The Effect of Globalstar MSS Transmissions on the Future Reception of GLONASS

John Cooper and Peter Daly

(*CAA Institute Of Satellite Navigation, The University of Leeds*)

This paper discusses the impact of a new generation of mobile communications, Mobile Satellite Services (MSS), on the reception of GLONASS signals in the future. The two systems are very closely located in the frequency spectrum, and the effect of this co-location has been derived. It is shown that the performance of GLONASS in a future GNSS-1 will be heavily affected by the current emissions proposed by the Globalstar consortium.

1. INTRODUCTION. In February 1998, the first satellites of the proposed constellation of 52 Low Earth Orbiters (LEO) that make up the Globalstar constellation (48 active satellites with four in-orbit spares) were successfully launched. Current Globalstar forecasts put 32 satellites in orbit by the summer of 1999, with commercial service commencing in September 1999 and a full constellation by December 1999. When operational, the system will provide personal communications on a global level with handsets approximately as small and light as those used for the current GSM (and similar) networks. The Globalstar system, and other similar systems, are known collectively as Mobile Satellite Services (MSS). For the system to function, a continuous two-way link is required between the handset (or Mobile Earth Station, MES) and the satellite and, consequently, enough signal power to overcome the space loss introduced by MES-satellite separation is required.

The choice of frequency band at which the service is located is important, and L-band is very desirable due to the small antenna and analogue processing size, cheap hardware requirements and favourable environmental effects (such as signal attenuation due to moisture in the air and space path). Unfortunately, these considerations make available bandwidth within L-band difficult to obtain. The band from 1559 to 1626·5 MHz is currently allocated worldwide to aeronautical radio-navigation satellite services but the band from 1610 to 1626·5 MHz was also allocated to MSS at the World Radiocommunications Conference in 1992 (WRC-92). It is in this band that the Earth-to-space (E-s) link of the Globalstar MSS network will transmit.

GLONASS is a radio-navigation system owned and maintained by the Russian Federation and is comparable to the US GPS. The system currently occupies the frequency band from approximately 1597·5 to 1620·6 MHz, and this bandwidth is divided into 24 channels that are separated from each other by Frequency Division Multiple Access (FDMA). The channels are numbered from 1 to 24 and the centre frequency of transmission is given by the formula:

$$L_{1i} = 1602{\cdot}0 + 0{\cdot}5625 \times i \quad \text{(MHz)}, \quad i = 1, \ldots, 24. \tag{1}$$

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Due to modulation of the carrier frequency by a wide-band spreading code, the bandwidth required to transmit each channel is approximately ± 5 MHz. To locate the receiver in four dimensions requires signals from at least four GLONASS satellites, and the FDMA ensures that this is possible with the minimum of intra-system interference.

The band from 1610·6 to 1613·8 MHz is also shared by the radio-astronomy service for observations of the spectral lines of hydroxyl radicals (OH^-). As a recognition of the shared status of the band, GLONASS is relocating its signals to a lower frequency band in two stages. The second stage of frequency allocation (1998–2005) sees antipodal satellites allocated the same frequency channel; the channel requirement then falls to 12 (channels 1–12: 1597·5–1613·9 MHz). Although this allocation still interferes with the radio-astronomy band, the high end of the spectrum is taken up with the wide-band P code signals which, although significant, are reduced from the higher power C/A signals located in-band from channels 15 to 21 (approx.). The third stage of frequency allocation (2005 onwards) relocates the 12 satellite channels from channel -7 to 4 (1593·0 to 1609·4 MHz).

