Geo++® White Paper

Additional Thoughts and Findings on Satellite Induced GNSS Phase Shifts, Receiver Tracking and the Impact on RINEX and RTCM

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Introduction

The modernization of existing GNSS and upcoming new GNSS changes the conditions for applications using phase measurements significantly. The changes do not only originate from additional satellites, but also from the variety of different frequencies and different signals available from the GNSS systems. In parallel, the receiver development is progressing and simultaneous tracking provides already multiple phase measurements on the same carrier frequency.

Depending on the GNSS system design, the signals on the same carrier differ by satellite induced phase shifts. The phase shift is in most cases a constant term but also variable phase shifts are possible.

Standards like RTCM and RINEX consider phase shifts to be addressed in the data formats. The formats have to be unambiguous and flexible enough to cover all present and upcoming signals and must maintain all signal properties to allow optimized processing with high accuracy requirements. This makes the development of standard even more challenging. Currently a static signal dependent phase shift correction table to align signals is favored.

A verification of a static phase shift correction table is pending. Different receivers are available which provide simultaneous phase measurements for different signals on the same carrier frequency. Therefore, a survey of different GNSS manufactures has been conducted based on tracking data to analyze the actual handling of phase shifts. The survey revealed notable differences and diversity among receivers. Phase shifts are not only signal dependent, but vary by manufacturer, receiver model and firmware.

The present paper discusses the differences and promotes a general strategy to handle phase shifts in data format standards. The proposed solution separates between so-called “untouched GNSS observables” as obtained from a GNSS receiver and additional information on phase shifts provided with the format standards.

General

There are basically two open standards for GNSS observables, RTCM[1] and RINEX[2]. RTCM V3 is a binary format primarily for real-time GNSS applications. RINEX V3 is an ASCII based format primarily for post-processing purposes initially developed in the IGS[3] community. Both standards are now maintained in RTCM SC104 working groups. The two formats do have of course intersections. Currently a Multiple Signal Message (MSM) is under discussion for RTCM V3 and an update of RINEX V3. Both standards consider GNSS phase shifts.

GNSS signals on the same carrier generally differ by a satellite induced phase shift. The phase shift is in most cases a constant term but also variable phase shifts are possible. In addition satellite induced signal delays or phase biases have to be considered as well as receiver hardware biases which are associated with different signals and tracking modes of the signals. At the receiver level even mixed mode tracking of two or more signals is possible. These biases are gaining much more importance with more signals from satellites, more tracking features of receivers and more GNSS systems. Details can be found in Wübbena et al. (2009).

The proposal for GNSS phase alignment in RTCM-MSM (RTCM-MSM 2012) (and also in RINEX (RINEX-3.02 2012)) implicitly assumes solely two groups of GNSS receivers.

- The first group provides already aligned phase observables
  (Trimble, Ashtech, refer to table 3.1-5 RTCM V3 Amendment 3 Standard).
- The second group provides non-corrected original receiver observables
  (all other manufacturers).

A corresponding correction table for GNSS signals has been proposed in RTCM-MSM (table 3.4-7) and RINEX-3.02 (table A17) to define for any receiver (now and in the future) the required shifts to align any GNSS phase observable. The table is also intended to serve the conversion of aligned observables back to original observables. It is implicitly assumed, that the correction to be applied for signal alignment is the same for all receiver types in the second group with non-corrected original observables, independent from receiver tracking architecture. No definition is given for receiver characteristics which are necessary to achieve phase alignment.

The following table 1 lists the phase shifts required for alignment as defined in the RTCM-MSM proposal (as well as in RINEX-3.02) as far as they are relevant for the further discussion in this paper.

