

Assessment of Radio Frequency Compatibility Relevant to the Galileo E1/E6 and Compass B1/B3 Bands

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The intersystem interference between Galileo and Compass, known as a radio frequency compatibility problem, has become a matter of great concern for the system providers and user communities. This paper firstly describes two fundamentally different methods to assess the Global Navigation Satellite System (GNSS) intersystem interference, by using different interference coefficients that are calculated for each combination of signals: the spectral separation coefficient (SSC) and code tracking spectral sensitivity coefficient (CT_SSC). And then a complete methodology combining the SSC and CT_SSC is presented. Real simulations are carried out to assess the interference effects where Galileo and Compass signals are sharing the same band (E1/B1 and E6/B3 bands) at every time and place on the Earth. Simulation results show that the effects of intersystem interference are significantly different by using these two methodologies. It is also shown that the Compass system leads to intersystem interference on Galileo but that the maximal values are lower than Galileo interference to Compass. The design and implementation of any new signal has to be conducted carefully in order for there to be radio frequency compatibility.

KEY WORDS

1. Compatibility.
2. Galileo.
3. Compass.

1. INTRODUCTION. The presence of the US GPS and the Russian GLONASS, and the upcoming constellations of a number of the new global and regional augmentation navigation satellite systems (the European Galileo, the Chinese Compass, the Japanese QZSS and the Indian GAGAN or IRNSS) will introduce additional end-user accuracy everywhere and improve service availability in environments where satellite visibility is often obscured (Gibbons, 2009). Meanwhile, multiple constellations broadcasting more signals in the same frequency bands will cause interference effects among the systems, making interoperability and compatibility more tedious (Hein, 2007a, Hein, 2007b).

Interoperability refers to the ability of global and regional navigation satellite systems and augmentations, and the services they provide, to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system. Compatibility refers to the ability of global and regional navigation satellite systems, and augmentations, to be used separately or

together without causing unacceptable interference and/or other harm to an individual system and/or service. In order to make open signals and services interoperable and maximize benefit to all global navigation satellite systems (GNSS) users, all GNSS signals and services must be compatible (Hein, 2006).

In April 2007, China launched the first middle-Earth orbit (MEO) satellite for Compass, which the nation plans to turn into a fully fledged GNSS system within a few years (XinhuaNews, 2007). In April 2009, a second Compass satellite – this one a geostationary satellite – was launched, which marks the return of China to its GNSS launch program two years after the initial venture into space. The country will complete a 30+ satellite Compass constellation by 2015 (XinhuaNews, 2009). Since Compass uses signal structures similar to other GNSS systems and shares frequencies close to or overlapping those of Galileo, the Galileo and Compass signal overlay becomes a matter of great concern for the system providers and user communities. This issue remains unresolved after two meetings between Chinese and European Union (EU) representatives. This paper mainly deals with the interference computation and simulation among the above-mentioned systems and displays some important analysis results.

Some methodologies for GNSS radio frequency compatibility analyses have been developed in order to assess the intrasystem (interference from the same system) and intersystem (interference from other systems) interference (Titus, 2003, Wallner, 2006, Wallner, 2005). These methodologies present an extension of the effective carrier power to noise density (C/N_0) theory introduced by John W. Betz (Betz, 2001) to assess the effects of interfering signals in a GNSS receiver. A parameter called spectral separation coefficient (SSC) (Betz, 1999) was also introduced to distinguish the effects of interference spectral shape from the effects due to the interfering power. The SSC parameter is an element of the effective C/N_0 , which is defined as an inner product of the power spectral densities (PSD) between the desired and interfering signals. In fact, the SSC parameter is appropriate for assessing the impact of interfering signals on the receiver prompt correlator channel processing phases, which are signal acquisition, carrier tracking loop and data demodulation, but not appropriate for the effects on the code tracking loop (DLL) phase. To describe the impact of interfering signals on the code tracking loop phase, a new parameter called code tracking spectral sensitivity coefficient (CT_SSC) was introduced in (Soualle, 2007a, Soualle, 2007b).

This paper firstly presents an extension of CT_SSC theory in order to assess the effects of intersystem interference on code tracking accuracy. And then a complete methodology combining the SSC and CT_SSC is presented. This method takes into account the space constellation, signal modulation, emission power level, space loss, satellites antenna gain and user receiver characteristic. Computer simulation approach will be adopted in the interference computation for pursuing more realistic results, though it is time consuming to perform the simulation for every interference scenario for different users at every time and place.

Considering the fact that a lot of attention was paid to the signal spectrum overlaps at E1/B1 and E6/B3 band between the above-mentioned systems, intersystem interference will be computed mainly on the two bands where Galileo and Compass signals are sharing the same band. All satellite signals which include (i) the Galileo E1 PRS, E1OS, E6 CS and E6 PRS signals, (ii) the Compass B1, B1-2 and B3 signals, will be taken into consideration in the simulations. In addition, several worse scenarios

are simulated, using a $5^\circ \times 5^\circ$ grid for latitude and longitude and sampling the period time by a small time steps, i.e. 60 sec.

