interference requirement without filtering (other than the two 0.5 dB and 2.0 dB violations noted previously in the breadboard FACS modulator). Minor bandstop filtering at the low power output of the modulator can easily be implemented to meet ITU-R protection criteria, as no spectral degradation was observed through either the TWTA or SSPA. This extra filtering would also provide margin over the mission life.

If high power filtering was necessary after the power amplifier, we have direct experience in specifying high-power, flight bandpass filters at a similar L-band frequency for another satellite program. Based on interpolation of existing high-power filter specifications and the same vendor's response to specific FACS requirements, an additional minimum attenuation of 30 dB (nominal vendor specs) could be achieved at 1 427 MHz, the closest worst-case spacing from a modulated downlink signal centred at 1 430 MHz. For the FACS ground-based uplink configuration, the vendor specifies a minimum attenuation of 42 dB at 1 400 MHz, the closest worst-case spacing from a modulated signal centred at 1 392 MHz.

3.6 Test relevance to proposed 1 390-1 392 MHz uplink

All laboratory tests were performed at a modulated carrier of 1 430 MHz, looking at potential interference in the 1 400-1 427 MHz band reserved for radio astronomy. There was no rise in interference observed up to 30 MHz away from the modulated carrier, and there is a reasonable expectation that an identical GMSK-modulated carrier operating on the low side of the 1 400-1 427 MHz band would perform similarly (i.e. comply with the 86 dBsd requirement). The two differences between the proposed uplink and downlink signals are in separation distance from the 1 400-1 427 MHz band, and amplifier power. A 1 300-1 392 MHz uplink would have a larger guardband (8 MHz vs. 3 MHz) to the radio astronomy band, leading to simpler filtering requirements. The proposed uplink of 10 W is five times lower than the tested 50 W laboratory signal. No spectral regrowth was observed in the 1 430 MHz tests, thus none is expected with a 10 W power amplifier.

4 Long term reliability aspects for operation in space

Normal aging effects and exposure to radiation, temperature and the space environment can have an impact on hardware performance.

4.1 Analogue components (including oscillator)

Long-term stability of the master crystal oscillator in space environments is well understood and generally not a problem in the satellite if specified prior to acquisition for flight. Typical frequency drift of less than 10^{-8} is reasonable to expect and well within the necessary performance to stay within ITU-R requirements. Phase noise degradation does not occur to the levels where it would impact spectral interference, other than in the event of catastrophic component failure.

4.2 Digital components (GMSK shaping)

Digital circuits have less sensitivity to ageing and temperature effects as compared with analogue circuits, and most necessary digital circuit building blocks are available in space qualified versions. The most common problem with digital circuitry in space is the effect of single event upsets (SEU) due to radiation. Where necessary, the selection of rad-hard digital devices (such as processors, memories and gate arrays) or the use of selective mechanical shielding provides the means to mitigate sensitivity to radiation. The FACS digital modulator will be used to process a constant flow of data, and as such is much less sensitive (from a system and practical user standpoint) to the effects of SEUs.

4.3 RF components (upconverter)

The most common degradation seen in RF components is a loss of gain in active amplifiers as characteristics change over time and exposure to radiation. The satellite industry mitigates these effects upon the overall system through the choice of properly designed and tested components with minimal sensitivity to these changes.

4.4 Power components

As with the above RF components, the satellite industry has much experience in designing and producing power amplifiers for 10-15 year life in orbit, and a graceful degradation is expected in a properly designed power amplifier. The use of redundant blocks mitigates unexpected random failures due to components or workmanship issues.

Annex 3

Filter characteristics of feeder links near 1 400 MHz

Table 9 provides data used to determine the attenuation of unwanted transmitter emissions needed for two frequency full duplex feeder-link operations.