MSM	**GPS**		**GPS**		**GLONASS**		**GLONASS**	
	L1CA	**L1P**	**L2C**	**L2P**	**L1CA**	**L1P**	**L2CA**	**L2P**
MSM	none	+0.25	-0.25	none	none	+0.25	-0.25	none

Tab. 1: GNSS alignment according to RTCM-MSM, Table 3.4-7 (value in cycles to be added to raw observables of all non-aligning receivers to get aligned observables)

1 **R**adio **T**echnical **C**ommission for **M**aritime Services
2 **R**eceiver **In**dependent **Ex**change format
3 **I**nternational **G**NSS **S**ervice

A first test of actual data already revealed a contradiction for at least one manufacturer. Therefore an empirical survey of more receivers/manufacturers based on actual GNSS data has been conducted to verify

- the assumption of identical tracking of receivers,
- the feasibility of a signal dependent, but receiver **in**dependent correction table to get aligned phase observables.

Empirical Survey of GNSS Manufacturer Alignment

The following empirical survey of GNSS manufacturer alignment lists the different phase tracking for GPS and GLONASS on the same frequency. It is based on actual data sets and signals commonly available today. The data sets were generally analyzed using Geo++ GNSMART software. Representative tracking information for Ashtech was separately provided (Kozlov 2012). The corresponding receiver models are listed in Tab. 2. The firmware of the receiver model is not documented.

Abbreviation	**Manufacturer**	**Receiver Model**
ASH	Ashtech	MB800 OEM
JAV	Javad	JAVAD TRE_G3TH DELTA
LEI	Leica	LEICA GR25
NAV	Navcom	NAVCOM SF-3050M
NOV	Novatel	OEM628
SEP	Septentrio	SEPT POLARX4TR
TPS	Topcon	TPS NET-G3A
TRM	Trimble	TRIMBLE NETR9

Tab. 2: GNSS manufacturer and receiver models used in survey

The following Tab. 3 contains the empirical results of GPS and GLONASS phase tracking on L1 and L2. The phase shift shown has to be added to the corresponding signal to achieve alignment with the reference signal. The reference signal is defined in the proposed correction tables (RTCM-MSM, RINEX-3.02), namely the CA-code based phase for GPS/GLONASS L1 and the P-code based phase for GPS/GLONASS L2. The phase shift for the reference signal is indicated by "none".

As well known from RTCM V3 Amendment 3, Table 3.1-5, Ashtech and Trimble receivers generate already aligned raw data output. Thus the phase shift cannot be detected in an empirical survey of raw data. Tab. 3 shows the internally applied phase shifts for manufacturers (ASH) and (TRM) as stated in the above mentioned Table 3.1-5 (released June 2009).

Data	GPS		GPS		GLONASS		GLONASS	
	L1CA	L1P	L2C	L2P	L1CA	L1P	L2CA	L2P
(ASH)	none	+0.25	+0.25	none			+0.25	none
JAV	none	-0.25	+0.25	none	none	-0.25	+0.25	none
LEI			-0.25	none			-0.25	none
NAV			+0.25	none				
NOV			-0.25	none			-0.25	none
TPS			-0.25	none			+0.25	none
SEP			0.00	none			0.00	none
(TRM)			+0.25	none	none	- 0.25	+0.25	none

Tab. 3: Empirical survey of GNSS manufacturer alignment (value in cycles to be added to tracked raw observables to get aligned observables)

From the survey some significant problems become obvious, which are highlighted in the Tab. 3:

- opposite signs for GPS L2C between manufacturers
- opposite signs for GLONASS L2CA between manufacturers
- opposite sign between in RTCM V3 Amendment 3, Table 3.1-5 and RTCM-MSM, Table 3.4-7
- aligned observables from a receiver formerly known as not-aligned

The occurrence of **opposite signs** for the same signal shows, that a receiver independent correction table is not capable to provide alignment for all receivers. Applying the proposed fixed correction table will result in quarter or even half cycle differences between the same signals from different receivers. This fact holds for both, GPS and GLONASS.

One manufacturer (SEP) **switched** from non-aligned to aligned observables. According to Septentrio (Sleewagen 2012), legacy receivers with firmware before December 2008 have non-aligned observables (as stated in table 3.1-5 RTCM V3 Amendment 3 Standard). Later firmware has aligned observables and legacy RTCM generated by a Septentrio receiver is aligned (Sleewagen 2012). Hence, an update of RTCM V3 table 3.1-5 is required.