This paper is organized as follows. Section 1 describes a complete methodology based on SSC and CT_SSC for the interference computation and simulation. Section 2 introduces the constellation and signal parameters used in the computer simulations. Section 3 presents all the simulation and analysis results, while Sections 4 draws conclusions.

2. METHODOLOGIES. This section provides a detailed derivation of the methodologies used for interference computation and simulation, which is based on the use of different interference coefficients that are calculated for each combination of signals: the spectral separation coefficient and code tracking spectral sensitivity coefficient.

2.1. Formulation. In order to provide a general quantity to reflect the effect of interference on characteristics at the input of a generic receiver, a quantity called effective carrier power to noise density (C/N_0), denoted $(C/N_0)_{eff_SSC}$, was introduced in (Betz, 2001). The $(C/N_0)_{eff_SSC}$ can be interpreted as the carrier power to noise density ratio caused by an equivalent white noise that would yield to the same correlation output variance obtained in presence of interference signal. When intrasystem (interference from the same system) and intersystem (interference from other systems) interference coexists, the $(C/N_0)_{eff_SSC}$ can be expressed as:

$$(C/N_0)_{eff_SSC} = \frac{C}{N_0 + I_{GNSS_SSC}} \tag{1}$$

where

$$I_{GNSS_SSC} = \sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j} \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f)G_{i,j}(f)df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df} \tag{2}$$

$G_s(f)$ is the normalized power spectral density of the desired signal. C is the received power of the useful signal. N_0 is the power spectral density of the thermal noise. In this paper, we assume N_0 to be -201.5 dBW/Hz. $G_{i,j}(f)$ is the normalized spectral density of the j -th interfering signal on the i -th satellite, $C_{i,j}$ the received power of the j -th interfering signal on the i -th satellite, β_r the receiver front-end bandwidth, M the visible number of satellites, and K_i the number of signals transmitted by satellite i . I_{GNSS_SSC} is the aggregate equivalent noise power density of the combination of intrasystem and intersystem interference.

From (2) it is clear that the impact of the interference on $(C/N_0)_{eff_SSC}$ is directly related to the spectral separation coefficient (SSC) (Betz, 1999) of an interfering signal from the j -th interfering signal on the i -th satellite to a desired signal s , the SSC is defined as:

$$\kappa_{i,j}^s = \int_{-\beta_r/2}^{\beta_r/2} G_s(f)G_{i,j}(f)df \tag{3}$$

In fact, the SSC parameter is appropriate for assessing the impact of interfering signals on the receiver prompt correlator channel processing phases (acquisition, carrier phase tracking and data demodulation), but not appropriate to evaluate the effects on the DLL phase. For this reason, a new parameter to assess the impact of interfering signals on the code tracking loop phase, called code tracking spectral sensitivity coefficient (CT_SSC) was introduced in (Soualle, 2007a, Soualle, 2007b). The CT_SSC is defined as:

$$\eta_{i,j}^s = \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_{i,j}(f) \sin^2(\pi f \Delta) df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df} \quad (4)$$

where Δ is the two-sided early-to-late spacing of the correlator.

To provide a metric of similarity to reflect the effect of interfering signals on the code tracking loop phase, a quantity called CT_SSC effective carrier power to noise density (C/N_0), denoted $(C/N_0)_{\text{eff_CT_SSC}}$, is derived in the following text. We recall the method to predict the effect of interference on code tracking accuracy for coherent early-late processing, developed in (Betz, 2000a, Betz, 2000b). When there are noise and one non-white interference signal, and the effect of filtering can be neglected within the pass-band, the variance of the code tracking error (in units of seconds squared) can be written as:

$$\sigma_{\text{CELP}}^2 = 2B_L T(1 - 0.5B_L T) \times \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df + \frac{C_i}{N_0} \int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_l(f) \sin^2(\pi f \Delta) df}{2(2\pi)^2 T \frac{C}{N_0} \left(\int_{-\beta_r/2}^{\beta_r/2} f G_s(f) \sin^2(\pi f \Delta) df \right)^2} \quad (5)$$

where $G_l(f)$ is the normalized spectral density of the interfering signal. C_i is the received power of the interfering signal. B_L is the one-sided equivalent rectangular bandwidth of the DLL. T is the integration time used in the discriminator. Δ is the two-sided early-late spacing of the correlator.

