Envisioning a Future GNSS System of Systems

Part 3 A Role for C-Band?

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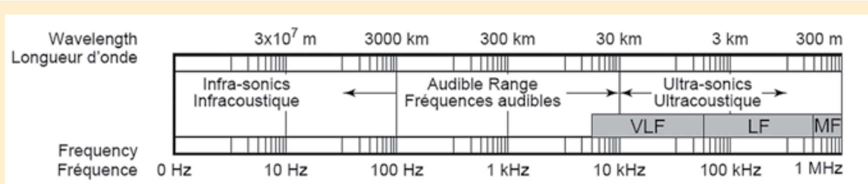
MEASAT-3 satellite with C-band and K-band transponders, The Boeing Company photo

The radio frequency spectrum is finite. Crowding in the L-band occupied — or planned for use — by the world's global navigation satellite systems is only going to get worse, as more systems and more signals come on line. Several gigahertz up the RF spectrum from L-band, however, lies a wide swath of bandwidth that is comparatively untapped: the C-band. In fact, early in its development the Galileo program received an allocation of C-band from the World Radiocommunications Conference. Although Galileo system designers decided quite early not to use the allocation for a variety of practical reasons, C-band remains an enticing subject because of certain characteristics that seem to complement or compensate for technical limitations of L-band, particularly the need for better indoor positioning capability. This column examines C-band as a candidate for a future GNSS signal or signals and evaluates its advantages and disadvantages compared with L-band signals.

The radionavigation satellite service (RNSS) portion of the RF spectrum is overcrowded, especially on L1 where GPS, Galileo, Compass overlap portions of one another's signal frequencies and GLONASS signals occupy more than 11 MHz of nearby bandwidth. Indeed, even those bands that have not been used so far will certainly be shared by many systems in the near future. Therefore, the search of alternative frequency resources is something that must inevitably occur with a high probability in the coming years.

During the World Radio Conference 2000 (WRC-2000), the Galileo program obtained authorization to use C-band frequencies. At the time, a dedicated portion of the C-band had been assigned for radionavigation, but technical complexities made it impossible for the first generation of Galileo to make use of it. Phase noise problems, increased signal transmit power requirements, and signal attenuation issues — to name only a few — knocked down all the proposed solutions. We will refer to these aspects in detail in the following discussion.

As happens with any kind of technology, however, many ideas that have been abandoned in the past due to excessive technical challenges or demanding drawbacks often become objects of interest some years or decades later. As tech-



EHF	Extremely high frequency (Microwaves)	VHF	Very high frequency
SHF	Super high frequency (Microwaves)	HF	High frequency
UHF	Ultra high frequency	MF	Medium frequency

FIGURE 1 Radio Spectrum [Source: Industry Canada]

nology evolves, constraints alter, and the environment of possibilities changes.

Against this background, the question emerges as to whether the use of C-band frequencies could represent a real alternative for a future GNSS. In this column, we will try to shed some light on this interesting possibility. Before that, let us first look at what we understand about C-band and how the regulatory RF spectrum situation affecting its use varies in different countries.

C-Band Definition

The general definition of C-band refers to the portion of the electromagnetic spectrum in the microwave range of frequencies between 4 and 8 GHz. It was the original frequency allocation for communication satellites, including those primarily in use today.

Typical antenna sizes on C-band–capable user equipment range from 2.5 to 3.5 meters on consumer satellite dishes, although larger ones and smaller ones can also be used depending upon signal strength. As one can imagine, smaller antennas are of special interest for radionavigation purposes.

Let's take a closer look at where C-band lies on the radio spectrum. **Figure 1** shows the current radio bands as categorized in wavelength and frequency domains. As we can clearly recognize, the C-band falls between the ultra high frequency (UHF) and super high frequency (SHF). In comparison, the L-band corresponds to UHF.

On closer inspection, some degree of arbitrariness occurs in defining the boundaries of the C-band, depending on the technical world we are moving in. Although in microwave techniques C-band refers to the frequency band between 3.5 GHz and 8.0 GHz, the definition of C-band for satellite communications ranges from 3.5 GHz to 6.4 GHz.

Specifically, C-band frequencies are preferred for geostationary satellites, generally occupying the uplink frequency band from 3.6 GHz to 4.2 GHz and downlink frequencies between 5.8 GHz to 6.4 GHz. Moreover, in optical networks the conventional C-band is defined in terms of wavelengths ranging between typical values of 1,530 and 1,560 nanometers.

In addition to these application-based categories, slight variations of C-band frequencies are approved for use in various parts of the world. **Table 1** presents some of these.

As an example of the diversity in the definition of the C-band in different countries, **Figure 2** and **Figure 3** show the particular regulatory situations in the United States and Canada, respectively, for the frequency range from 3 GHz to 7 GHz. As we can see, each country presents slightly different allocations for the different services.

Could C-Band Work for Galileo?

Although not considered for the first generation of European Galileo satellites, the (additional) use of C-band frequencies was subject of a study carried out back in the year 2001 shortly after WRC-2000 delegates assigned the frequency band between 5000 MHz and 5030 MHz to Galileo. (For details of this study, see the article by M. Irsigler listed in the Additional Resources section near the end of this column.) The filed C-band portion of Galileo is partitioned into the uplink service band (5000 - 5010 MHz) and the RNSS band between 5010 MHz and 5030 MHz.

