



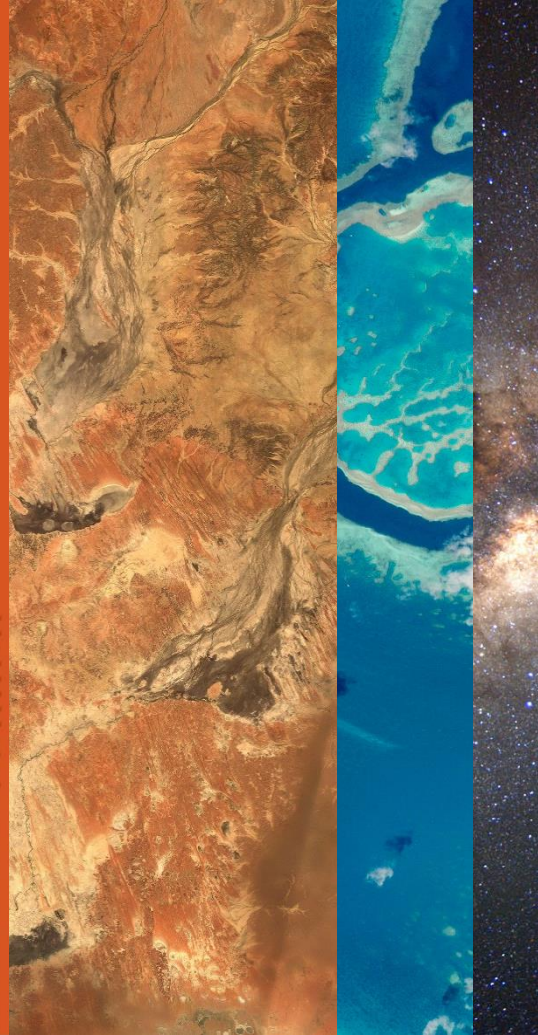
Australian Government
Geoscience Australia



POSITIONING
AUSTRALIA

GINAN (Analysis Centre Software) Technology Review

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Product Development Manager
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Australian Government

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Introduction

Ginan is part of an exciting and innovative Australian Government program to enable precise position technology, as a public service, across the whole of the Australian continent. Ginan is an open source software toolkit and on-line service that lets anybody use the precise point positioning (PPP) technique.

This presentation describes some of the technical considerations of PPP. For more information on the Positioning Australia program follow [this link](#) or read the Ginan Project Overview.



Ginan and Precise Point Positioning

Ginan is a precise point positioning (PPP) application. PPP is not one thing but a collection of mathematical models and techniques, supported by large amounts of data. PPP makes use of the following:

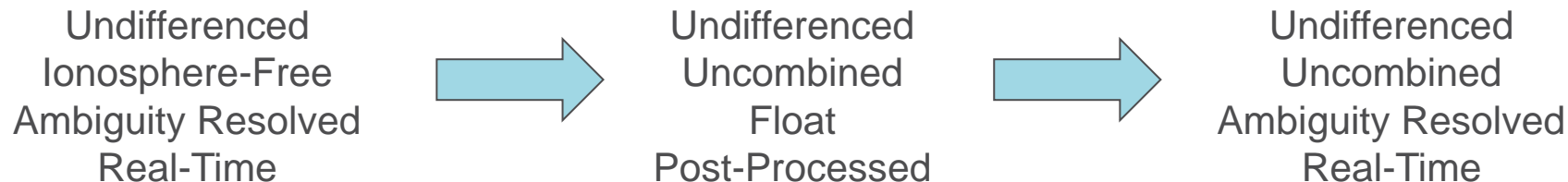
- Applying corrections to reduce satellite orbital eccentricities and satellite clock drift,
- Employing techniques to remove the effects of Ionospheric refraction,
- Applying corrections to remove signal delays caused by the Troposphere,
- Using precise locations for satellite and receiver antenna phase centres,
- Allowing for the satellite signal carrier phase wind-up effect,
- Making corrections for satellite transmission power changes,
- Compensating for Earth solid tides,
- Using undifferenced and uncombined raw observations.

Ginan Development

Ginan is on a development journey. That development will see Ginan be released in versions incorporating new techniques and algorithms that improve:

- The timeliness of the analysis products i.e. reduction in latency.
- The accuracy of the data within analysis products.
- The time it takes to resolve an accurate position.

Stages in the Ginan development journey:

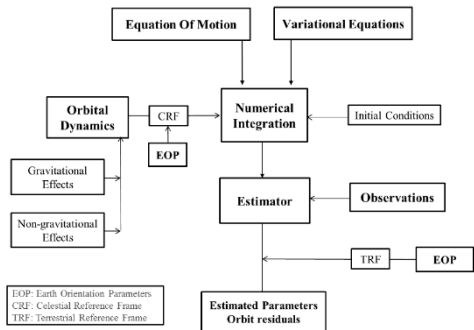


This presentation aims to explain, at a high level, the meaning and significance of those terms and the mechanics of precise point positioning.

Precise orbits and clocks I

Satellites broadcast data about their orbit (ephemeris) on a regular basis, and this data is used by GNSS receivers to derive positions. The ephemeris data, while accurate, is not as accurate as it could be. The original GPS ephemeris had a precision of about a meter. The newer system Galileo broadcasts data which is three times more precise. As the technology and techniques develop, so will the precision of the ephemeris data.