Justification for the co-location of Globalstar and GLONASS has so far concentrated on the third stage frequency allocation which means that there is a period of at least six years for which there is no analysis of the potential effect of the MSS signals on GLONASS reception. GLONASS will be of great importance in the near future as the realisation that high integrity, high availability applications of radio-navigation cannot be satisfied with the use of GPS alone, and the effective blanking of GLONASS reception in the proximity of a MSS handset for a period of six years will then be unacceptable. This paper goes on to show a general analysis of the effect of the MSS transmissions on GLONASS for all stages of its frequency (re)location. Due to the difficulty of generating MSS-like interference in the laboratory, a theoretical analysis has been carried out, although any assumptions made are confirmed by a series of practical measurements on the flexible GLONASS receiver architecture developed over many years by the ISN.

2. CODE DIVISION MULTIPLE ACCESS AND SPREAD-SPECTRUM. The primary Globalstar E-s signal utilises both frequency and Code Division Multiple Access (CDMA) in the frequency band of 1610 to 1621·35 MHz. There are nine channels allocated (FDMA), each of which has further multiple access achieved by CDMA. CDMA involves mixing the processed voice/data stream with a high rate *pseudo-random spreading code*, which has the effect of increasing the bandwidth required to transmit the signal (spread-spectrum processing). Since the power of the signal is unchanged, this effectively reduces the signal power density. The power density can only be restored by mixing (*correlating*) with an in-phase replica of the spreading code that effectively removes the code and concentrates the power back into the data stream bandwidth. The important point that makes the technique desirable for MSS is that without the replica code, the power density cannot be increased and so multiple signals, i.e. multiple voice/data streams, modulated by different, orthogonal codes can occupy the same bandwidth with minimal interference.

As a result, any undesirable CDMA signal incident on a receiver, which does not correlate with an identical in-phase code, will remain spread over the bandwidth of the spreading code. Globalstar uses a modified IS-95 scheme for CDMA processing which results in a channel bandwidth of 1·2288 MHz. The power density of the

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transmitted signal is therefore spread over this wide bandwidth, and is pseudo-random in nature – i.e. it resembles band-limited noise.

3. THE EFFECT OF NOISE ON GLONASS RECEPTION. Another of the important features of spread-spectrum processing is its increased tolerance to in-band interference. This is sometimes used to justify co-locating different services. The correlation of the incoming signal with a locally-generated code is in fact a comparable operation to the original signal spreading when an unspread signal is processed. If this unspread signal is a source of narrow-band (with respect to that of the spreading code) interference, then its power density will be reduced by the correlation operation, and subsequent filtering in the receiver signal processing will remove a portion of the interference, thus reducing its effect. However, this effect is only apparent when the interference is narrow-band. This effect can be shown by exploring code correlation in the frequency domain using the convolution integral.

$$y(t) = x(t) \times h(t)$$

$$Y(f) = X(f) * H(f) = \int_{-\infty}^{+\infty} X(\phi)\, H(f-\phi)\, d\phi = \int_{-\infty}^{+\infty} H(\phi)\, X(f-\phi)\, d\phi. \qquad (2)$$

It can be shown that correlation in the time domain is equivalent to convolution of the power spectral densities (p.s.d.) of both signals in the frequency domain.[1] The convolution integral then describes the integration of the spread signal power of every frequency component of the input spectrum. This equation can be evaluated numerically using a mathematical package such as Matlab with wide-band noise as an input, and the frequency response of the GLONASS spreading code. By this method, it can be shown that the p.s.d. of the noise both before and after code correlation is identical. It is therefore clear that code correlation has no effect on the p.s.d. of wide-band noise interference.

To show the effect of an elevation of input noise level on a GLONASS receiver, a series of trials was performed. In these trials, excess noise interference was generated by a calibrated wide-band noise source and coupled into the RF processing chain of an ISN receiver. The interference was introduced at the front-end of the receiver combined with the satellite signals, which had been processed by the antenna, low noise amplifier (LNA) and a length of co-axial cable. The gains and losses of these components were determined from manufacturers' data sheets and from calibration when no data was available. The gain towards the satellite signal and sky noise is therefore known. Because the signals from actual satellites are used in the test, the absolute signal power cannot be known. However, the received carrier-to-noise ratio (CNR) is computed by the receiver and, using an assumed sky noise temperature of 100 K,[2] the absolute signal power can be calculated, neglecting losses introduced by the receiver processing. The losses in the receiver are unimportant because the tests were designed to determine the effect of increasing the input noise level, and so the receiver losses will be constant over the period of the test.