Band	TX Frequency	RX Frequency
Extended C-Band	5.850 - 6.425 GHz	3.625 - 4.200 GHz
Super Extended C-Band	5.850 - 6.725 GHz	3.400 - 4.200 GHz
INSAT C-Band	6.725 - 7.025 GHz	4.500 - 4.800 GHz
Palapa C-Band	6.425 - 6.725 GHz	3.400 - 3.700 GHz
Russian C-Band	5.975 - 6.475 GHz	3.650 - 4.150 GHz
LMI C-Band	5.725 - 6.025 GHz	3.700 - 4.000 GHz

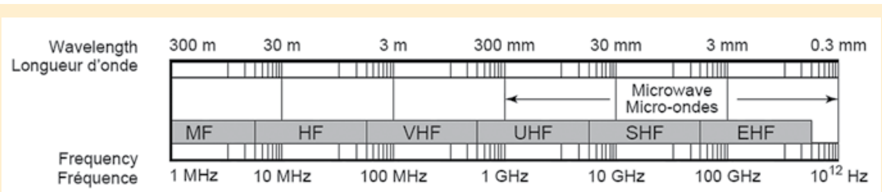
TABLE 1. C-band frequency variants at the satellite

Thus, a future C-band signal could use the frequency band between 5010 MHz and 5030 MHz, offering a rather limited bandwidth of 20 MHz but allocated in a frequency band not yet overloaded by other systems. Although 20 MHz does not seem to be a very broad bandwidth (especially if we compare it with the well known L-band), one of the initial drivers to use the C-band was that it could solve the limited frequency band resources of GNSS.

The exact carrier frequency of a C-band signal would be 5,019.86 MHz, resulting in a carrier wavelength of only 6 centimeters. The use of such a short carrier wave has a significant effect on various aspects of signal propagation and signal processing and comprises a series of benefits and drawbacks that we will address next.

Characteristics of the C-Band. The application of C-band navigation signals provides both advantages and drawbacks. At C-band, the increased free space loss represents the most significant issue. Despite its name, "free space loss" actually refers to the fact that an omnidirectional antenna must not exceed a certain dimension, a constraint that relates to the signal wavelength.

Thus, an omnidirectional C-band antenna (for 5 GHz) is 3.2 times smaller in linear dimension than an L-band antenna (with a 19-centimeter wavelength at 1.575 GHz). Its area is 10 times smaller than that of a standard L-band



LF Low Frequency
VLF Very Low Frequency
VF Voice frequency
ELF Extremely low frequency

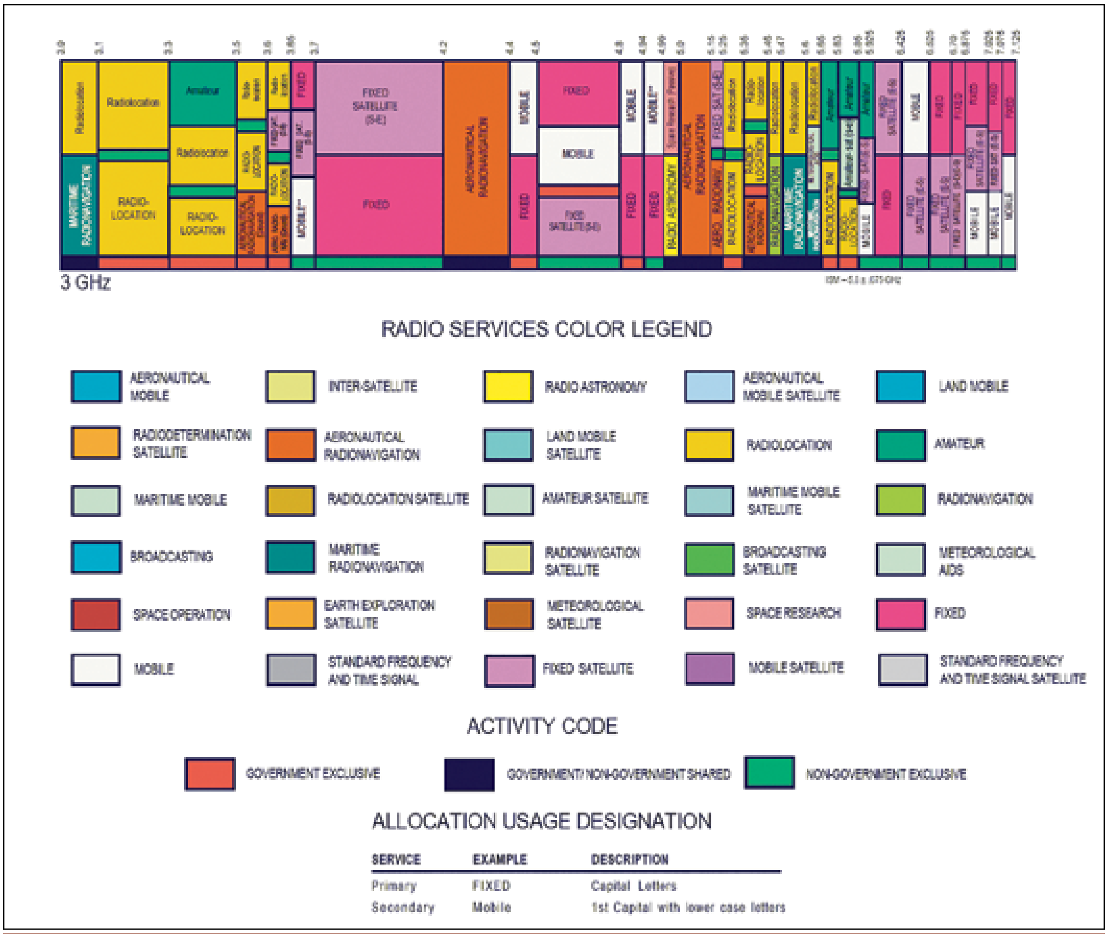


FIGURE 2 United States Frequency Allocations within the C-Band (October 2003) [US Department of Commerce. National Telecommunications and Information Administration. Office of spectrum management]