The Precise Orbit Determination (POD) component within Ginan



The clock and orbit data broadcast by the satellites is calculated within the satellite and periodically adjusted by ground control stations. At the same time ground based GNSS reference stations collect GNSS data (observables) and using sophisticated orbit and correction models, are able to produce very accurate GNSS satellite orbit and clock data. Ginan has its own Precise Orbit Determination (POD) component to do this type of work. Using very accurate orbit and clock data increases the subsequent accuracy of calculated positions.

A crucial role is played by the International GNSS Service (IGS) - up to eight IGS Analysis Centres (AC) contribute daily Ultra-rapid, Rapid and Final GPS orbit and clock solutions to form IGS analysis products. Properly weighted combinations of results from the ACs can produce products which are superior in precision, accuracy, stability, reliability, and robustness compared to the results of any individual AC.

Currently Geoscience Australia is an IGS Analysis Centre Coordinator. In time, using Ginan, Geoscience Australia will offer to supply analysis products to IGS.

Table 3.8: GPS/Galileo/Beidou broadcast ephemeris and clock message parameters.

Parameter	Explanation
t_{oe}	Ephemerides reference epoch in seconds within the week
\sqrt{a}	Square root of semi-major axis
e	Eccentricity
M_0	Mean anomaly at reference epoch
ω	Argument of perigee
i_0	Inclination at reference epoch
Ω_0	Longitude of ascending node at the beginning of the week
Δn	Mean motion difference
\dot{i}	Rate of inclination angle
$\dot{\Omega}$	Rate of node's right ascension
c_{uc}, c_{us}	Latitude argument correction
c_{rc}, c_{rs}	Orbital radius correction
c_{ic}, c_{is}	Inclination correction
a_0	Satellite clock offset
a_1	Satellite clock drift
a_2	Satellite clock drift rate

IGS product type, accuracy and latency

Orbit type	3D accuracy	Clock accuracy		Latency	Updates
	(metres)	(nsec)	(metres)		
Broadcast	2.00	7.0	2.10	Real-time	----
Ultra-rapid (predicted)	0.10	5.0	1.50	Real-time	0.25
Ultra-rapid (observed)	<0.05	0.2	0.06	3 hours	0.25
Rapid	<0.05	0.1	0.03	17 hours	1
Final	<0.05	<0.1	<0.03	13 days	7

Precise orbits and clocks II

Over time organisations with expertise have been contributing their PPP products – in the example below precise orbits – to the International GNSS Service (IGS). The accuracy of the combined product has been steadily increasing.

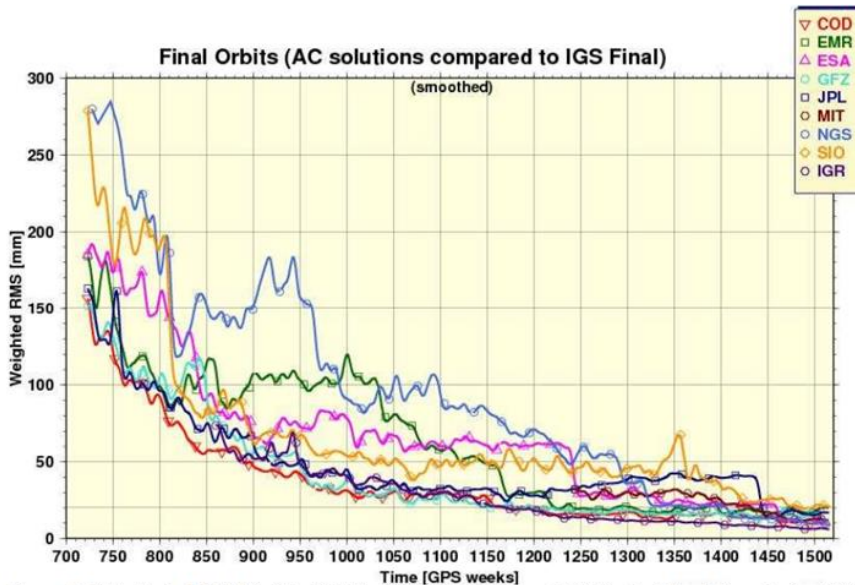


Figure 1: Weighted orbit RMS of the IGS Rapid (*IGR*) products and AC Final orbit solutions during 1994-2009 with respect to the IGS Final orbit products.

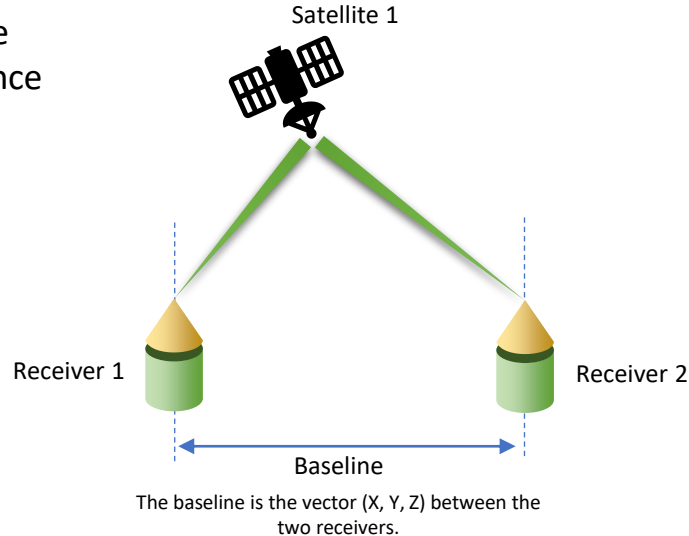
From: A GUIDE TO USING INTERNATIONAL GNSS SERVICE (IGS) PRODUCTS, Jan Kouba, Geodetic Survey Division, Natural Resources Canada

- COD – Center for Orbit Determination
- EMR – Natural Resources Canada
- ESA – European Space Agency
- GFZ – GeoForschungsZentrum
- JPL – Jet Propulsion Laboratory
- MIT – Massachusetts Institute of Technology
- NGS – National Geodetic Survey
- SIO – Scripps Institute of Oceanography
- IGR – International GNSS Service Rapid products

Concept: differencing – eliminating unknowns

The use of observations of the same GNSS satellites by two or more receivers allows factors that contribute to errors in positions to be eliminated.