A period of data with no excess interference is logged by the receiver to determine the received CNR and so the received signal power. The level of excess noise interference is then increased in steps and data logged for a period of time. The expected value of CNR, using the convolution analysis, is calculated by a software signal and noise simulator, and this is compared with the observed values. Because real satellite signals are used for the tests, there is the potential for multipath to affect the CNR measurements. To minimise this effect, the receiver antenna was mounted in a favourable location, away from potential sources of reflection, and the data from a large number of trials using high elevation satellites was gathered. The results of one such trial is shown in Table 1. The expected CNR and predicted CNR are compared

Table 1. Comparison of Predicted and Actual Receiver Performance under Wide-band Noise Interference.

Noise power density from interference generator	−89·8 dBm/MHz	−84·8 dBm/MHz	−75·8 dBm/MHz
Combined thermal/interference density	−83·5 dBm/MHz	−81·7 dBm/MHz	−75·3 dBm/MHz
Effective noise temperature to give the combined noise density	174 K	340 K	1988 K
Predicted CNR at this noise temperature	50·7 dBHz	47·8 dBHz	40·1 dBHz
Observed CNR at this noise temperature	51·6 dBHz	47·5 dBHz	40·1 dBHz

and seen to correlate very well. The small error when low input noise powers are used is due to the assumption of the sky noise temperature. With high-powered noise interference, the small contribution of the background noise level is masked by the excess interference and the predicted effect agrees very well with the observed.

The application of this technique for determination of the p.s.d. of an interfering signal after code correlation is not confined to wide-band noise and can be applied to any arbitrary interference source. This has allowed the equivalent wide-band noise interference of the proposed Globalstar in-band and out-of-band signal to be determined. In conjunction with the wide-band interference trials, this will allow the effect of Globalstar signals on GLONASS reception to be evaluated.

4. THE PROPOSED GLOBALSTAR EMISSIONS' MASK. The emissions' mask of the Globalstar signal is shown in Table 2. Although it might

Table 2. Globalstar MSS Emissions' Mask.

Frequency (MHz)	Carrier-on EIRP (dBW/MHz)
1550–1559	−60
1559–1573·42	−70
1573·42–1580·42	−70 (averaged over 20 ms)
1580·42–1590	−70
1590–1605	Linearly interpolated from −70 to −64
1605–1610	Linearly interpolated from −64 to −10
1610–1626·5	In-band – minimum emissions of −10†

† Although the in-band emissions are not defined, it is assumed that the *minimum* emissions' level will be no less than the out-of-band level at 1610 MHz.

appear that the GLONASS band is protected, due to the spread-spectrum processing, the presence of large amounts of interference immediately adjacent to the band will cause in-band interference. The reason for this is explained by the convolution operation; the process of convolution will integrate the power from a large bandwidth

Table 3. The Effect of MSS Interference on GLONASS Reception for All Possible Transmission Channels.