When there is only white noise, expression (5) can be rewritten as:

$$\sigma_{\text{CELP}}^2 = 2B_L T(1 - 0.5B_L T) \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df}{2(2\pi)^2 T \frac{C}{N_0} \left(\int_{-\beta_r/2}^{\beta_r/2} f G_s(f) \sin^2(\pi f \Delta) df \right)^2} \quad (6)$$

In white noise and nonwhite interference signal, when the variance of the code tracking error σ_{CELP}^2 is known, an effective C/N_0 is defined as the carrier to noise density ratio (with no interference and only white noise) that would yield the

same σ_{CELP}^2 . From expression (6), another effective C/N_0 can be defined as:

$$\left(\frac{C}{N_0}\right)_{eff_CT_SSC} = 2B_L T(1 - 0.5B_L T) \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df}{2(2\pi)^2 T \sigma_{CELP}^2 \left(\int_{-\beta_r/2}^{\beta_r/2} f G_s(f) \sin^2(\pi f \Delta) df\right)^2} \quad (7)$$

Substituting expression (5) into expression (7) yields:

$$\left(\frac{C}{N_0}\right)_{eff_CT_SSC} = \frac{\frac{C}{N_0} \int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df + \frac{C_I}{N_0} \int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_I(f) \sin^2(\pi f \Delta) df} \quad (8)$$

When there is intrasystem and intersystem interference coexistence, the $(C/N_0)_{eff_CT_SSC}$ can be expressed as:

$$\begin{aligned} (C/N_0)_{eff_CT_SSC} &= \frac{C \int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df}{N_0 \int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df + \sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j} \int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_{i,j}(f) \sin^2(\pi f \Delta) df} \\ &= \frac{C}{N_0 + \frac{\sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j} \int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_{i,j}(f) \sin^2(\pi f \Delta) df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df}} \\ &= \frac{C}{N_0 + I_{GNSS_CT_SSC}} \end{aligned} \quad (9)$$

where

$$I_{GNSS_CT_SSC} = \sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j} \frac{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) G_{i,j}(f) \sin^2(\pi f \Delta) df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f) \sin^2(\pi f \Delta) df} \quad (10)$$

$I_{GNSS_CT_SSC}$ is the aggregate equivalent noise power density of the combination of intrasystem and intersystem interference.

From (9) it is clear that the impact of the interference on $(C/N_0)_{eff_CT_SSC}$ is also directly related to CT_SSC.

When considering a DLL using non-coherent early-late tracking, the variance of the code tracking error (Betz, 2000a) is

$$\sigma_{NELP}^2 = \sigma_{CELP}^2 \cdot \theta_{square_loss} \quad (11)$$

As we can see the variance of the code tracking error of non-coherent DLL is the product of σ_{CELP}^2 and a squaring loss, θ_{square_loss} , that is greater than unity, but approaches unity for the usual range of C/N_0 . So in the case of non-coherent DLL (Soualle, 2007b), the same CT_SSC and $(C/N_0)_{eff_CT_SSC}$ can be obtained.

2.2. *Equivalent noise power density.* When more than two systems are operating together, the aggregate equivalent noise power density I_{GNSS} (I_{GNSS_SSC} or $I_{GNSS_CT_SSC}$) is the sum of two components:

$$I_{GNSS} = I_{Intra} + I_{Inter} \quad (12)$$

where I_{Intra} is the equivalent noise power density of interfering signals from satellites belonging to the same system as the desired signal, and I_{Inter} is the aggregate equivalent noise power density of interfering signals from satellites belonging to the other systems.

In fact, recalling the SSC and CT_SSC definitions, hereafter denoted $\kappa_{i,j}^s$ or $\eta_{i,j}^s$ as $\gamma_{i,j}^s$, the equivalent noise power density (I_{Intra} or I_{Inter}) can be simplified as follows:

$$I_x = \sum_{i=1}^M \sum_{j=1}^{K_i} C_{i,j} \gamma_{i,j}^s \quad (13)$$

The user received power $C_{i,j}$ of the j -th signal belonging to the i -th satellite can be written in terms of satellite transmit power, satellite and user receiver antenna gains, space loss and polarization loss (Owen, 2002):

$$C_{i,j} = \frac{P_{i,j} G_i G_{user}}{L_{dist} L_{atm} L_{pol}} \quad (14)$$

where $P_{i,j}$ is the transmit power of the j -th signal belonging to the i -th satellite, L_{dist} is the free-space loss due to the distance between i -th satellite and user, L_{atm} is the loss of the signal due to atmospheric loss, L_{pol} is the polarization mismatch loss, G_i is the satellite antenna gain between the i -th satellite to the user receiver, G_{user} is the user receiver antenna gain between the user receiver to the i -th satellite.

The atmospheric loss L_{atm} is estimated to be 0.5 dB for all systems (Titus, 2003). The satellite antenna gain G_i is a function of the off-boresight angle α (Wallner, 2005), and is illustrated in Figure 1. It must be noted that different signals from Galileo and Compass have different satellite antenna gain profiles. For example, a typical profile of GPS Block IIA satellite antenna gain is depicted in Figure 2.

The free-space loss L_{dist} can be expressed as:

$$L_{dist} = \left(\frac{c}{4\pi d f_0} \right)^2 \quad (15)$$

where c is the speed of light, d is the distance between satellite and user, and f_0 is the carrier centre frequency.