Single Difference

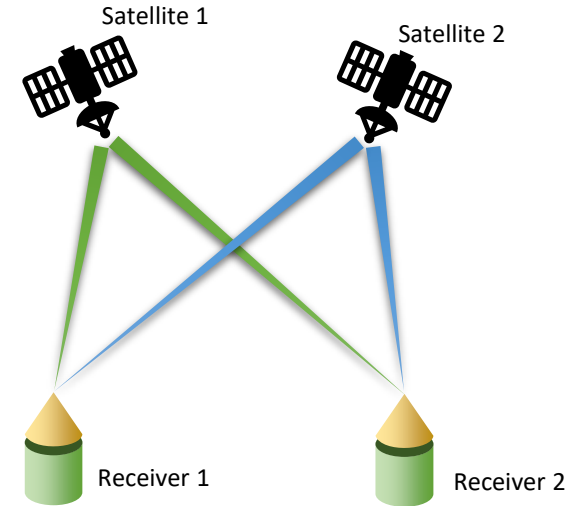


Because satellite 1 is observed by both receivers, when combining the pseudorange equations for the two receivers to determine position, two factors can be eliminated from the equations:

- The satellite clock error,
- The satellite orbit error.

If the baseline is small (< 20km) atmospheric delays are also eliminated. Removing these factors makes solving for position simpler – **differenced solution**.

Double Difference



Double differencing delivers the benefits of single differencing and also removes **receiver** clock errors.

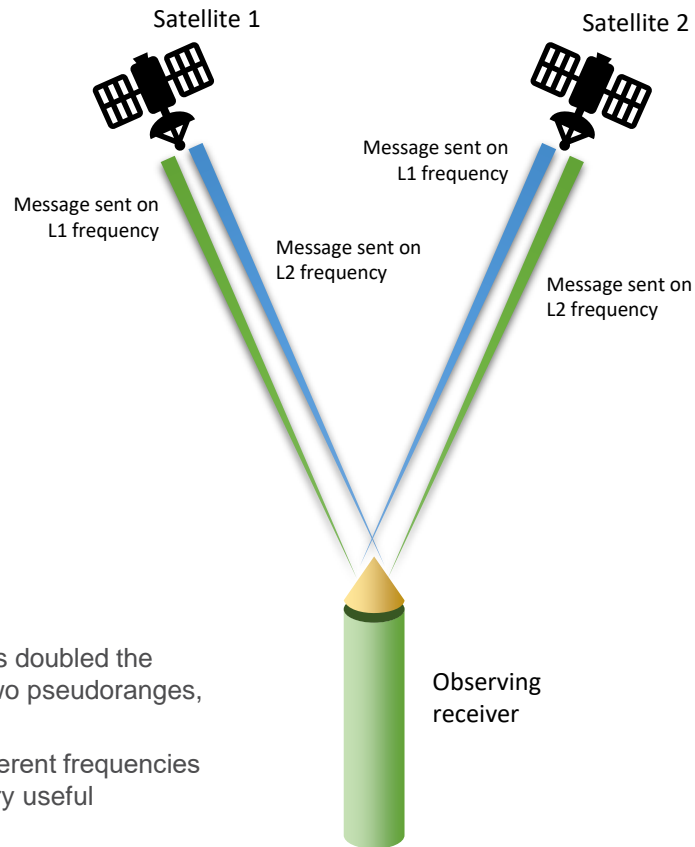
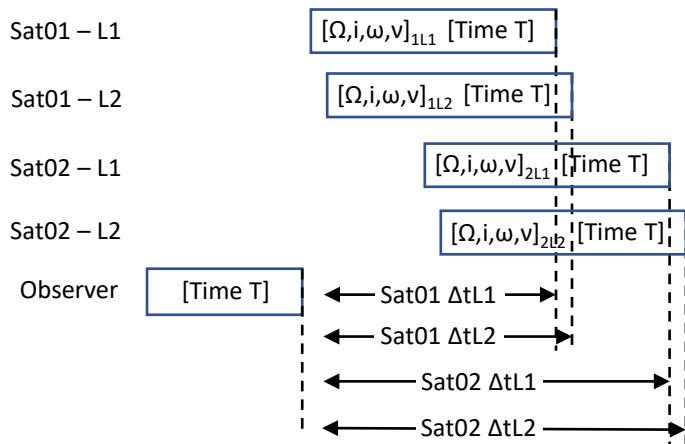
But:

The differencing technique comes with a cost in the form of signal noise. With single differencing the noise increases by 1.4 (square root of 2) and for double differencing the noise doubles with respect to a one-way measurement.

Ultimately Ginan will be an un-differenced solution.

Using a second frequency

Position and time messages sent from the satellites are received by the observing receiver at different times.



In its simplest form receiving two ranging messages from a satellite means the receiver has doubled the information it has available when it comes to calculate the position – you would hope the two pseudoranges, calculated by the receiver would be the same – or very similar.

