GPS-704X Antenna Design and Performance

NovAtel Inc.

ABSTRACT

This report discusses the application and performance of NovAtel's GPS-704X Global Navigation Satellite System (GNSS) multi-band antenna. The 704X antenna has a wide bandwidth that is capable of acquiring RF signals from several GNSS systems. In this report, the multi-band antenna design is compared to NovAtel's 702-GG antenna design and the results of tests performed on the multi-band units are presented. The outcomes of the tests confirm that, compared to the 702-GG antenna, the bandwidth of the 704X antenna is wider, enabling the use of satellite ranging systems in the 1100 to 1600 MHz bands.

Figure 1: NovAtel's GPS-704X Antenna

INTRODUCTION

As of June 2006, GNSS multi-band antennas are relatively new to GPS technology. There are some known wide bandwidth antennas for dual-constellation GPS + GLONASS applications, but they tend to have a high profile structure and are not suitable for applications that require an antenna with a small form.

Wide bandwidth is important to GPS because it allows users to take advantage of more frequencies. This enhances the accuracy, integrity, continuity and availability of GPS. The availability of more frequencies improves the elimination of ionospheric errors that can only be approximated with a single frequency using the Klobushar model and broadcast GPS messages. The ability to receive more than one GNSS constellation also improves the ability to receive good quality satellite observables, particularly in challenging environments.

This report examines the design of NovAtel's GPS-704X multi-frequency antenna (see *Figure 1*) and investigates its performance. The test results demonstrate that the GPS-704X is capable of covering the frequency bands associated with the three most popular GNSS systems: GPS, Galileo and GLONASS.

METHODOLOGY

Resources for this report were provided by NovAtel Inc.. This report also includes information from Waldemar Kunysz, who is the developer of NovAtel's Pinwheel™ technology and a leader in the enhancement of multi-frequency, multi-band antennas. Recently some announcements have been made regarding the availability of GPS/GLONASS/Galileo capable antennas, but little information is currently available.

Antenna design was facilitated by using HFSS (high frequency structure simulator), a 3-D electromagnetic design software from Ansoft. This report contains results from those simulations as well as data from tests conducted in an anechoic chamber.

ANTENNA OVERVIEW

A number of satellite ranging systems are available for commercial and military use. Examples of these systems include GPS, GLONASS, and Galileo. Commercial services, like OmniSTAR, provide a high-quality correction link that eliminates the requirement for a ground-based correction signal. Government sponsored correction services, such as the Government of Canada's CDGPS (Canadian Differential GPS) provide a sub-meter correction signal for use in Canada and the northern USA. These satellite systems use signals in different frequency bands, which range from 1175 MHz to 1610 MHz (see *Table 1*).

Table 1: Satellite System Frequencies

Satellite System & Signal	Frequency (MHz)
GPS L1	1575
GPS L2	1227
GPS L5 and E5a	1176
Galileo E5a	1164
Galileo E5b	1207
Galileo E1	1575
GLONASS L1	1598 - 1609
GLONASS L2	1243 - 1252
Oministar VBS, XP, HP	1520-1565
CDGPS	1520-1565

GPS, GLONASS and Galileo all operate on multiple frequencies to provide restricted access / military services and to allow ground-based receivers to eliminate ionospheric error. Receivers and antennas designed to take advantage of these signals must be designed for simultaneous multi-frequency operation.

Even though there are principal frequencies for GNSS receivers (*see Table 1)*, the power spectral density of the signal transmitted from satellites varies. For example, the power spectral density that contains 99% of the energy of the GPS L1 and L2 signals is 18 MHz. Galileo signals have similar power spectral densities. Some arrangements of Galileo signals, including one known as alt-BOC, have a power spectral density of 92 MHz.

Because an antenna acts as a resonant element, its behaviour fluctuates with the exact signal frequency being captured. Maintaining similar electrical performance at more than one frequency has been a difficult task that has led to a large body of academic and industrial research in the GPS / GNSS industry.

The design of NovAtel's 704X antenna is an evolution of NovAtel's Pinwheel™ antenna family. It has approximately a 20% increase in bandwidth and maintains excellent electrical characteristics across the band. NovAtel's patented Pinwheel™ coupled slot array design is shown below (see *Figure 2*).

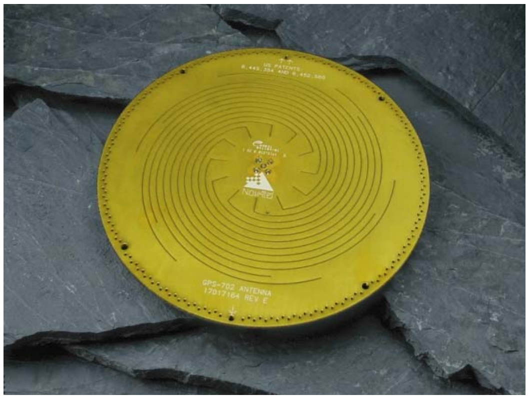


Figure 2: NovAtel's Pinwheel™ Design

Positioning measurements are calculated with reference to the electrical center of the antenna (known as the phase center), so it is important that a multi-band antenna has a common phase center across frequencies for incoming signals with as little error as possible.