For the aggregate equivalent noise power density calculation, the constellation configuration, satellite and user receiver antenna gain patterns, and the space loss are included in the link-budget equation. User receiver location must be taken into account when measuring the interference effects. When a receiver at a given

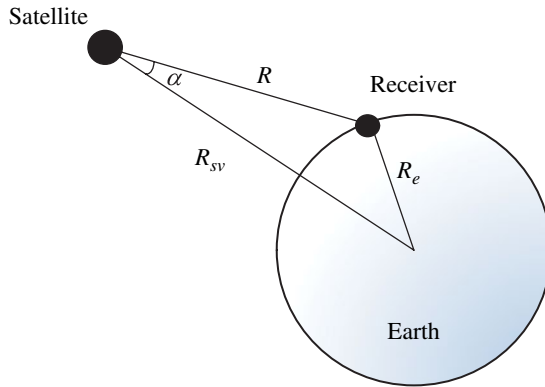


Figure 1. Illustration of off-boresight angle.

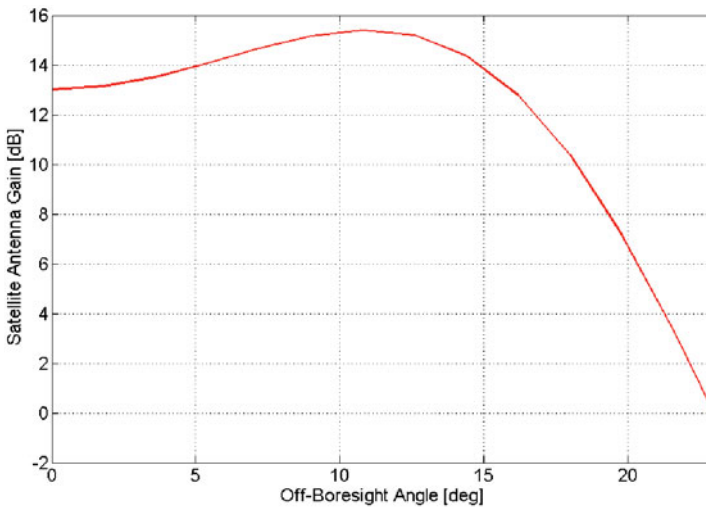


Figure 2. Typical satellite antenna gain.

location m on the Earth at any time over a 24-hour period, the aggregate equivalent noise power density to a desired signal s can be written as follows:

$$I_m^s(t) = \sum_{i=1}^{M(t)} \sum_{j=1}^{K_i} \frac{P_{i,j} G_i(t) G_{user}(t)}{L_{dist}(t) L_{atm} L_{pol}} \gamma_{i,j}^s \tag{16}$$

Equation (16) is the sum of all equivalent noise power density from all signals of all satellites in view at any time. When the desired satellite is used, it must be subtracted from the power spectral density of the desired signal from the desired satellite.

2.3. Degradation of effective C/N_0 . A general way to calculate $(C/N_0)_{eff}$ ($(C/N_0)_{eff_SSC}$ or $(C/N_0)_{eff_CT_SSC}$) introduced by interfering signals from satellites belonging to the same system or other systems is based on equation (1) or (8). In addition to the calculation of $(C/N_0)_{eff}$, calculating degradation of effective C/N_0

Table 1. Space constellation parameters.

Parameter	Galileo	Compass
Constellation	Walker 27/3/1	5GSO+30NGSO 5GEO: 58-75°,80°,110-5°,140° and 160° E 3IGSO 27 MEO: Walker27/3/1
Inclination (°)	56	55
Eccentricity	0	IGSO:0 MEO:0
Semi-major axis(km)	29601-297	IGSO: 421642 MEO: 27878

is more interesting when more than two systems are operating together. The degradation of effective C/N_0 in the case of the intersystem interference is:

$$\begin{aligned} \Delta(C/N_0)_{eff} &= \frac{\frac{C}{N_0 + I_{Intra}}}{\frac{C}{N_0 + I_{Intra} + I_{Inter}}} \\ &= 1 + \frac{I_{Inter}}{N_0 + I_{Intra}} \end{aligned} \quad (17)$$

Therefore, the expression of intersystem interference in dB as:

$$\phi_{Inter} = 10 \cdot \log \left(1 + \frac{I_{Inter}}{N_0 + I_{Intra}} \right) \quad (18)$$

For example, if Galileo and Compass are operating together, regarding Galileo E1 OS signal on the i -th satellite as the desired satellite and the desired signal, I_{Intra} and I_{Inter} can be expressed as:

$$I_{Intra} = I_{E1OS, others} + I_{PRS} \quad (19)$$

$$I_{Inter} = I_{Compass} = I_{B1} + I_{B1-2} \quad (20)$$

Where $I_{E1OS, others}$ is the equivalent noise power density of Galileo E1 OS signal belonging to the other satellites of the Galileo constellation.

3. SIMULATION PARAMETERS. This section provides the space constellations and signals parameters of Galileo and Compass for computer simulations.

3.1. Space constellations. The space constellation parameters of Galileo and Compass are summarized in the Table 1. Galileo will be composed of 30 satellites in three orbital planes, with 27 operational spacecraft and three in-orbit spares (1/plane) (ICD-Galileo, 2008). Here we take the 27 satellites for Galileo constellation. Compass will consist of 27 MEO satellites, five GEO and three IGSO satellites (China, 2006, Liu, 2009). Due to the fact that Galileo and Compass are under construction, ideal constellation parameters are taken from Table 1 and the Galileo and Compass space constellations are shown in Figure 3.