In practice the best outcome is “very similar”. The fact the messages are transmitted at different frequencies does lead to slight differences in calculated pseudorange – but it turns out this provides very useful information in dealing with the effects of the Ionosphere – see later.

Using a third frequency (like L5) provides even more information.

Ionosphere

The Ionosphere has two main effects on the signal from GNSS satellites:

1. It changes the refractive index of the atmosphere and bends (thus extends) the path the signal takes.
2. The presence of ions actually slows down the signal¹.

Any delay to the signal causes a position error at the receiver – for the ionosphere it is not huge but is significant – 2 to 30m.

Receivers using one GNSS frequency, such as the GPS L1 signal, need to use an ionosphere model to make an adjustment. The more sophisticated the model the longer it takes to make the adjustment but the more accurate it will be.

Crucially the effect of the ionosphere is different for different frequencies. GNSS receivers that can decode two signals (e.g. GPS L1 and L2) can use an algorithm – a linear combination of code or carrier measurements – to remove much of the ionosphere effect.

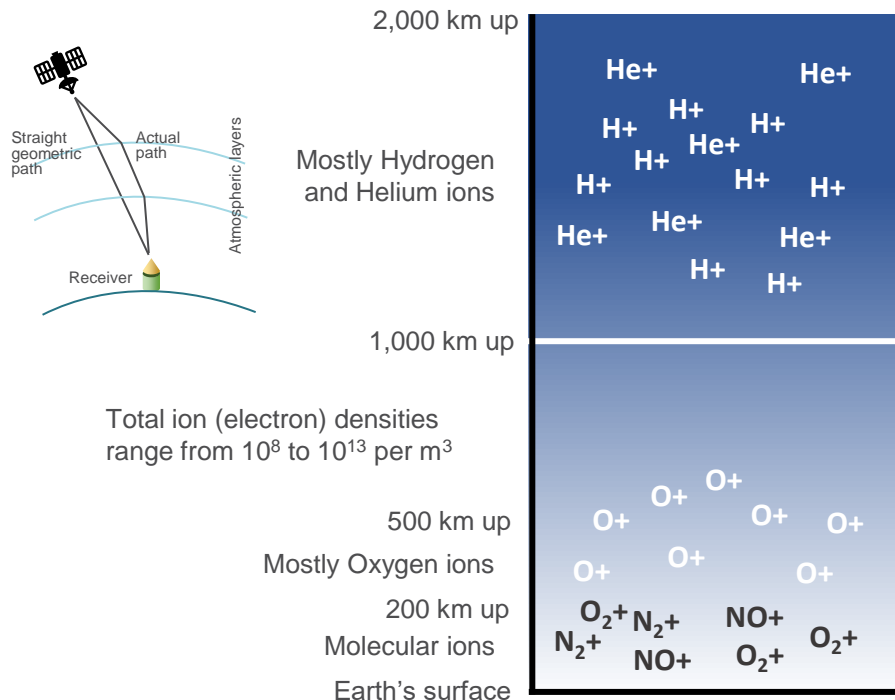
The use of this algorithm is referred to as deriving a position which is **ionosphere-free**. GINAN has implemented an ionosphere-free solution.

Ionosphere models typically describe four main parameters:

- Electron density,
 - Electron temperature,
 - Ion temperature,
 - Ion composition.
- The value of parameters vary by time of day, position in the Sun spot cycle, latitude, longitude and altitude.

1: It actually advances the carrier wave (negative delay) and delays the code signal.

The ionosphere is a shell of electrons and electrically charged atoms and molecules that surrounds the Earth. It is considered to start at an altitude of 85 km and extend to about 2,000 km above the Earth's surface.



Troposphere

Delays to GNSS messages caused by the Troposphere differ to the Ionosphere in one very important aspect – they are uniform across the GNSS frequencies. This means that the techniques used to create Ionosphere-free solutions cannot be used for the Troposphere. Troposphere models have to be used to adjust for delays.

Models make a clear distinction between the dry and wet components of the Troposphere. The dry component, typically 90% of the delay, can be modelled accurately using temperature and pressure (the gas laws). Thankfully the wet component (water vapour) contributes a fraction of the delay as it is unpredictable and complex to model accurately.

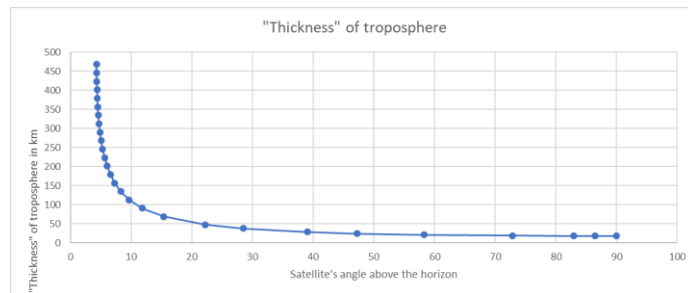
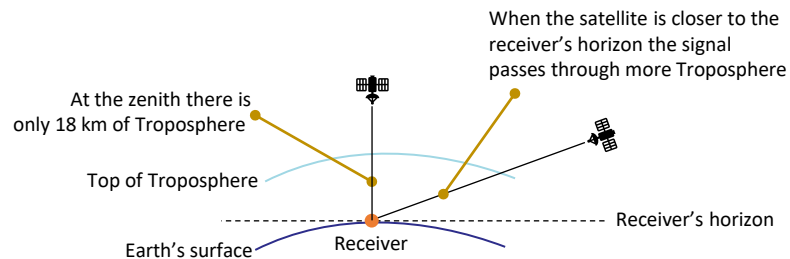
Models include UNB developed by Collins and Langley and used by the US WAAS, the Saastamoinen Standard Total Delay Model and TopGrid by Kreger et al..