There are methods to correct phase center variation when the geometric phase and electrical center of an antenna are misaligned. In high accuracy applications, ranging from wide open spaces to dense urban canyons, any misalignment has to be minimal because geodetic measurement must be accurate to the millimeter level. One advantage of the Pinwheel™ design is that it is inherently aligned and cannot become misaligned because of the etching technique used.

NovAtel's original Pinwheel™ antenna consists of an array of slotted openings in a ground plane. The active region of the spiral slot array is optimized for L1 and L2 band reception. Radiation passing through the slots is coupled to a spiral pattern on the reverse side of the element and delivered to the antenna LNA (low noise amplifier).

When an electromagnetic signal is fed into one end of a transmission line and sequentially coupled into the slotted openings of the Pinwheel™, a strong corresponding signal is emitted from the antenna in the direction of the antenna axis. To reduce the diffraction of the emitted signal at the edge of the antenna, the front exterior has a surface wave suppression region that has a multitude of openings and encloses the slotted array.

To help increase the accuracy of geodetic measurement, NovAtel's Pinwheel™ design has a radiation pattern roll-off near the horizon and maintains good sensitivity to usable low-elevation satellites. This can eliminate multipath generated replicas of the original line-of-sight (LOS) signal. This design also exhibits sensitivity to right-hand circularly polarized signals over a wide range of elevations and in all azimuth directions.

The Pinwheel™ design has an excellent axial ratio to reject reflected signals. The axial ratio defines the antenna's ability to reject multipath generated replicas of the original satellite system signal. The design allows 13dB of roll off from zenith to horizon, ensuring that a minimum of ground reflected signal can be detected at the element. The result is enhanced immunity against EMC/EMI (electromagnetic capability and interference) and electromagnetic pulse interference.

The original Pinwheel™ design works well for a dual-frequency antenna but was not intended to receive a wider bandwidth, including satellite ranging signals from the other systems like GLONASS and Galileo.

This design, which is patent-pending, was modified for the GPS-704X to enable a wider bandwidth. The modifications include interconnected slots shaped to begin as spiral slots that flare at the end into fractal loop configurations. These loops are coupled to another loop in an adjacent slot (see *Figure 3*). The radiating structure of interconnected apertures creates many RF paths that open the bandwidth. They also provide a common phase center for the new frequencies.

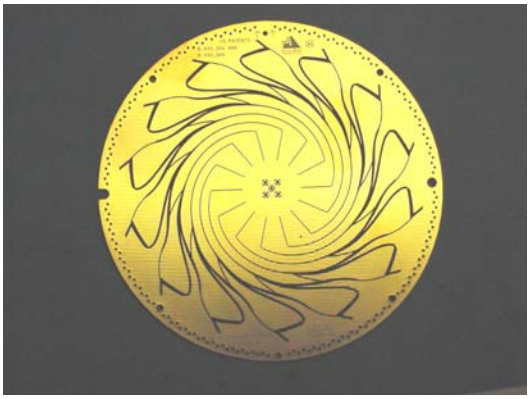


Figure 3: Modified Pinwheel™ Design

The accuracy of the phase centre depends on a smooth current distribution across the antenna plane. This design modification for the 704X antenna reduces the current distribution by increasing the impedance at the end of the arm. This diminishes any discontinuities that might have existed previously. The result is an even current distribution across the antenna. The design smoothes out amplitude and phase variation in the azimuth plane of the antenna.

The new design of the 704X has a microstrip multiple-turn spiral transmission line arranged on a lower surface of the substrate. The spiral shape improves the efficiency of the antenna and has a larger bandwidth than circular feeding structures.

TESTS AND RESULTS

The following parameters of the GPS-704X antenna were carried out in a 10 meter anechotic chamber at the David Florida Labs of the Canadian Space Agency in Ottawa to determine its performance:

- Antenna Gain
- Pattern Roll-Off
- Front-Back Ratio
- Axial Ratio
- Phase Center Movement
- Amplitude Ripple

The 704X antenna element was tested at 3 GPS, 6 GLONASS, and 3 Galileo channels. The edge of bands E5b, E6 and E1 were also tested. The antenna range, phase and axial ratio patterns for each frequency were the main objectives of the anechoic chamber tests.