GLN channel	Equivalent wide-band noise [dBW/MHz]	Excess over worse-case (tracking) [dB]	Separation required for successful tracking [m]	Excess over worst-case (acquisition) [dB]	Separation required for successful acquisition [m]
−7	−66·7	65·6	28·3	75·6	89·5
−6	−66·5	65·8	29·0	75·8	91·6
−5	−66·3	66·0	29·6	76·0	93·7
−4	−66·1	66·2	30·5	76·2	96·4
−3	−65·9	66·4	31·3	76·4	99·0
−2	−65·6	66·7	32·2	76·7	101·9
−1	−65·2	67·1	33·8	77·1	106·8
0	−64·3	68·0	37·6	78·0	118·8
1	−62·1	70·2	48·2	80·2	152·5
2	−58·1	74·2	76·1	84·2	240·7
3	−52·8	79·5	140·8	89·5	445·4
4	−46·9	85·4	277·1	95·4	876·4
5	−40·8	91·5	555·5	101·5	1756·7
6	−36·4	95·9	922·0	105·9	2915·5
7	−34·1	98·2	1212·7	108·2	3835·0
8	−32·2	100·1	1502·3	110·1	4750·8
9	−30·4	101·9	1853·5	111·9	5861·4
10	−28·2	104·1	2381·1	114·1	7529·6
11	−25·2	107·1	3349·5	117·1	10591·9
12	−21·2	111·1	5297·0	121·1	16750·5
13	−16·4	115·9	9219·5	125·9	29154·5
14	−11·5	120·8	16289·7	130·8	51512·6
15	−10·2	122·1	18959·9	132·1	59956·6
16	−10·1	122·2	19116·1	132·2	60450·6
17	−10·1	122·2	19173·8	132·2	60632·9
18	−10·0	122·3	19203·6	132·3	60727·0
19	−10·0	122·3	19221·6	132·3	60784·2
20	−10·0	122·3	19233·8	132·3	60822·5
21	−10·0	122·3	19242·6	132·3	60850·3
22	−10·0	122·3	19248·7	132·3	60869·7
23	−10·0	122·3	19250·9	132·3	60876·6
24	−10·0	122·3	19244·4	132·3	60856·1

(10 MHz in the case of GLONASS) and present this in-band to the desired signal to some extent. Following from this point, the full bandwidth of the GLONASS signal is considered because, unlike GPS, it is very difficult to band-limit the signal to include only the C/A code due to the FDMA nature of the signal. If the signal is filtered to the C/A code, an asymmetrical frequency response results which causes channel-dependent biases in the measurements.

The post-correlation p.s.d. is computed using (2) and then filtered to the pre-detection bandwidth. This operation is relatively narrow-band when compared with the CDMA-noise bandwidth and effectively removes all noise except that centralised about the signal centre frequency. In this case, the complex noise power spectrum is modelled by a flat, wide-band spectrum with a power density as computed at the centre frequency. This is achieved by setting ϕ to zero in (2). The results of this analysis are shown in Table 3 (column 2).