GNSS signals can actually be used to make readings of the Troposphere and specifically the wet component for use in weather forecasting applications. Using very accurate satellite orbit and clock details, an Ionosphere-free model and models for the dry (hydrostatic) part of the Troposphere, it is possible to determine the effect of the wet part of the Troposphere by comparing the actual measured GNSS signal against a calculated signal.

GINAN is capable of calculating Zenith Troposphere Delay (ZTD).

The Troposphere contains the bulk of the Earth's atmosphere and all its weather. It starts at the Earth's surface and extends upwards to an altitude of 18 km.

Like the Ionosphere it causes delays to GNSS signals due to refraction bending radio paths and making them slightly longer – between 2 and 30 m. The effects of the Troposphere depend to an extent on the elevation above the horizon of the satellite from the point of view of the receiver. At low elevations the GNSS signal has to pass through more Troposphere compared to the zenith (directly above):



Stars twinkle or scintillate in the sky because of dynamic changes in the Troposphere – changes which cause continuous variations to the refractive index of the atmosphere. These scintillations affect GNSS signals and are observable by receivers.

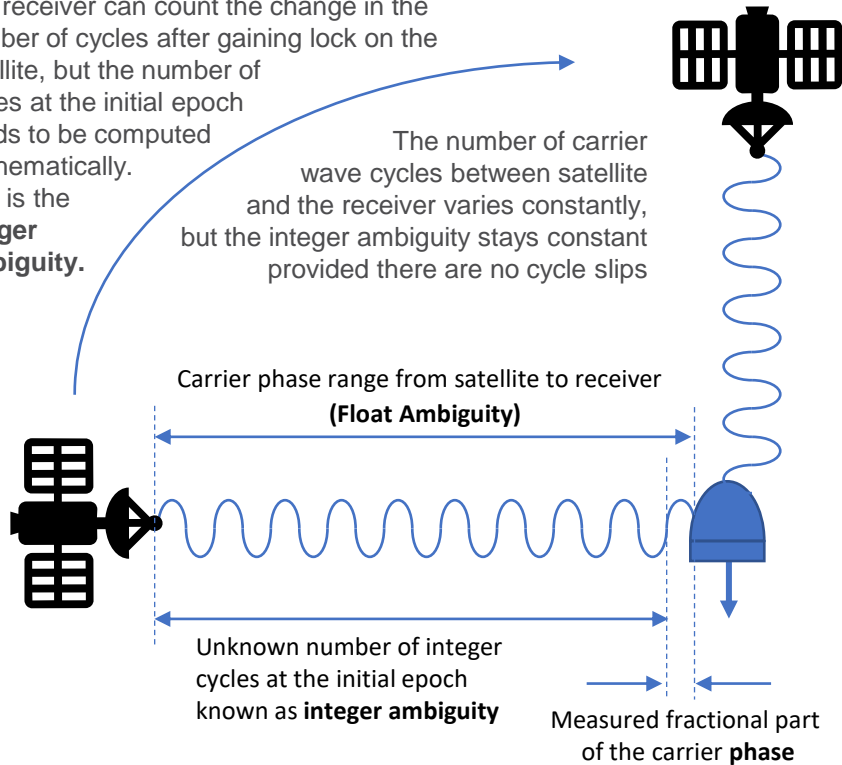
Carrier Wave Observations: understanding ambiguity

As the satellite tracks across the sky ...

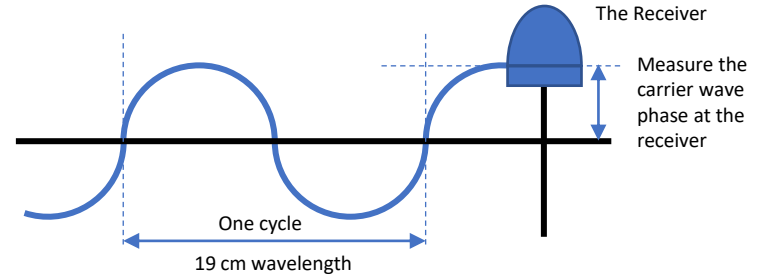
The receiver can count the change in the number of cycles after gaining lock on the satellite, but the number of cycles at the initial epoch needs to be computed mathematically. This is the **Integer Ambiguity**.

Initial epoch => first time observed (first second)

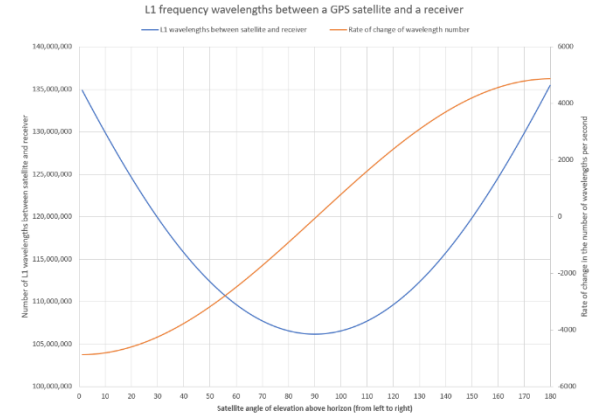
The number of carrier wave cycles between satellite and the receiver varies constantly, but the integer ambiguity stays constant provided there are no cycle slips



The wave length of the carrier frequency – for L1 this is 1575.42 Mhz – is $c = 299,792,000$ m/s divided by $1,575,420,000$ hz which gives 0.1903 m or about 19 cm.