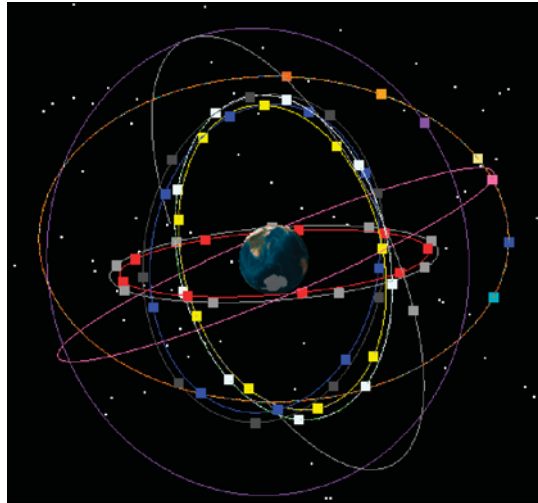


Figure 3. Galileo and Compass space constellations.

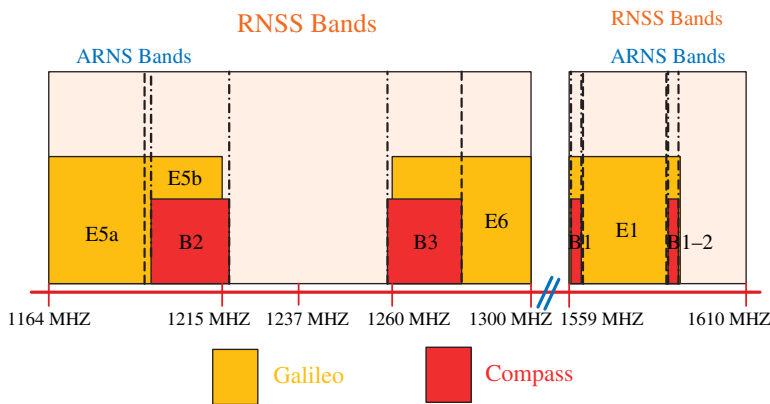


Figure 4. Galileo and Compass frequency bands.

3.2. *Signal parameters.* The frequency bands of Galileo and Compass are shown in Figure 4. It can be seen that a lot of attention must be paid to the signal spectrum overlaps at E1/B1 and E6/B3 bands between these systems. Thus, we will concentrate the interference only on the E1/B1 and E6/B3 bands in this paper. All satellite signals which include (i) the Galileo E1 PRS, E1OS, E6 CS and E6 PRS signals, (ii) the Compass B1, B1-2 and B3 signals will be taken into account in the simulations. Table 2 summarizes the characteristics of Galileo and Compass signals to be transmitted in E1/B1 and E6/B3 bands (Avila-Rodriguez, 2007, Liu, 2009). The detailed information about the signal parameters can be found in the Galileo interface control document and International Telecommunication Union (ITU) related document (China, 2006, ICD-Galileo, 2008). The power spectral densities of the Galileo and Compass signals in E1/B1 and E6/B3 bands are shown in Figure 5 and Figure 6, respectively.

Table 2. Galileo and Compass signal parameters in E1/B1 and E6/B3 bands.

System	Service type	Carrier frequency (MHZ)	Modulation type	Chip rate (Mcps)
Galileo	E1 OS	1575.42	MBOC(6,1,1/11)	1.023
	E1 PRS	1575.42	BOC _c (15,2.5)	2.5575
	E6 CS	1278.75	BPSK(5)	5.115
	E6 PRS	1278.75	BOC _c (10,5)	5.115
Compass	B1	1561.098	QPSK	2.046
	B1-2	1589.742	QPSK	2.046
	B3	1268.52	QPSK	10.23

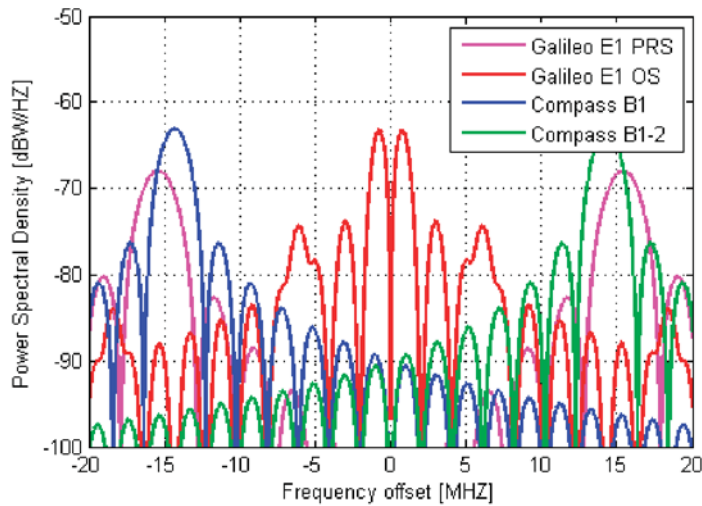


Figure 5. PSD of the Galileo and Compass signals in E1/B1 band.