The switch to phase alignment of the latest Septentrio receiver firmwares indicates, that any static information (in a table) is not practicable. Manufacturers will use, develop and switch signal tracking architectures (further discussed in next chapter) or alignment concepts. This will even be more relevant with increasing variety of GNSS signals and receivers.

The detected problems cannot be resolved by simply adjusting the values given in the RTCM-MSM, Table3.4-7.

Signal Tracking in a GNSS Receiver

What are the reasons for the obvious contradictions of tabled phase shift corrections and actual receiver tracking?

The phase shifts at the satellites are known for GPS signals and are constant for most signals. One exception is "flex power" mode for GPS L2C (IS-GPS-200D), where the phase shift can be switched at the satellite (Wübbena et al. 2009). For other GNSS the phase shift is assumed to be constant. However, this assumption may not hold for GNSS without publicly available interface documents.

A GNSS receiver tracks the incoming carrier phase with respect to the phase of a signal replica or reference signal (beat signal).

- An "***ideal***" receiver which uses coherently derived individual replica for each signal component with the same nominal phase shifts as introduced at the satellite (e.g. I and Q replicas), will directly generate "aligned" phase observations. The differences between the observed phases of the different signal components will contain only small biases from satellite and receiver hard- and software. The amount of the small biases is typically in the order of a few millimeters. A specification is available for GPS satellites but not for other GNSS or receivers.
- A "***typical***" receiver which uses the same reference signal for different signal components will observe the satellite induced phase shifts as difference between the phase observations for the different components in addition to the small satellite and receiver dependent biases.
- A "***general***" receiver may use coherently derived but arbitrarily shifted reference signals or may track the different signal components with non-coherently derived signal replicas. The receiver will then observe arbitrary biases between the observations of different phase components. These biases may even not be constant but varying with time. Although a non-coherent physical receiver design may be unlikely, a non-physical receiver, like a virtual reference station, may not allow "coherent tracking" with fixed phase shifts and thus will fall in general into this category of receiver designs.

For data signals (as opposed to pilot signals) the receivers must resolve a half cycle ambiguity by analyzing and identifying the "sign"/"polarity" of the data signal. This is normally done by identifying a synchronization pattern or its binary inverse in the data signal and, if the polarity does not match the reference polarity, by applying a half cycle correction to the observed carrier phase. It is up to the manufacturer to define the reference polarity and thus the "sign" for which a half cycle correction is applied.

For different receiver types the reference polarity may be different and thus resulting in a half cycle phase shift difference. If the signal is modulated with an unknown data signal (like GLONASS-M P2), a manufacturer might be able to identify a synchronization pattern which can be used to resolve the half cycle ambiguity. However, a constant half cycle bias may exists with respect to other manufacturers which have identified the synchronization pattern, but have chosen a different sign/polarity.

All the empirical derived differences between receiver types can be explained with one or more of the above effects. Other differences are possible if more receiver types and signals are analyzed.

Handling of Satellite induced Phase Shifts

An application utilizing the carrier phase measurements has different options to deal with the satellite and/or receiver induced phase shifts.

The most rigorous approach is the modeling of individual signal biases for each signal and each satellite and each receiver. These biases are in general varying with time. Highest precision applications must follow this approach, because every signal component contains satellite and receiver dependent biases regardless of the phase shift issue. Applications utilizing double differences should build the differences only between phase measurements from the same signal type. This general approach works with any of the above mentioned receiver types. Additional information about the tracking properties of the receivers is not needed, but may be desired and utilized to optimize the performance of the application.

An application with less accuracy requirements might correct known phase shifts ("phase alignment”) and intermix phase measurements from different signals on the same frequency without modeling the remaining biases. However, as shown above, a general rule how to correct the phase shifts cannot be defined and an alignment might even not be possible. Additional information about the tracking properties of the involved receivers is needed to follow this approach. A standardized data format should allow the transmission of such properties.