This carrier wave phase gives us a distance greater than zero and less than 19 cm. But how many whole carrier waves are there to the satellite at the initial epoch? That number is **ambiguous** ... The ambiguity needs to be resolved => **ambiguity resolution**.



Resolving Ambiguity: combined and uncombined

Determining the number of carrier waves between the satellite and the receiver (integer ambiguity) is a mathematically complex and challenging task.

There are a number of well established mathematical techniques used for ambiguity resolution. They involve **combining** two or more observable carrier waves and pseudoranges, of different frequencies, to provide additional information. These are **combined solutions**. [Ultimately Ginan will not use these techniques but will be un-combined.]

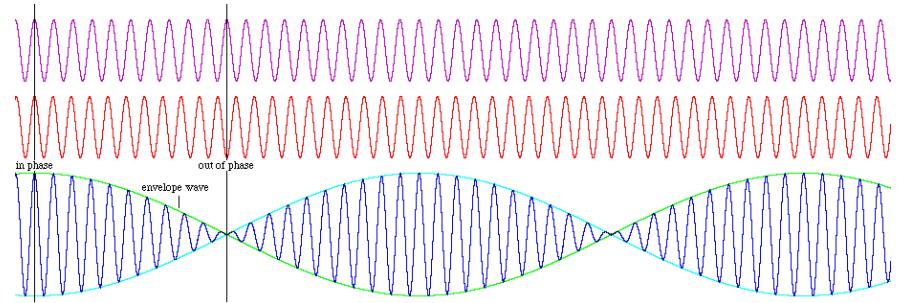
The most common combinations are referred to as:

- Wide-lane,
- Narrow-lane,
- Melbourne-Wubben Wide-lane.

System	Signal	Frequency (MHz)	Wavelength λ_i (m)	Signals combined	Wide-lane λ_w (m)	Narrow-lane λ_N (m)
	i	f_i	$\lambda_i = c/f_i$	ij	$c/(f_i - f_j)$	$c/(f_i + f_j)$
GPS	L_1	1575.420	0.190	L_1, L_2	0.862	0.107
	L_2	1227.600	0.244	L_1, L_5	0.751	0.109
	L_5	1176.450	0.255	L_2, L_5	5.861	0.125
GLONASS ($k = 0$)	G_1	1602.000	0.187	G_1, G_2	0.842	0.105
	G_2	1246.000	0.241	G_1, G_3	0.760	0.107
	G_3	1204.704	0.249	G_2, G_3	7.827	0.122
Galileo	E_1	1575.420	0.190	E_1, E_{5b}	0.814	0.108
	E_{5b}	1207.140	0.248	E_1, E_{5a}	0.751	0.109
	E_{5a}	1176.450	0.255	E_{5b}, E_{5a}	9.768	0.126
BDS	B_1	1561.098	0.192	B_1, B_3	1.024	0.105
	B_3	1268.520	0.236	B_1, B_2	0.846	0.108
	B_2	1207.140	0.248	B_3, B_2	4.884	0.121

Source: Adapted from (Sanz Subirana et al., 2013) and De Oliveira (2017).

Wide-lane: two carrier wave frequencies are subtracted from each other to produce a lower frequency with a longer wavelength – which makes resolving ambiguity simpler.



Narrow-lane: two carrier wave frequencies are effectively added to each other to produce a higher frequency with a shorter wavelength.

Melbourne-Wubben Wide-lane: combines carrier wave phase and pseudorange range measurements – typically wide-lane carrier and narrow-lane pseudorange:

$$L_{MW} = \frac{1}{f_1 - f_2} (f_1 L_1 - f_2 L_2) - \frac{1}{f_1 + f_2} (f_1 P_1 + f_2 P_2) = L_W + P_N$$

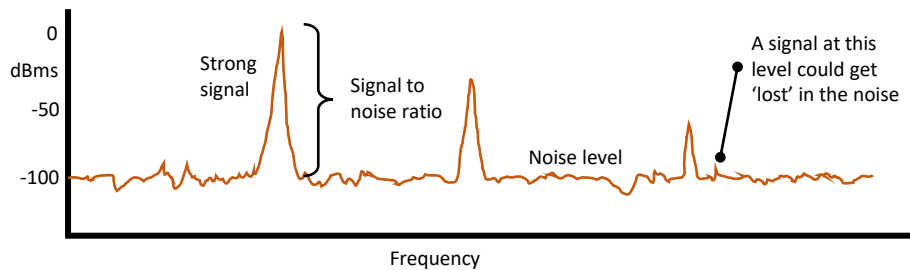
This table shows the effect of frequency combinations.

The large wavelength of the wide-lane combination is useful for ambiguity resolution algorithms as well as cycle-slips – a cycle-slip indicates a change in the value of the initial integer phase ambiguity of carrier-phase measurements. The down-side is that wide-lane amplifies the noise present in the original observation. Narrow-lane reduces the noise but resolution is harder.