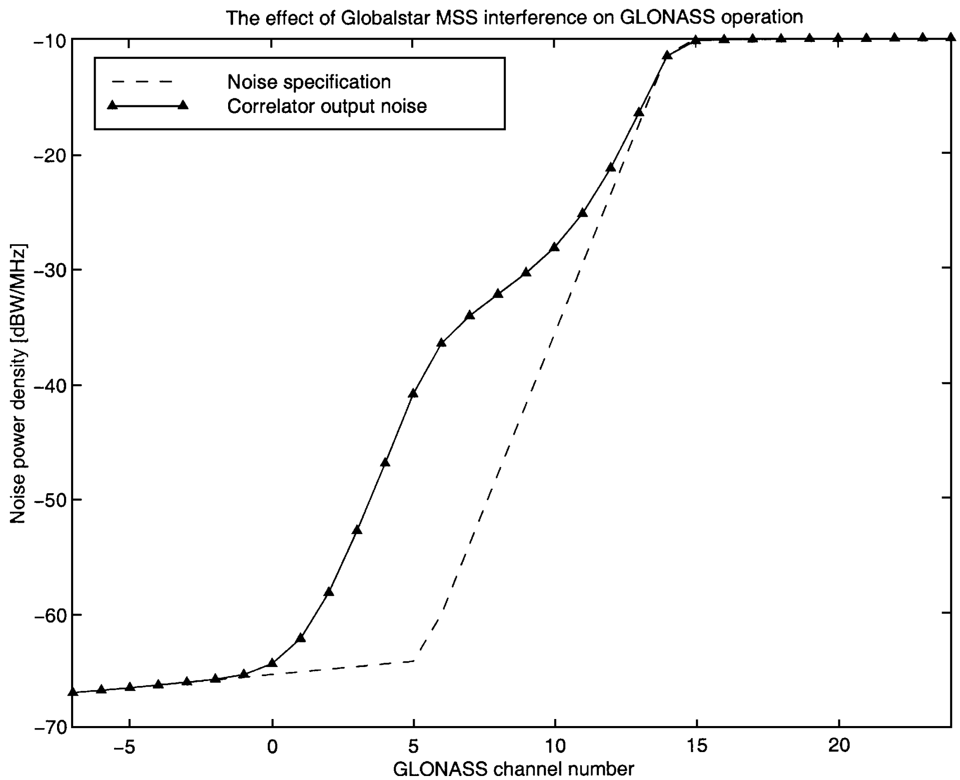

Figure 1. A Comparison of the Effective Noise of Globalstar Emissions before and after Code Correlation.

It is often quoted that the minimum required received CNR to allow a receiver to function adequately for precision approach is 28 dBHz.[3] The authors contend this figure but, due to the limited scope of this paper and the limited published justification for this value, this will not be discussed in detail; an outline of the problems is given in Section 5. Instead, the figure of 28 dBHz requirement for tracking will be used as a basis for the computation of the effect of MSS interference from Globalstar. These results give the best case for the tracking and acquisition performance.

Much emphasis is placed upon the tracking performance of the receiver under interference and very little is said of the acquisition performance. In steady-state tracking, the pre-detection interval (PDI) used within the receiver (which defines the bandwidth at which the tracking error is deduced in order to close the tracking loops) is set to the length of the data bit, which is 10 ms (equivalent to 100 Hz) for GLONASS C/A code tracking. This reduces the two-sided receiver noise bandwidth to 100 Hz. When acquiring a satellite signal, this is not possible as the phase of the satellite data message is not immediately known. The minimum PDI that can be used corresponds to the period of the code chip which is 1 ms (1 kHz). This increases the receiver noise bandwidth by 10 dB and therefore reduces the receiver tolerance to MSS interference by 10 dB. The result is that to acquire satellite signals successfully requires a receiver CNR of 38 dBHz.