In case the phase shift correction is not possible or known, an application can still model the unknown biases. Double differences should then be formed only between satellites where the signal types used to compute the between receiver single differences are identical. For example, if the two receivers are tracking L2P and L2C, the possible between receiver single difference groups are L2P-L2P, L2C-L2C, L2C-L2P and L2P-L2C. The phase shifts are canceled in all double differences formed within the groups, even if the between receiver single difference is computed with different signal types. However, double differences across the groups may contain phase shifts and should not be used or the bias should be modeled.

Standardization of Data Formats and Phase Shifts

For RTCM-MSM, RINEX V3 and RINEX-3.02, the idea so far was to always align all carrier phases for the same carrier frequency. The RTCM MSM and RINEX working groups considered a fixed and receiver independent correction table a feasible approach to enable phase alignment, but empirical tests did not proof it.

The approach is no longer feasible because it only allows the transport of observations from an “***ideal***“ receiver type. Data from “***typical***” and “***general***” receiver types would have to be converted to an ideal receiver type. This conversion is only possible for certain receiver types, if type dependent additional information on the tracking properties is available to the conversion tool. In general this conversion is not possible, for example for certain non-physical receiver types or if the tracking properties are unknown or unavailable.

Thus, the data format should not require an ideal receiver type. Instead, the format should be receiver independent and allow the transport of untouched measurements and in addition the transport of receiver properties like phase shifts.

The standards should not force and/or restrict any receiver tracking developments. It should focus on the clear, simple and secure transport of all signals available from a receiver without any restriction and/or dependency on mandatory additional information. Additional/external information should be provided within the streams if available, but should not enforce any limitations. Only the end user application should decide on possibly necessary alignments by using the additional information provided within the data or from external information sources.

Resolution:

- Transmit the "untouched" (i.e. non-corrected) observables as provided by the receiver interface.
- Provide additional/external information if available
  (new message type carrying the phase shifts to perform alignment).
- Leave it to the developer of the final application how to deal with the issue
  (apply corrections, model biases etc.)

To make it clear, "untouched" means, that e.g. Ashtech data is still aligned in MSM.

The resolution is capable to solve almost all technical demands raised so far in RTCM-MSM developments. The major ones are:

- transmission of mixed mode tracking observables
- change of phase shift due to flex power is implicitly resolved
- every converter can provide any observable provided by a receiver
- the original observable can be re-covered without any ambiguity
- support of RINEX header information on phase shift

Why do not force alignment and take the burden from the end-user?

At first sight, to demand aligned data at the beginning of a data chain is reasonable. But one has to have reliable information on the correction of phase shift, which is currently difficult to obtain and which is – as learned from empirical analysis – not static information. As a consequence any observables with uncertain tracking properties cannot be converted to RTCM MSM and thus not be transmitted. It is desirable for an end user to have all available data, because the application can reject data or apply sophisticated algorithms to use the observables. This is of importance to e.g. support industrial progress and for scientific application. In certain cases it is even not possible to convert RTCM V3 to MSM messages and vice versa.

The "untouched" approach does not put any restriction on the converter and provides all observables available. With the additional phase shift message, the alignment issue can be resolved for all cases, where the necessary information is available, i.e. there is no limitation when compared with the "always align" approach.

Conclusion

A signal dependent and receiver independent GNSS correction table for satellite induced phase shifts is not feasible. Empirical analysis of tracking data demonstrated, that such a correction table is not yielding the desired result of aligned observables.

The correction of phase shifts at the start of a data chain puts to much complexity and restrictions on the data converters. A clear and simple strategy is to transmit the "untouched" (i.e. non modified) observables as provided by the receiver interface. In addition, the information on phase shifts is provided in a separate message, but only if available. This approach enables to transmit any signal and can be implemented into RTCM MSM very easily. There is basically no significant change, but a gain of simplicity, reliability and flexibility.

The concept can be applied to phase shifts (additional information for alignment), but also to biases like e.g. GLONASS Code Phase Bias (CPB message) (RTCM-MSM 2012) and possibly new additional information in the future. For now, a new message for phase shifts should be developed.

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