TABLE 9

Required attenuation for two frequency full duplex feeder-link operation

	Earth station	**Spacecraft**
Thermal noise density (dBW/Hz)	–204	–204
Receive system NF (dB)	1.5	2.5
Tx *I*/*N* (dB)	–10	–10
Maximum Tx noise density in Rx band (dBW/Hz)	–212.5	–211.5
Tx power, to antenna (dBW)	10	0
Carrier bandwidth 100 kbaud GMSK (dB-Hz)	–50	–50
Tx dBsd	–90	–90
Tx noise density in Rx band (dBW/Hz)	–130	–140
Filter passband loss (dB)	3	3
Tx attenuation required (dB)	85.5	74.5
Antenna return loss (VSWR = 2.0)	–9.5	–9.5
Circulator isolation (dB)	–18	–18
Tx Rx isolation (dB)	–9.0	–9.0
Tx filter attenuation required (dB)	76.5	65.5
Frequency separation (MHz)	40	40
Frequency separation (%)	2.9	2.8

The assumed post-transmit-filter is a conventional 3 pole Chebychev filter of conservative design and there are many options available that would allow for better performance. Figures 28 and 29 provide the emission spectrum of the feeder link at the antenna input of the space-to-Earth and the Earth-to-space links respectively.

FIGURE 28

Earth-to-space post transmit filter spectrum 300 kbaud GMSK (BT = 0.5), 30 W at antenna input

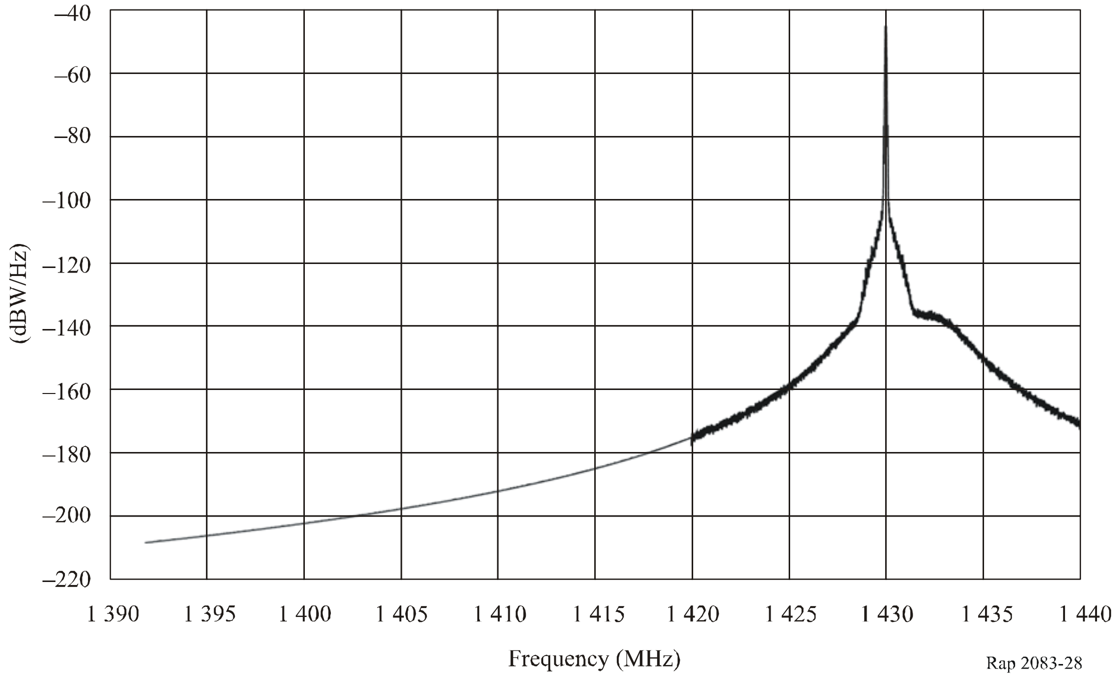

FIGURE 29

Space-to-Earth post transmit filter spectrum 300 kbaud GMSK (BT = 0.5), 3 W at antenna input