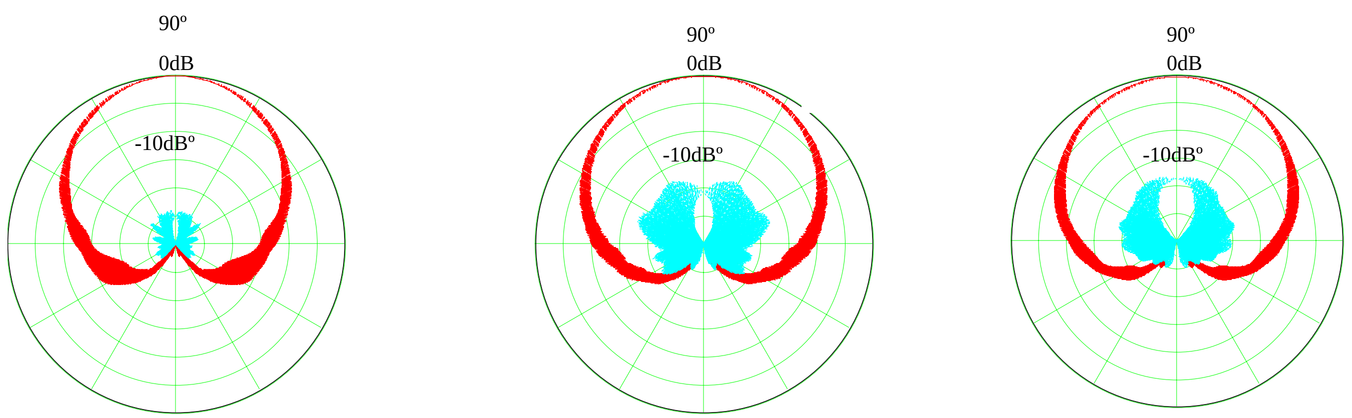
Antenna Gain

The data collected from tests performed on the 704X shows antenna gains at 90 º elevation, known as zenith (see *Table 2*). The gain pattern is a graphical depiction of the relative field strength received by the antenna in relation to the elevation angle of the satellite transmitting the signal. The minimum operational performance standard for GNSS is -2 dBic at elevation angles over 15º.

Table 2: Antenna Gain at 90º

Satellite System & Signal	Frequency (MHz)	Antenna Gain at 90º (dBic)
GPS L1	1575	6.8
GPS L2	1227	2.9
GPS L5 and E5a	1176	2.7
Galileo E5a	1164	2.8
Galileo E5b	1207	2.8
Galileo E1	1575	6.8
GLONASS L1	1602, 1608, 1616	7.0
GLONASS L2	1240, 1250, 1260	3.2

These results show that at 90º, the antenna's gain far exceeds the low-elevation requirement. The antenna also exceeds the minimum specification on the L5/E5a frequency (the lowest) and on GLONASS L1 frequency (the highest).



L1 Pattern
Peak Gain = 6.0 dBic

L2 Pattern
Peak Gain = 2.5 dBic

L5 Pattern
Peak Gain = 2.0 dBic

Figure 4: Antenna Gain Plots

The plots of the vertical sections of antenna gain (*Figure 4*) confirm the consistency of the 704X's performance at high and low frequencies. The thickness of the pattern's red line indicates the amount of variation in gain in the azimuth plane. The symmetry of the plots shows that there is minimal variation for the L1, L2 and L5 bands and that there is equal gain across different elevations at these frequencies.

Pattern Roll-Off

The antenna's rate of radiation pattern roll-off was tested at different frequencies. The pattern roll-off measures attenuation at the edges of the antenna's passband and should be between 8 and 14 dB. This test measured the roll-off from zenith to horizon and the results are recorded in *Table 3*.

Table 3: Pattern Roll-Off

Satellite System & Signal	Frequency (MHz)	Pattern Roll-Off (dB)
GPS L1	1575	13.2
GPS L2	1227	11.1
GPS L5 and E5a	1176	10.9
Galileo E5b	1207	11.0
Galileo E1	1575	13
GLONASS L1	1602, 1608, 1616	13.7
GLONASS L2	1240, 1250, 1260	11.4

Front-Back Ratio

The front-back ratio measures an antenna's directivity and its ability to reject reflected signals. For a multi-band antenna, the front-back ratio should measure 25 dB minimum at L2 and 30 dB minimum at L1. The test results for the front-back ration of the 704X are in *Table 4*.

Table 4: Front-Back Ratio

Satellite System & Signal	Frequency (MHz)	Front-Back Ratio (dB)
GPS L1	1575	32
GPS L2	1227	28
GPS L5 and E5a	1176	27
Galileo E5b	1207	31
Galileo E1	1575	31
GLONASS L1	1602, 1608, 1616	32
GLONASS L2	1240, 1250, 1260	27

Axial Ratio

The axial ratio defines the antenna's ability to reject multipath generated replicas of the original satellite system signal. The lower the ratio of the major axis to the minor axis of the polarization ellipse, the better the multipath rejection capability of the antenna.