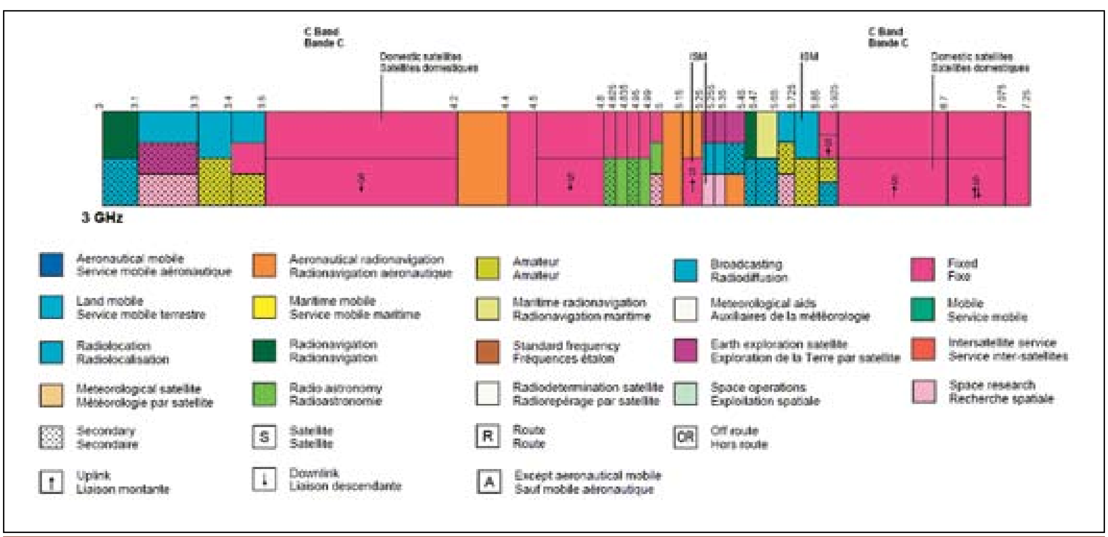


FIGURE 3 Canada Frequency Allocations in the C-Band. This chart is based on the 2000 Canadian Table of Frequency Allocations, which bases on decisions of World Radio Conferences, including WRC-1997. For further information on spectrum or radio matters, contact the Spectrum and Radio Policy Directorate, Industry Canada, Ottawa.

antenna. As a result, a C-band antenna picks up only one-tenth as much broadcast signal power as L-band.

The free-space-propagation-loss in the antenna's far field region is actually independent of the frequency because the loss is only proportional to the inverse of the squared distance between transmitter and receiver. One can, of course, build bigger C-band antennas (which would pick up more energy from the satellites), but those antennas inevitably have a directional characteristic. Overcoming this major issue would require significant modifications with respect to the satellite payload and/or the user equipment.

Research has identified other significant drawbacks to C-band including increased signal attenuation due to foliage or heavy rain as well as negative effect on signal tracking. On the other hand, C-band's smaller ionospheric errors and technological progress might balance some of the disadvantages from a long-term point of view.

C-Band's Suitability for GNSS

In order to assess the feasibility of future C-band technology for satellite navigation purposes, we will recapitulate the major findings of Irsigler's 2000-2001 study for DLR mentioned earlier, which examined various aspects of signal propagation and satellite signal tracking at C-band. To allow comparison between the current GPS and the planned Galileo system, we compare the performance expected at C-band to that of the L-band under similar or identical conditions.

Signal Parameters		GPS L1-C/A	Assumed Galileo C Band
Carrier Wave	f [MHz]	1575.42	5019.86
	λ [m]	0.19	0.06
Chipping Rate [Mcps]		1.023	8.184
Chip Length [m]		293.05	36.63
Data Rate [bps]		50	150
Predet. Int. Time [s]		0.02	0.0067
Bandwidth [MHz]		2.046	20
Chip Shape/Modulation Scheme		BPSK	RC

TABLE 2. GPS and Galileo C-Band signal parameters

Table 2 lists the relevant Galileo and GPS signal parameters. Unless otherwise stated, this column bases all subsequent computations, diagrams, and tables on these parameters. Interestingly, instead of using BPSK or BOC modulation, a raised cosine (RC) pulse shaping scheme with a chipping rate of 8 Mcps was then assumed in the study to be implemented for a C-band Galileo signal. The shape of a raised cosine chip is defined by the so-called roll-off factor. For the Galileo C-band signal, a roll-off factor of 0.22 was assumed.

RC-signals are band-limited signals and were abandoned for the L-band very early in the Galileo program due to the fact that the resulting services would have very limited assigned bandwidths with a handicapped performance from the very beginning. In fact, no matter how much we would increase the receiver bandwidth, given the limited bandwidth of the transmitted signal, no improvement in the positioning performance could be obtained.

Although this was true in the L-band where many services had to co-exist, in the C-band wider bandwidths are expected and, thus, if the number of services is reduced, the use of this modulation scheme could potentially bring some benefits, especially regarding the limitations of the emissions.

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Signal Propagation at C-Band. **Table 3** compares the various signal propagation characteristics of L- and C-band. Benefits with respect to the other frequency band are indicated by "+" whereas drawbacks are indicated by "-". The quantitative difference with respect to the L-band is assessed in the last column.