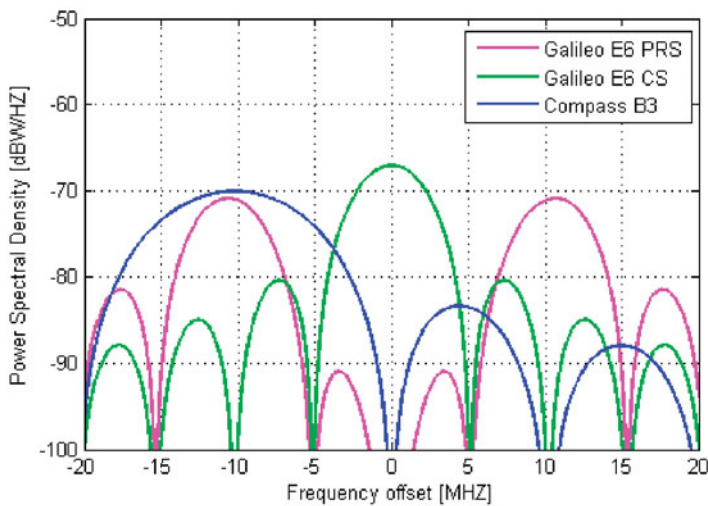


Figure 6. PSD of the Galileo and Compass signals in E6/B3 band.

Table 3. Simulation parameters.

Parameter	Value
Time period	1 day
Time step	60 second
Coverage	Global
Grid spacing	5° × 5°
Elevation angle	5°
Emission bandwidth	Galileo: 40.92 MHz
	Compass: 40.92 MHz
Front-end bandwidth	40.92 MHz

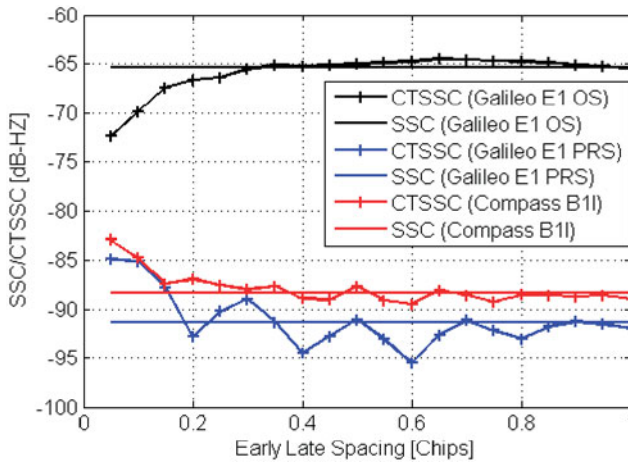


Figure 7. SSC and CT_SSC for Galileo E1 OS as desired signal.

4. SIMULATION RESULTS. Table 3 summarizes the simulation parameters which are simulated for the aggregate equivalent noise power densities. Here, we assume a transmitter filter bandwidth of 40.92 MHz for the Galileo and Compass signals so that at least one of the secondary lobes falls inside it.

We can see from equation (1) or (8) that $(C/N_0)_{eff}$ is directly related to SSC or CT_SSC of the desired and interfering signals. Figure 7 shows both SSC and CT_SSC for the different interfering signals and for a Galileo E1 OS as desired signal. It obviously shows that CT_SSC is significantly different from the SSC. It also shows that CT_SSC depends on the early-late spacing and its maximal values appear at different early-late spacing.

The CT_SSC for different civil signals in E1/B1 and E6/B3 bands are calculated using equation (4). The power spectral densities are normalized to the transmitter filter bandwidth and integrated in the bandwidth of the user receiver. As we saw in equation (4), when calculating the CT_SSC, it is necessary to consider all possible values of early-late spacing. In order to determine the maximum equivalent noise power density (I_{Intra} or I_{Inter}), the maximum CT_SSC will be calculated within the typical early-late spacing ranges (0-1– 1chip space). The results are shown in

Table 4. Code tracking spectral sensitivity coefficients in E1/B1 and E6/B3 bands.

Max. CT_SSC [dB-Hz]	Galileo		Compass		
	E1 OS	E6 CS	B1-I	B1-2-I	B3-I
Transmit BW[MHz]	40-92	40-92	40-92	40-92	40-92
Front-end BW[MHz]	40-92	40-92	40-92	40-92	40-92
Galileo	{ E1 OS	—	—79-12	—79-12	—
	{ E6 CS	—	—69-82	—	—79-19
Compass	{ B1-I	—84-79	—	—96-28	—
	{ B1-2-I	—84-79	—	—96-28	—
	{ B3-I	—	—76-03	—	—72-55

Table 4. If we compare the maximum CT_SSC and the SSC, the maximum CT_SSC can vary up to 9.2 dB for the pair of Compass B1-I as desired and Galileo E1OS as interfering signal.