To meet operational standards for a multi-band antenna, the axial ratio should meet these requirements at the following elevation angles:

- At 45º: not to exceed 3 dB
- At 15º: not to exceed 6 dB
- At 5º: not to exceed 8 dB

Table 5 contains the results of the tests conducted on NovAtel's 704X antenna:

Table 5: Axial Ratio

Satellite System & Signal	Elevation Angles (Degrees)	Axial Ratio (dB)
GPS L1	45	1.0
	15	1.4
	5	1.6
GPS L2	45	2.0
	15	3.8
	5	5.0
GPS L5 and E5a	45	2.1
	15	3.1
	5	4.0
Galileo E5b	45	2.0
	15	2.9
	5	5.0
Galileo E1	45	1.1
	15	1.7
	5	2.1
GLONASS L1	45	0.9
	15	1.5
	5	2.1
GLONASS L2	45	2.0
	15	4.0
	5	6.0

The results indicate that the overall axial ratio is within operational parameters.

Phase Center Movement

The phase center movement of NovAtel's 704X was tested by using Ansoft simulation software. These tests applied a detailed electromagnetic simulation from high frequency structure simulator (HFSS). Geodetic-grade antennas require less than 2 mm of phase center movement. The test results are in *Table 6*.

Table 6: Phase Center Movement

Satellite System & Signal Type	Vertical Phase Center (mm)		Horizontal Phase Center (mm)	
	Max	Ave	Max	Ave
GPS L5/Galileo E5a	1.2	0.7	1.0	0.7
Galileo E5b	1.3	0.8	1.1	0.7
GPS L2	1.5	0.8	1.2	0.8
GLONASS L2	1.8	1.2	1.5	1.1
Omnistar L-Band	0.4	-0.1	1.0	0.8
Galileo E1	0.4	0.0	0.9	0.7
GPS L1	0.5	0.0	0.8	0.6
GLONASS L1	0.7	0.4	1.2	0.7

Results confirm that the antenna element meets all requirements for a high performance, low multipath, and high stability phase centre commercial antenna.

Amplitude Ripple

The 704X was tested for amplitude ripple; the results are in *Table 7*. This test demonstrates the range performance of an antenna. A multi-band antenna should have a maximum of 3 dB at 15º elevation at any azimuth.

Table 7: Amplitude Ripple

Satellite System & Signal	Amplitude Ripple (dB)
GPS L1	2.1
GPS L2	2.0
GPS L5 and E5a	1.9
Galileo E5b	1.7
Galileo E1	2.1
GLONASS L1	2.2
GLONASS L2	2.2

CONCLUSION

The tests performed on NovAtel's 704X antenna confirm that it is suitable for multi-band GNSS applications because the results show reliable wideband performance from +1.15 to +1.7 GHz. Indications of this include the following:

- Satellite tracking is maintained at sufficient antenna gain levels at low elevation angles
- All antenna gain requirements for bands between 1150 and 1600 MHz
- All peak antenna gain requirements met in all bands

The test results also prove that the 704X exceeds requirements because it has excellent front-back ratio and amplitude roll-off for all bands, ensuring low susceptibility to multipath.

NovAtel's 704X antenna meets the axial ratio requirements, however the performance at the L1 band frequencies is slightly better than at the L2 frequencies. The antenna designer decided to increase the axial ratio at the L2 channel in favour of increased antenna efficiency on the L2 channel.

The 704X also has excellent amplitude pattern uniformity at 15º of elevation from the horizon for all bands (see *Table 7*). The 15º elevation mask is important because it avoids satellites near the horizon as they often have a lower signal to noise ratio than satellites overhead.

The WAAS (Wide Area Augmentation System) has a 10mm phase center stability standards for the L1 and L2 bands This requirement is easily met by the 704X antenna with an offset of only +1.5 to +2.0 mm between bands, such as L5, (see *Table 6*). This antenna is also suitable for tracking the Omnistar HP signal, which requires dual-frequency observations from a receiving antenna with a stable phase center.

The measured phase center location for various GNSS bands (see *Table 6*) shows that it is possible to have a single antenna with a phase center variation that does not exceed 2 mm for all bands of interest. Therefore, range error introduced by the antenna is minimal when using a combination of GPS, GLONASS and Galileo positioning satellite systems. These results demonstrate a functional and reliable antenna with a wide bandwidth and a common phase center across the frequency bands of interest.

As seen from the data presented, NovAtel's GPS-704X antenna provides excellent performance and is an ideal solution for positioning systems requiring combined GPS, GLONASS and Galileo. Currently, a commercial LNA is used for the 704X antenna but NovAtel is developing a GNSS LNA and the initial test results are promising.

For more information on the GPS-704X, contact NovAtel at 1-800-NovAtel or visit our website at www.novatel.com.