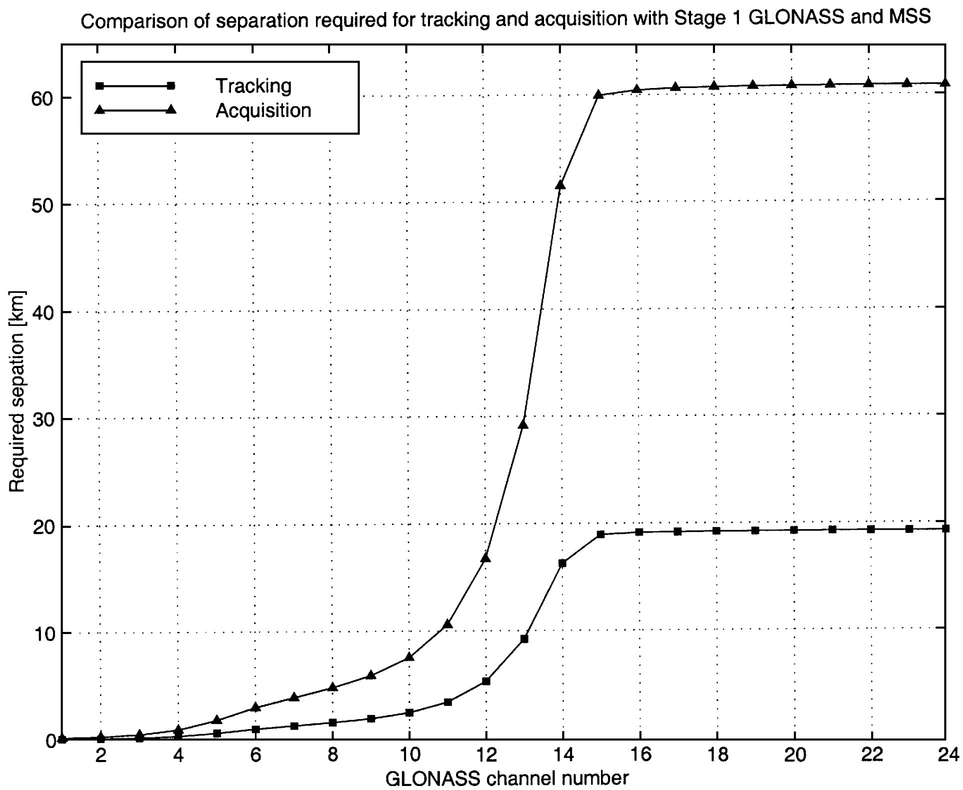

Figure 2. Separation Required to Acquire and Track a GLONASS Satellite in the Presence of Globalstar Interference with the Stage 1 Frequency Allocation.

Added to this, the receiver processing will impose additional signal-to-noise ratio losses prior to the digital tracking loops. This loss is heavily dependent on receiver architecture but a worst-case scenario is set out in Table 4. From this, it is seen that

Table 4. Worst-case Receiver Architecture and Loss.

Front-end filter loss (P code bandwidth)	0·04 dB
1-bit sampling loss at P bandwidth	2·07 dB
Phase rotation loss	0·91 dB
Total receiver architecture loss	3·02 dB

the losses incurred from receiver processing are 6·0 dB including a worst-case receiver noise figure of 3 dB. Using the signal/noise simulator, it was determined that with the worst-case scenario, the effective GLONASS signal power incident to the tracking loops is −165·4 dBW; the tracking CNR of 28 dBHz is realised with a noise power of −132·3 dBW/MHz, and the acquisition CNR of 38 dBHz is realised with a noise power of −142·3 dBW/MHz. This analysis is combined with the equivalent wide-band noise power of the Globalstar transmissions already described and shown in Table 3. The amount by which the MSS emissions exceed the maximum tracking and

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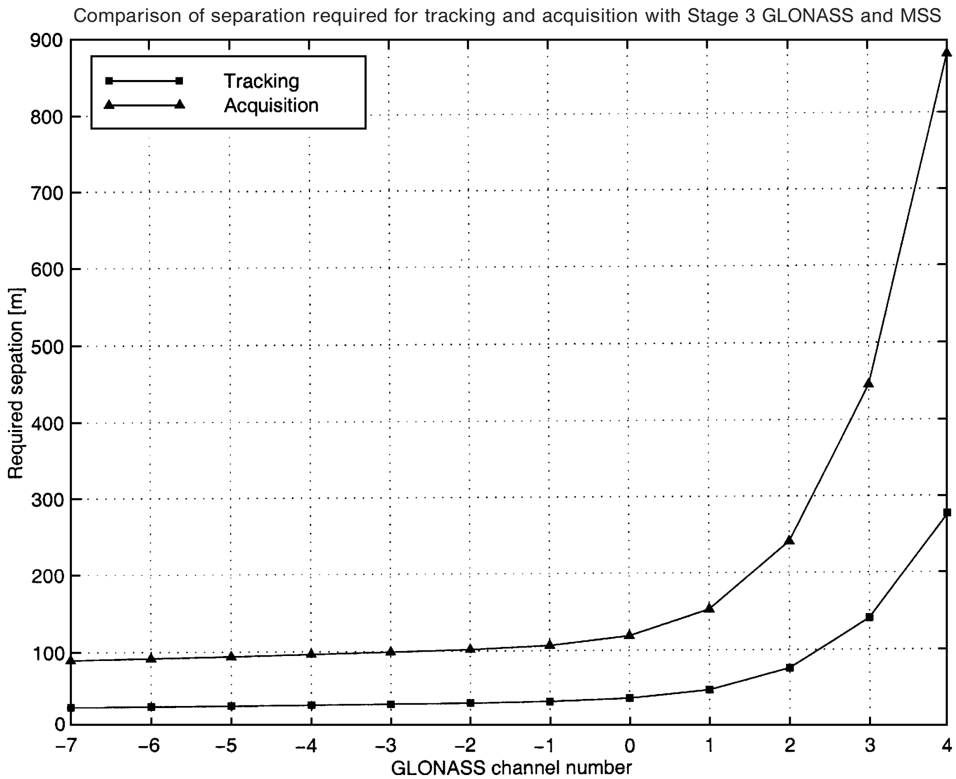