All intersystem interference simulations refer to the worst scenarios. The worst scenarios assume minimum emission power for the desired signal, maximum emission power for all interfered signals and maximum $(C/N_0)_{eff}$ degradation of interference over all time steps. The maximum and minimum received power of Galileo and Compass in the bands of interest – E1/B1 and E6/B3 – can be found in (China, 2006, Liu, 2009). In this paper we only show the results of the worst scenarios where Galileo and Compass are sharing the same band. The worst scenarios include:

- *Scenario 1:* Galileo E1 OS ← Compass B1 and B1-2 (Galileo E1 OS is interfered by Compass)
- *Scenario 2:* Compass B1-I ← Galileo E1 OS and E1 PRS (Compass B1-I is interfered by Galileo)
- *Scenario 3:* Compass B1-2-I ← Galileo E1 OS and E1 PRS (Compass B1-2-I is interfered by Galileo)
- *Scenario 4:* Galileo E6 CS ← Compass B3 (Galileo E6 CS is interfered by Compass)

It must be noted that we only display all civil signals' interference results. Therefore, because Compass B3 signal belongs to an authorized signal, the result of Compass B3 signal interfered by Galileo is not displayed in this paper.

4.1. *Galileo and Compass intersystem interference on E1/B1 band.* Figure 8 shows the maximum $(C/N_0)_{eff_CT_SSC}$ degradation of Galileo signal due to Compass intersystem interference on E1/B1 band (Scenario 1). As can be seen, Galileo E1 OS signal maximum $(C/N_0)_{eff_CT_SSC}$ degradation is raised from 0.0213 dB to 0.0369 dB. The maximum $(C/N_0)_{eff_CT_SSC}$ degradations of Compass B1-I and B1-2-I signals interfered by Galileo signals in E1/B1 band (Scenario 2 and Scenario 3) are shown in Figure 9 and Figure 10. We can obtain the maximal value of 2.8462 dB and 2.8515 dB of Compass B1-I and B1-2-I signals, respectively.

Figures 8–10 show that the maximal values of Galileo interfered by Compass are lower than Galileo interfering with Compass on E1/B1 band. If we compare the result of $(C/N_0)_{eff_CT_SSC}$ with $(C/N_0)_{eff_SSC}$, we can clearly see that the maximal value of $(C/N_0)_{eff_CT_SSC}$ degradation is approximately 0.02 dB higher than the maximal value of $(C/N_0)_{eff_SSC}$ degradation when Galileo E1 OS is interfered by

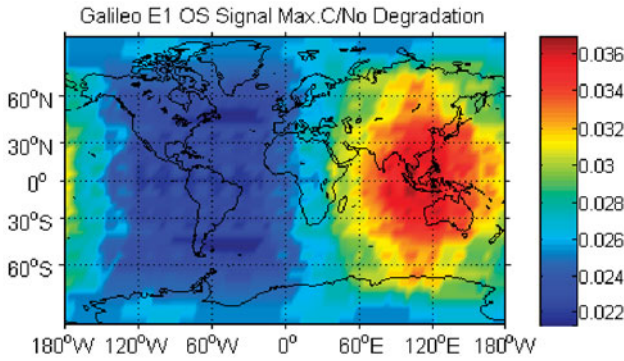


Figure 8. $\text{Max}(C/N_0)_{\text{eff-CT_SSC}}$ degradation of Galileo E1 OS Signal due to Compass intersystem interference on E1/B1 band.

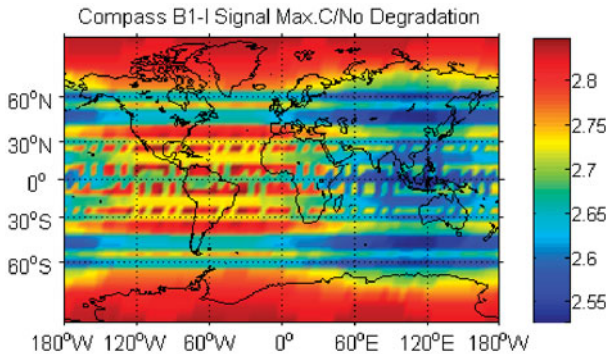


Figure 9. $\text{Max}(C/N_0)_{\text{eff-CT_SSC}}$ degradation of Compass B1-I Signal due to Galileo intersystem interference on E1/B1 band.

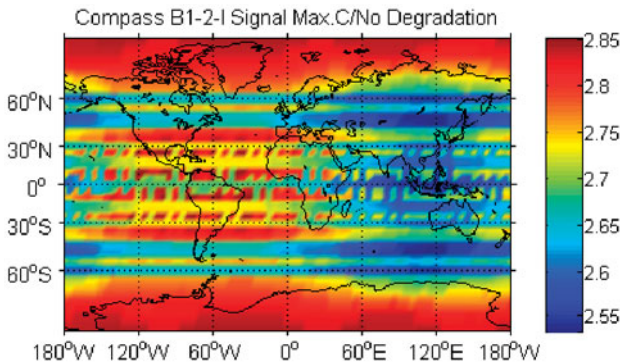
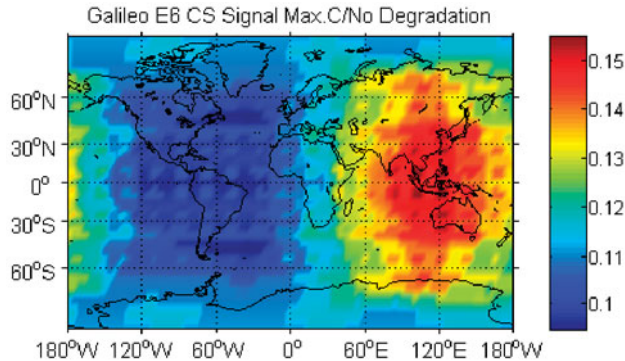


Figure 10. $\text{Max}(C/N_0)_{\text{eff-CT_SSC}}$ degradation of Compass B1-2-I Signal due to Galileo intersystem interference on E1/B1 band.