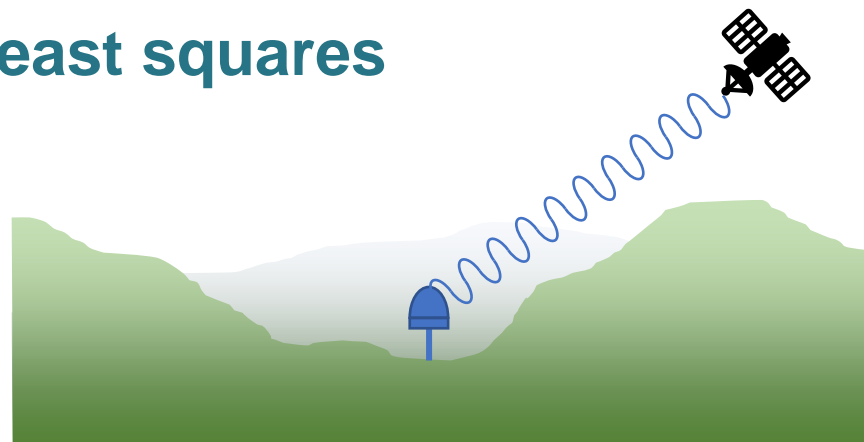
Resolving Ambiguity: best fit, least squares

As a GNSS satellite rises above a receiver's horizon the signals from that satellite become visible to the receiver. The receiver locks on to the carrier wave of the signal and has to solve the ambiguity problem – what is the integer number of carrier waves between it and the satellite at the initial epoch?

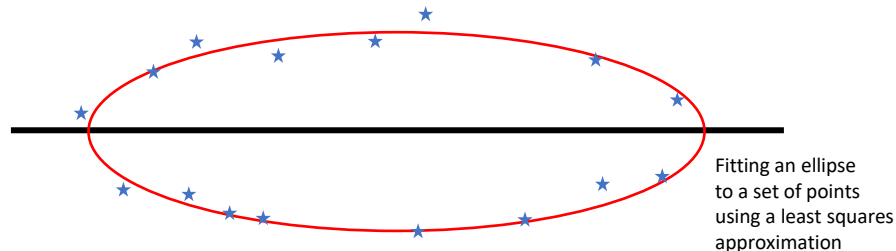
Once the integer ambiguities are known, the corresponding carrier-phase measurements will act as if they are high-precision pseudorange measurements, thereby allowing the remaining parameters, such as receiver coordinates, to be estimated with high precision.



A mathematical model describing the position of the receiver and the satellites it can see is used to estimate those positions relative to each other. These estimated positions are then compared to the observed positions which produces residuals – the difference between the estimated and observed values. The “best model fit” is when the sum of the squares of the residual values is at a minimum. So the model is tried with different carrier wave numbers till that best fit is found. This is part of the work done in the Kalman filter (see later).



The noise in the signal means that there is an uncertainty in the carrier wave integer number – so there are always two data items – the integer value and its associated degree of certainty (covariance value). Because the position of the satellite is known approximately through its orbit, there is a finite possible range of values for the integer value. In the first instance a “least squares” algorithm is used to estimate the number of carrier waves as a floating point number – the **float solution**.



Fitting an ellipse to a set of points using a least squares approximation

Resolving Ambiguity: bootstrapping

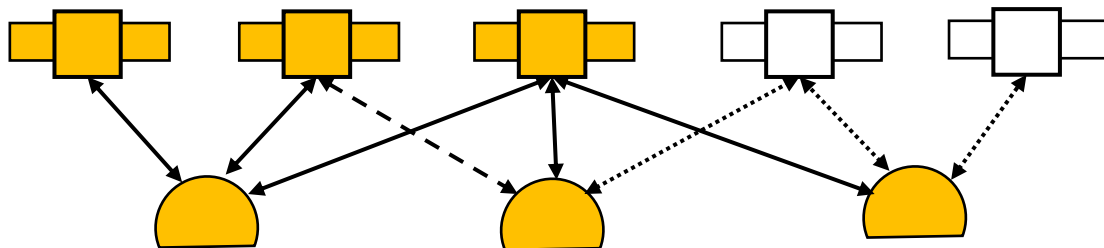
Once the float solution has been calculated, the next step is to determine integer values for the ambiguities. Ginan is researching and developing software based on a number of techniques including *Integer Rounding*, *Integer Least-Squares*, *Best Integer Equivalent* and *Integer Bootstrapping*.

Once integer values for ambiguities have been determined, the values are substituted into the calculations used during the float solution to get better values for the other parameters.

It must be remembered that the GNSS observations are very dynamic. Satellites are appearing and disappearing all the time and the receivers are having to work to obtain and maintain locks on their signals. Ginan is developing the concept of maintaining a Network Pivot to help resolve ambiguities. At any given time there will be satellites and receivers in different states of ambiguity resolution.

Integer Bootstrapping – from Teunissen

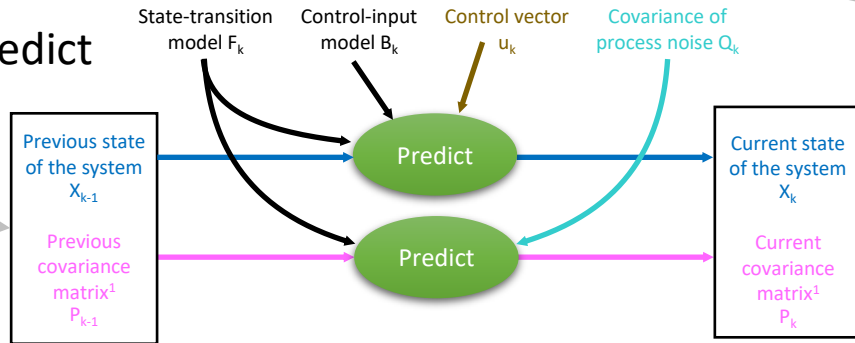
If n ambiguities are available, one starts with the first ambiguity \hat{a}_1 and rounds its value to the nearest integer. Having obtained the integer value of this first ambiguity, the real-valued estimates of all remaining ambiguities are then corrected by virtue of their correlation with the first ambiguity. Then the second, but now corrected, real-valued ambiguity estimate is rounded to its nearest integer. Having obtained the integer value of the second ambiguity, the real-valued estimates of all remaining $n-2$ ambiguities are then again corrected, but now by virtue of their correlation with the second ambiguity. This process is continued until all ambiguities are accommodated. Thus the bootstrapped estimator reduces to 'integer rounding' in case correlations are absent, i.e. in case the ambiguity vc-matrix is diagonal.