As can be derived from Table 3, all ionospheric effects are less severe at C-band. The expected ionospheric path delays are smaller than at L-band by a factor of 10, and scintillation effects become less significant as well.

A major issue of using C-band frequencies is the increased influence of signal attenuation. Due to the increased free space loss at higher frequencies, a C-band signal transmitted at identical transmit power as an L-band signal is 10 dB weaker when it arrives at the user antenna. Moreover, in case of heavy rain, a

Parameter	C	L	Factor
Free space loss	-	+	-10.0 dB
Ionospheric path delay	+	-	+10.0
Ionospheric amplitude scintillation	+	-	+5.6
Ionospheric phase scintillation	+	-	+3.1
Ionospheric refraction	+	-	+10.0
Ionospheric Doppler shift	+	-	+3.0
Tropospheric path delay	0	0	---
Tropospheric amplitude scintillation	-	+	-2.0
Tropospheric phase scintillation	-	+	-3.0
Attenuation by water vapor and oxygen (worst case)	-	+	-0.2 dB
Rainfall attenuation (worst case)	-	+	-4.5 dB
Attenuation by clouds and fog (worst case)	-	+	-0.8 dB
Foliage attenuation	-	+	-1.0 dB

TABLE 3. Signal propagation at L- and a C-Band

Link Budget Parameter	C-Band	L-Band
Received Power Level	-163 dBW	-163 dBW
Total Sign. Attenuation	204.8 dB	189.3 dB
Gain Satellite Antenna	14 dB	14 dB
Gain User Antenna	0 dB	0 dB
Required Satellite Antenna Input Power	27.8 dBW **602.6 W**	12.3 dBW **17.0 W**

TABLE 4. Required minimum satellite antenna input power (C-Band vs L-Band payload). Total signal attenuation includes free space loss, worst-case tropospheric attenuation, polarization mismatch loss and antenna depointing losses, see Table 5.

C-band signal is attenuated up to 4.5 dB greater than an L-band signal. Foliage attenuation, which is assumed to be around 1 dB/m at L-band and around 2 dB/m, can also be an issue.

Effect of C-Band on Power Budget. The main signal propagation parameter that affects a satellite payload design is signal attenuation. Compared to the L-band, free space loss and rain attenuation are significantly greater at C-band.

In order to compensate for the increased signal attenuation, a C-band signal will have to be much stronger (increased transmit power) than an equivalent L-band signal. Otherwise, if we assume identical satellite transmit power at L- and at C-band, the received C-band signal will be much weaker.

The following reverse computation of the minimum transmit power assumes that the power level of a future C-band signal for a 0 dBic antenna is –163 dBW. Assuming that the noise density is N_0=-204 dBW/Hz, the corresponding C/N_0 is 41 dB-Hz. **Table 4** summarizes the results of these calculations.

Normally, the specified received power level needs to be much higher than -163 dBW to provide a good $(C/N_0)_{eff}$ within the tracking loops. The following computation is based on the requirement that the signal should be tracked with a C/N_0 of at least 45 dB-Hz, a value that is easily obtained for GPS signals. **Table 5** compares the computation of the

Link Budget Parameter	Unit	C-Band	GPS L1
Effect. C/N_0 (tracking loop)	dB-Hz	45	45
Implementation loss	dB	6	6
C/N_0 @ user antenna output	dB-Hz	51	51
Power level (user ant. output)	dBW	-153	-153
Gain of user antenna	dBic	3	3
Power level (user ant. input)	dBW	-156	-156
Depointing loss (user)	dB	0.25	0.25
Polarization Mismatch Loss	dB	3	3
Tropospheric attenuation	dB	5.9	0.4
Free space loss (E=10°)	dB	195.4	185.4
Depointing loss (satellite)	dB	0.25	0.25
EIRP	dBW	48.8	33.3
Gain of satellite antenna	dBic	14.0	14.0
Required satellite antenna input power	dBW	34.8	19.3
	W	3020.0	85.1

TABLE 5. Required satellite antenna input power to provide a C/N_0 of 45 dB-Hz within the receiver tracking loops. For the tropospheric attenuation at C-band the major contributions are a worst-case rainfall attenuation of 4.6 dB and attenuation by clouds and fog of 0.9 dB. The corresponding L-band values are much smaller (0.1 dB, respectively).

required satellite antenna input power for C-band and GPS L1. The results are obtained considering the following parameters:

- Receiver Implementation Loss: 6 dB (low-end receivers)
- Maximum atmospheric attenuation: see Table 5
- User antenna gain: 3 dB
- Satellite antenna gain: 14 dB
- Noise density: -204.0 dBW/Hz

To provide an effective C/N_0 of 45 dB-Hz, the satellite antenna input power at C-band will have to be approximately 35 times higher than at L-band. We must note that the preceding calculation of the tropospheric attenuation includes rainfall attenuation and attenuation due to clouds, fog, water vapor, and oxygen. We also need to emphasize that these values are the result of a calculation under worst-case assumptions.

The actual required satellite antenna input power strongly depends on the receiver quality (implementation loss), the type of user antenna (phased array versus omnidirectional), and the actual atmospheric attenuation. Whatever scenario is assumed, the required satellite antenna input power at C-band will be significantly higher than at L-band (assuming identical conditions at both bands).

Higher C-Band Signal Power

Due to the increased free space loss and tropospheric attenuation, a future C-band signal will be approximately 10-16 dB weaker than an L-band signal when received at the ground (assuming identical satellite transmit power and identical user antennas). Signal strength at the user antenna also determines the $(C/N_0)_{eff}$ with which the signal is tracked within the tracking loops.