Table 5. Effective carrier power to noise density degradations based on SSC and CT_SSC.

Scenario	Max. $(C/N_0)_{eff_SSC}$ degradation (dB)	Min. $(C/N_0)_{eff_SSC}$ degradation (dB)	Max. $(C/N_0)_{eff_CT_SSC}$ degradation (dB)	Min. $(C/N_0)_{eff_CT_SSC}$ degradation (dB)
1	0.0169	0.0097	0.0369	0.0213
2	0.2865	0.2412	2.8462	2.5273
3	0.2874	0.2422	2.8515	2.5331
4	0.0335	0.0204	0.1548	0.0947

Figure 11. Max $(C/N_0)_{eff_CT_SSC}$ degradation of Galileo E6 CS signal due to Compass Intersystem Interference on E6/B3 band.

Compass. The $(C/N_0)_{eff_SSC}$ results are shown in (Liu, 2009). When Compass B1-I and B1-2-I signals are interfered by Galileo signals, all the maximal values of $(C/N_0)_{eff_SSC}$ degradation are around 0.2865 dB and 0.2874 dB for Compass B1-I and B1-2-I signal, respectively. Obviously, as can be seen from Table 5, the maximal values of $(C/N_0)_{eff_CT_SSC}$ degradation are much higher than the maximal values of $(C/N_0)_{eff_SSC}$ degradations. This is because the maximum CT_SSC is 11.23 dB higher than the SSC of the pair of Compass B1-I as desired and Galileo E1 PRS as interfering signal, resulting in the higher I_{Inter} in the intersystem interference computation. It is also shown that the maximum interference Galileo had suffered induced by Compass on E1/B1 band is below 0.25 dB using existing rules of coordination at ITU.

4.2. *Galileo and Compass intersystem interference on E6/B3 band.* Figure 11 shows the maximum $(C/N_0)_{eff_CT_SSC}$ degradation of Galileo signal due to Compass intersystem interference on E6/B3 band (Scenario 4). Compared with Figure 8, it can be seen that the Galileo E6 CS signal $(C/N_0)_{eff_CT_SSC}$ degradation is approximately 0.1179 dB higher than that of Galileo E1 OS signal. Again, If we compare the result of $(C/N_0)_{eff_CT_SSC}$ with $(C/N_0)_{eff_SSC}$ listed in Table 5, we can clearly see that the maximal value of $(C/N_0)_{eff_CT_SSC}$ degradation is approximately 0.1213 dB higher than the maximal value of $(C/N_0)_{eff_SSC}$ degradation when Galileo E6 CS is interfered by Compass.

With the results from the above simulation results, it is clear that the Compass system leads to intersystem interference on Galileo and that the maximal values are

lower than those of Galileo interfering on Compass. The results also show that the effects of interfering signals on code tracking performance may be underestimated in the former radio frequency compatibility methodologies.

5. CONCLUSIONS. The exponentially increasing number of navigation systems, hand-in-hand with the new signals, including civil, commercial, and military signals, result in the need to assess radio frequency compatibility carefully. The design and implementation of any new signal has to be conducted carefully in order to avoid interferences. In other words, all GNSS signals and services must be compatible.

In this paper, a more complete methodology based on the SSC and CT_SSC for the radio frequency compatibility assessment has been described. A detailed derivation of the methodology including equations and computation principle are provided. This methodology takes into account the space constellation, signal modulation, emission power level, space loss, satellite antenna gain and user receiver characteristic. Real simulations are carried out to assess the interference effects where Galileo and Compass signals are sharing the same band (E1/B1 and E6/B3 bands) at every time and place on the Earth. Simulation results show that the effects of intersystem interference are significantly different by using these two methodologies. The effects of interfering signals on code tracking performance must be considered in the radio frequency compatibility assessment. It is also shown that the Compass system leads to intersystem interference on Galileo and the maximum values are lower than Galileo interference on Compass.

Finally it has to be pointed out that the intersystem interference results shown in this paper refer mainly to the worst scenario simulations. Although the value is higher than normal it is feasible for GNSS system interference assessment. It must also be noted that PRN codes have impact on the PSD, e.g. short PRN code. And the effects of Doppler differences on the SSC and CT_SSC also need to be considered in future work.

ACKNOWLEDGEMENT

This work has been sponsored by the National High Technology under the following contracts: 2009AA12Z322.

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