Figure 3. Separation Required to Acquire and Track a GLONASS Satellite in the Presence of Globalstar Interference with the Stage 3 Frequency Allocation.

acquisition values is shown, along with the required separation of interference source and GLONASS antenna, in order to allow tracking or acquisition. This is computed using the space loss equation:

$$L_s = \left(\frac{\lambda}{4\pi d}\right)^2. \tag{3}$$

5. RESULTS. Studying Table 3, and the graphic representation of the data in Figures 1–3, shows the potentially drastic effect of MES emissions. The values computed in this table do not take into account any differential gain of signal to interference by the GLONASS receiver (worst-case) but equally, it assumes only a single source of interference which is unlikely to be the case should both systems be widely adopted.

Figure 1 shows the equivalent wide-band noise at the output of the correlation process (Table 3, column 2) compared with the effective input noise from the Globalstar emissions. Figures 2 and 3 show the separation of Globalstar MES to GLONASS receiver required to acquire and track GLONASS signals in both the current stage of frequency location and the final, Stage 3 allocation (Table 3, columns 4 and 6).

The first result to note is that until the high channel satellites (> 12) of the current GLONASS constellation are replaced (of which there are currently five), Globalstar's

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own minimum tracking performance can only be reached with a single source of interference located no closer than 9·2 km from the receiver. Also, no new satellite track will be possible with a MES located within 29 km of the receiver. This will seriously restrict GLONASS use. Also, in the intervening six-year period until the stage 3 frequency allocation is scheduled to be in place, the limits in distance for a single transmitter are 5·2 km for tracking and 16 km for acquisition. This period of time will be critical in practical studies into the use of GLONASS within the framework of GNSS-1. Finally, from 2005 onwards, significant separation will still be required (280 m or 880 m) but, by this time, is the assumption of a single interference source going to be valid?

Using the figure of 28 dBHz is also unrealistic. When users are requiring very high measurement precision and integrity, significantly more signal power is necessary. An assumption of carrier smoothing is made to give sufficient precision to the pseudorange. There is a latency involved in this operation which means that newly-acquired satellite signals are not available immediately; this has a great impact on integrity. Finally, at 28 dBHz, the carrier loop is close to its unlocking threshold, which presents two problems: first, multipath affects the received CNR and fades of 5 dB are not uncommon which will cause the loop to unlock. These fades can last for reasonable periods of time removing large amounts of data. Secondly, because the loop is close to its threshold, the signal processing which detects unlock has to be very sensitive which is both difficult and potentially unreliable (impacting again on data integrity).

6. CONCLUSIONS.

This paper has introduced the interference effects of the Globalstar MSS E-s link on GLONASS. It has shown that significant interference will be caused to GLONASS reception both at the present time and into the future. It has also highlighted that in-depth studies are required into the acceptable received CNR to allow GLONASS to be used as part of GNSS-1 to allow high precision, high integrity, high availability operations.

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KEY WORDS

1. GLONASS. 2. Radio Communications. 3. Satellites.