We consider two general measures to compensate for the 10–ß16 dB loss at C-band: Increasing satellite transmit power in conjunction with implementing suitable antenna/receiver design. As energy is a limited resource on board a satellite, the following section will concentrate more on antenna design as a means to guarantee sufficiently high $(C/N_0)_{eff}$ at C-band.

The following approaches are suitable to achieve this goal:

- *Use of Phased Array Antennas.* In contrast to standard omnidirectional user antennas, phased array antennas consist of multiple antenna elements that are arranged in the form of an array. By means of digital beam forming, several antenna beams can be generated. The beam widths and the resulting antenna gains depend on the number of antenna elements: With such an antenna design, typical gains of approximately 10 dBic can be achieved. Compared to a 3 dBic standard omnidirectional user antenna, the received power level can be increased by 7 dB. A phased array antenna is also a suitable approach to cancel out multipath and/or interfering/jamming signals.
- *Minimization of Receiver Implementation Losses.* As we derived in Table 5, the effective C/N_0 also depends on the receiver implementation loss. Because the C/N_0 of the received C-band signal will be much lower than an equivalent L-band signal (assuming identical conditions), no additional losses can be accepted. In Table 5, an implementation loss of 6 dB has been assumed. This is a typical value for low-end receivers. In high-quality receivers we can expect implementation losses of only 1-2 dB. Especially at C-band, the implementation losses should be as small as possible. The main parameters that determine the receiver implementation loss are the LNA (low noise amplifier) noise figure and the quantization process of the A/D (analog/digital) conversion.

  With respect to the A/D conversion, the quantization process causes signal degradation, which depends on the resolution of the quantization process. It can be shown that the actual signal degradation decreases with increasing resolution. A minimum of two bits is required to limit the signal degradation to 1-1.5 dB. The use of 3-5 bit quantization can reduce the corresponding signal degradation down to 0.5-0.7 dB, as described in the article by B. Parkinson and J. Spilker cited in Additional Resources. As a result, multi-bit quantization is strongly recommended for future C-band receivers.
- *Bite the bullet.* Current high-sensitivity receivers are known to be capable to cope with signal attenuations of even more than 20 dB. Thus a straight extension of this high sensitivity L-band signal processing technology (mostly based on multiple correlators and optimized signal tracking/acquisition algorithms) is capable of tracking C-band signals. The accuracy is, however, reduced, and such receiver designs ultimately cannot compensate for any further

power reduction of C-band signals by a "real" indoor environment.

After having shown possible approaches for loss reduction by improved antenna designs at the user side, we are going to ponder whether the power increase or the sophisticated antenna approach is a more promising path to follow.

Transmit Power versus Phased Array Antenna

The use of phased array user antennas and the construction of high-end C-band receivers with very low implementation losses may not be necessary if the satellite antenna input power can be increased significantly.

Increase of Satellite Transmit Power. Many drawbacks of C-band navigation could be compensated by increasing the satellite transmit power by a minimum of 10 dB. By means of this approach, the following enhancements can be achieved:

- compensation of the increased free space loss
- increase of $(C/N_0)_{eff}$ within the signal tracking loops, thereby reducing the influence of thermal noise and the probability of cycle slips while enhancing the performance of the various lock loops (delay, frequency, phase)
- compensation of the increased tropospheric attenuation, thereby increasing availability
- use of omnidirectional user antennas, resulting in a relatively simple receiver architecture, moderate power consumption, low manufacturing costs, and enhanced mass-market suitability

Parameter	C	L
Code tracking performance	0	0
Phase tracking performance	-	+
Code noise	0	0
Phase noise	+	-
Code multipath	0	0
Carrier multipath	+	-
Carrier smoothing efficiency	+	-

TABLE 6. Signal tracking performance at L- and a C-Band.

- Feasibility of low-end C-band receiver manufacturing using simple one-bit-quantization techniques

On the other side, an increase of the satellite transmit power results in additional problems, such as an increased power consumption at the satellite, which would result in additional or larger solar panels. This, in turn, negatively affects satellite launches (more space required within the satellite-launching rocket, increased satellite weight, and increased launch cost).

Use of Phased Array Antennas. At first sight, the use of phased array antennas seems like a suitable approach to limit the required satellite transmit power and to compensate the occurring signal losses at C-band. The main advantages of this approach are the increased antenna gain compared to an omnidirectional antenna and the ability to null out multipath and/or interfering/jamming signals by means of beam forming. However, the main drawbacks of using such antennas are that they would be larger, heavier, more unwieldy, and complex compared to omnidirectional antennas and, consequently, their manufacturing cost would be higher. Moreover, due to their increased size, they cannot be used for certain applications.

Moreover, because a phased array antenna consists of several antenna elements, a corresponding amount of front ends would be necessary (one front-end per antenna element). Additionally, a beam-forming and beam-steering unit would have to be implemented. In contrast to an omnidirectional receiver, then, the phased array approach thus results in complex receiver architecture, thereby increasing size, weight, power consumption, and manufacturing cost.

Thermal Noise σ_T	- Loop Noise Bandwidth B_L
	- Predetection Int. Time T
	- C/N_0
Oscillator Phase Noise (frequency instabilities) $(\sigma_{A,Rec}, \sigma_{A,Sat})$	- Loop Order
	- Loop Noise Bandwidth B_L
	- Clock Parameters h_0, h_{-1}, h_{-2}
	- Carrier Frequency f
Vibration Induced Phase Noise σ_{vib}	- Loop Order
	- Loop Noise Bandwidth B_L
	- G-Sensitivity of Oscillator
	- PSD of Vibration
	- Carrier Frequency f
Dynamic Stress Error $e(t)$	- Loop Order
	- Loop Noise Bandwidth B_L
	- Signal Dynamics (LOS)
	- Carrier Frequency f

TABLE 7. Signal and loop parameters affecting the PLL error sources. A more detailed analysis can be found in [Irsigler, Eissfeller, 2002]

Signal Tracking at C-Band

Table 6 summarizes the signal tracking performance at L- and at C-band. Benefits with respect to the other frequency band are again indicated by "+" while drawbacks are indicated by "-". Note that the classification in Table 6 is only valid in cases that assume identical conditions in both bands (identical signal structure, C/N_0, smoothing constants, and so forth).

Performance parameters related to code tracking (DLL performance, code noise, and code multipath) do not depend on the carrier frequency; so, the two frequency bands perform similarly in this regard. Due to the smaller carrier wavelength at C-band, phase noise, and carrier multipath are smaller than at L-band (if expressed in meters).

Another benefit of C-band is the increased carrier smoothing efficiency. Due to the fact that multipath variations occur more often at C-band, multipath effects can be smoothed out easily (assuming identical smoothing constants). However, major problems appear when we take a closer look at the carrier tracking performance at C-band.

Enhancing Poor PLL Performance. One major drawback of using the C-band for satellite navigation is the very poor carrier tracking robustness, as noted in Table

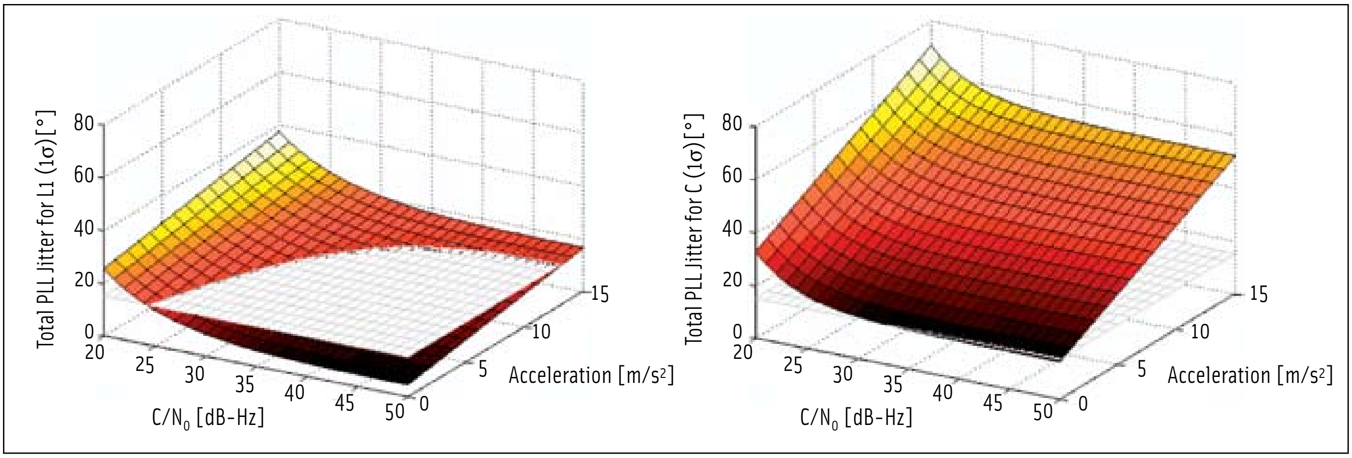

FIGURE 4 **Total PLL jitter for the GPS L1 signal (left diagram) and a C-band signal (right diagram) as a function of C/N0 and the signal dynamics (Line-of-sight (LOS) acceleration).**

6. The dominant error sources of a phase lock loop are the thermal phase noise σ_T, the oscillator phase noise induced by frequency instabilities of the receiver and/or satellite clock ($\sigma_{A,Rec}$,$\sigma_{A,Sat}$), the vibration induced oscillator phase noise σ_{vib}, and the dynamic stress error *e(t)*. The occurring error sources depend on the parameters listed in **Table 7**, and the PLL can be deemed to be stable if the following equation holds:

$$\sigma_{PLL}=\sqrt{\sigma_T^2+\sigma_{A,Rec}^2+\sigma_{A,Sat}^2+\sigma_{vib}^2}+\frac{e(t)}{3}\leq 15^o \quad (1)$$

Oscillator phase noise, vibration induced phase noise, and dynamic stress error are proportional to the carrier frequency. As a result, we can expect a significant increase of PLL jitter at C-band. Thus, we would expect the PLL performance at C-band to be much poorer than at L-band. This statement can be verified by means of a PLL performance analysis which is based on the following assumptions:

- Non-coherent carrier tracking (e.g. Costas Tracking)
- Second-order PLL
- Loop noise bandwidth: BL=15Hz
- Predetection integration times: 0.02s (L-band), 0.0067 (C-band)
- Carrier frequencies: 1475.42MHz (L-band), 5019.86 MHz (C-band)
- Satellite clock: Rubidium
- Receiver oscillator: TCXO
- PSD of vibration: 0.05 g^2/Hz
- Frequency of vibrations: $25Hz < f_{vib} < 2500Hz$

Figure 4 illustrates the result of this analysis. The total PLL tracking error is plotted as a function of the C/N_0 and the line-of-sight acceleration. Additionally, the tracking threshold defined by equation (1) is plotted as a gray plane. The PLL can be deemed to be stable if the total tracking error is less than the tracking threshold, i.e., for all parts of the surface that lie below the gray plane.

The poor PLL tracking performance at C-band is obvious. In this example, the total PLL jitter is mostly higher than the tracking threshold defined by equation (1). Even in cases of only weak accelerations, the receiver would not be able to track the signal, and if several loop, clock, or vibration parameters are modified, the PLL performance at C-band is always much poorer than at L-band.

In order to improve the PLL performance at C-band, the following approaches can be taken into account:

- *Enhancement of the reference oscillator's g-sensitivity.* The influence of random vibration strongly depends on the oscillator's *g*-sensitivity. The resulting phase jitter is directly proportional to the oscillator's *g*-sensitivity so that a reduction of this parameter results in less phase jitter. Random vibration is an issue especially for kinematic applications, whereas such influences are not present in static applications. The main drawback of this approach is that appropriately optimized oscillators are more expensive than standard temperature compensated crystal oscillators (TCXOs) due to the more stringent performance requirements.
- *Use of high stable reference oscillators.* The oscillator's frequency instability can be described by its Allan deviation. As is the case for random vibration, frequency instabilities also result in phase jitter. In order to reduce the resulting phase errors, the use of a highly stable reference oscillator (for example, an oven controlled crystal oscillator, OCXO) instead of a standard TCXO should be considered.

  The main drawbacks of this approach are increased cost and power consumption compared to a standard TCXO. (Note that in mass-market GPS receivers, even lower quality quartz oscillators are in use). Additionally, the influence of frequency instabilities also depends on the loop noise bandwidth. A reduction of the resulting phase jitter can principally be achieved by increasing this bandwidth. However, the resulting enhancements are marginal and by increasing the loop noise bandwidth, the thermal noise correspondingly increases.
- *Significant increase of the loop noise bandwidth.* The dynamic stress error strongly depends on the loop noise bandwidth. The smaller the loop noise bandwidth, the harder it is to track the signal dynamics. On the other hand, increase of the loop noise bandwidth reduces the influence of dynamic stress and is, there-

BENEFITS	
Ionospheric Path Delay	All ionospheric effects are inversely proportional to the carrier frequency *f* (or a power of *f*). The ionospheric path delay at C-band, for example, is smaller than at L1 by a factor of 10.
Ionospheric Refraction	
Ionospheric Doppler shift	
Ionospheric Scintillation	
Iono-Free Linear Combination L/C	By combining pseudorange observations at different carrier frequencies, the ionospheric effect can be eliminated. The resulting observable, however, is significantly noisier than the individual pseudoranges. Compared to the L1/L2 observable, however, an L1/C combination would be less noisy (by a factor 2.8).
Carrier Multipath	The maximum carrier multipath error is a function of the carrier wavelength. Maximum errors at C-band would be 1/3 of the expected error at L1.
Carrier Smoothing Performance	Carrier smoothing can be used to mitigate code noise and code multipath. Noise mitigation: The carrier smoothing process performs better at C- than at L-Band, as the ratio between carrier frequency and code rate is larger. Due to the small ionospheric influences at C-band, longer smoothing constants than at L-Band can be used. Multipath mitigation: Fading frequencies at C-band are larger than at L-band by a factor of 3, i.e., multipath variations can be smoothed out more efficiently (assuming identical smoothing constants in both bands).
Phase Tracking Accuracy	The influence of thermal noise is proportional to the carrier wavelength. i.e., thermal noise at C-band is by a factor of 3 smaller than at L-band.
Doppler Accuracy	
Antenna Size	C-band antennas can be built three times smaller than L-band antennas. For miniaturized applications, this could be an advantage.
DRAWBACKS	
Free-Space Loss	Proportional to the squared carrier frequency, resulting in a range spreading loss at C-band which is larger than in L-Band by a factor of 10 (can be compensated by increase of satellite transmit power).
Effective C/N_0	Depends on transmit power, antenna gains, implementation losses, and actual atmospheric attenuation. Assuming identical transmit power, antenna gains, and implementation losses in both bands, the effective C/N_0 at C-Band is 10-16 dB-Hz smaller than at L-band (due to increased range spreading loss and atmospheric attenuation)
Tropospheric Attenuation	Includes attenuation due to water vapor and oxygen (up to 0.2dB larger at C-Band), rainfall attenuation (up to 4.5 dB larger) and attenuation due to clouds and fog (up to 0.8 dB larger). Rainfall attenuation up to 4.6 dB must be expected at C-band.
Foliage Attenuation	Typical values at L- and C-band are 1 dB/m and 2 dB/m, respectively. These values may strongly vary subject to foliage types and densities.
Power Consumption Payload	In order to compensate for all the attenuation effects listed above, the satellite transmit power would have to be increased significantly (with negative effects on satellite size, weight and launch costs).
Tropospheric Scintillation	Includes amplitude scintillation, which is larger at C-band by a factor of 2, and phase scintillation, which is larger by a factor of 3.
Signal Acquisition	Due to higher maximum Doppler shifts at C-Band (~11 kHz vs. ~6 kHz at L-Band), the Doppler search region increases. Assuming identical code lengths at both bands, signal acquisition takes about 1.8 times longer than at L-Band.
Carrier Tracking Robustness	Carrier tracking robustness at C-band is much poorer than at L-band. It depends on the influences of thermal noise, oscillator phase noise, vibration-induced phase noise, and dynamic stress. Except for thermal noise, all influences are proportional to the carrier frequency and, thus, larger than at L-band (by a factor of 3).
Cycle-Slip Probability	Depends on effective C/N_0, data rate, and oscillator phase noise. Due to increased oscillator phase noise (see "carrier tracking robustness") and possibly smaller C/N_0, the cycle-slip probability at C-band is expected to be larger than at L-band.
Oscillator Requirements	The poor carrier tracking robustness can be enhanced by minimizing the oscillator's g-sensitivity and by enhancing its frequency stability. This requires the use of high-quality oscillators.

TABLE 8. Benefits and drawbacks for C-Band satellite navigation

fore, another possible approach to enhance the PLL performance. The main drawback of this approach is that by increasing the loop noise bandwidth, thermal noise also increases.

Conclusions about C-Band Performance

As we have seen, C-band navigation offers both benefits and drawbacks. Although it might be feasible to overcome the technical issues, it is still uncertain whether a (future) C-band navigation system could ever compete with current sophisticated L-band equipment. However, a future C-band signal might be an interesting option in combination with L-band signals.

As discussed, many of the drawbacks could be balanced by increasing the satellite transmit power. This measure could also enhance the poor carrier tracking performance by reducing the influence of thermal noise as well as the cycle-slip probability. It also leads to an enhancement with respect to the availability of the navigation service because it compensates for the increased signal attenuation values at C-band.

Nonetheless, this measure would have negative effects on important payload characteristics such as power consumption, weight, and size that, in turn, increase the costs for manufacturing and launching the satellites. Moreover, even if satellite transmit power is increased, some basic problems such as the poor carrier tracking performance would still remain.

We summarize the benefits and drawbacks in Table 8.

Potential Users of C-Band

As we mentioned earlier, the C-band was not considered for the first generation of Galileo because of the technical implications that we outlined in this column. Nonetheless, the European Space Agency is planning a series of activities in recognition of the fact that the C-band could conceivably be used for navigation purposes in the next decade.

Of course, C-band is not an exclusive asset of Galileo. Indeed, other global navigation satellite systems have filed for this band, although at the moment no one has used it yet for navigation. Moreover, also regional systems such as the Indian Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS) have also declared their intention of making use of the band.

As we have seen in our analysis here, the use of the C-band raises serious technical challenges, although, as we have also pointed out, an increase of power in the transmission of the satellites together with directional antennas could solve the current drawbacks of the C-band. Moreover, once we solve these technical problems, the accuracy potential of the C-band could be used to help solve many GNSS-related problems that we have today.

The question that arises is: who could afford such directional antennas and such an increase of power? A first reaction would be to say that military or protected governmental applications could fully satisfy such requirements even today. Can you imagine having all the military signals in the C-band? For Galileo that could be an interesting decision, because by moving its PRS signals to the C-band, many of the great limitations in terms of signal and power that Galileo encountered in the L1 band would be history.

The idea of moving military signals and governmental protected services to the C-band would consequently mean that the L-band would be then reserved for Open Services. But can we imagine the opposite situation?

In addition, separating military and civil applications would also have other consequences of interest. As we saw in the first part of this series (January-February 2007 issue), such an architecture would allow further separation of the military and civil payloads, which might well accommodate the fact that many civil and military applications work with different standards.

Today civil and military payloads are mounted together aboard the satellites so that in the final consideration the more demanding standards of the military have to be applied also to civil components that might not require them at all. Moreover, consideration could be given to allow the civil community access to the ground segment, which is at the moment controlled by military operators (in case of the GPS). Such a move would further facilitate the development of different concepts for civil and military sectors without having to depend on what the other does. In fact, this would really open the possibility of true interoperability of GNSS system control segments.

Let us reflect for a moment on the pseudolite concept of pulsing. The reason for pulsing in mixed GNSS/pseudolite applications is mainly to avoid the jamming of signals coming from space due to the higher power of terrestrial pseudolite transmitters. The solution to this near/far (strong/weak) problem was to transmit the total power only in pulses. Although these individual pulses are very strong, the averaged pseudolite signal (taking into consideration the absence of power in the interval between pulses) ultimately matches the level of the weak signals from the satellite.

Could we not perhaps apply similar ideas to C-band in order to avoid the high power figures that are needed to compensate for the higher propagation losses of the C-band? Another approach might be to design C-band satellites that only serve users in certain locations and then allow satellite transmissions only while flying over those designated regions and for selected periods of time. Such a time-multiplexing could indeed prove to be interesting one day. Equally interesting would be to use special C-band-emitting satellites with LEO orbits to cope with the problem of signal power loss and navigation data transmission.

Another area where C-band could play an interesting role is in indoor positioning and navigation, which is becoming a driving issue for new applications for present and future positioning and navigation systems. The attenuation in the C-band is expected to be larger than in the L-band. Moreover, worse scattering effects are expected to be observed in this band. In fact, in typical indoor environments we can find many objects that the navigation signals have to go through which have a comparable size as the wavelength of the signals.

On the other hand, the delay spread that results from these scattering effects is longer in the C-band, and at the moment a real understanding of the C-band channel for indoor use is still missing. Could C-band be the indoor band of the future?

Additional Resources

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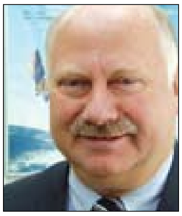

"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by **PROF. DR.-ING. GÜNTER HEIN.**

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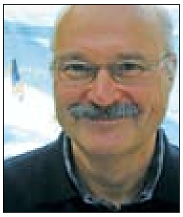

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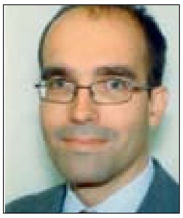

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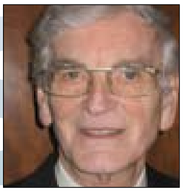

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