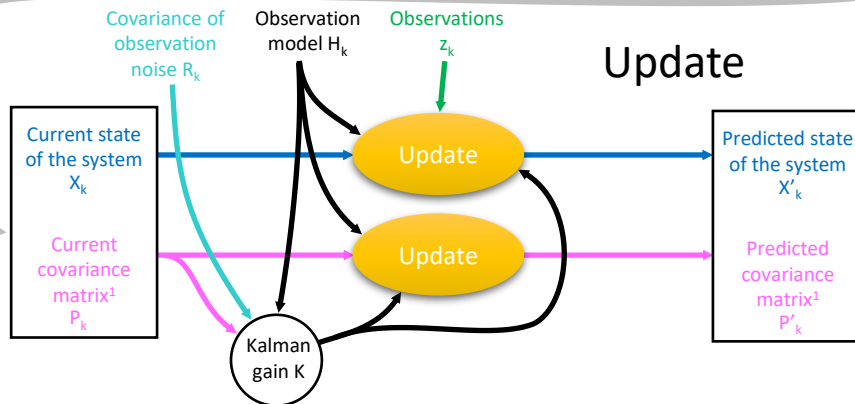
- Visible
- Ambiguity set to zero
- Ambiguity to be solved

Kalman Filter: parameter estimation

Predict



Update



A Kalman filter is a very efficient mathematical technique that is used to make predictions about a system's state based on the operation of a mathematical model of the system and real-world observations or measurements of the system.

The filter can be set up to take account of the noise or uncertainty (covariances) surrounding any particular measurement and control the extent to which changes in a measurement control changes to the prediction (Kalman gain).

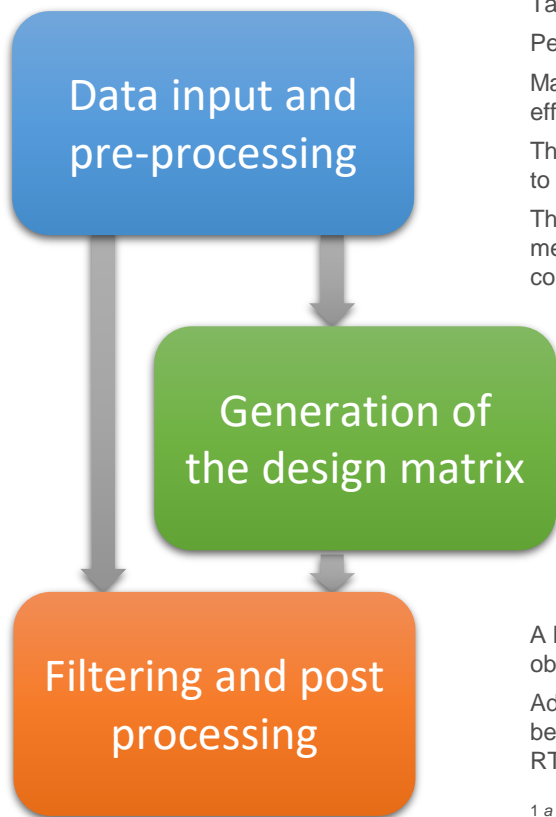
The state of the system and the covariances are contained within matrices. The transformations applied to those matrices represent the state-transition model.

For Ginan the challenge is to represent the complex system of GNSS satellites and their observables and model their system of movements, along with the noise inherent in system, to make accurate predictions of position – and crunch those numbers fast enough to operate in real-time. This includes ambiguity resolution.

1 – the covariance matrix informs us as to how correlated (dependent on each other) are the values of system parameters

Ginan Parameter Estimation: Kalman Filter

Many thanks to Aaron Hammond
FrontierSI for the contents of this slide.



Takes in GNSS observation data from a stream or file (RINEX or RTCM/IGS),

Performs quality control checks including cycle slip/clock jump detection,

Makes corrections for phenomena that are well modelled using *a priori*¹ data e.g. time of flight, relativity effects, tidal motion of receivers, dual frequency ionosphere removal and known antenna offsets,

The observations are also assigned a covariance value specifying the uncertainty in the measurement due to measurement noise and other error sources.

These form the basis for the 'measurements' passed to the Kalman filter. In some cases these measurements are not directly passed in, but the difference from their expected value is (observed minus computed).

Forms a set of linear equations (one for each measurement) that specifies the relationships between the measurements and the 'parameters' that are estimated in the filter,

State elements of the matrix are parameters of interest that are not known *a priori*¹, and may drift over time, requiring estimation in the filter e.g. position adjustments, biases, troposphere, ionosphere, orbit adjustments and ambiguities.

The relationships between the observables and measurements incorporates knowledge of calculated satellite-receiver geometry and the receiver/satellite/signal/frequency used in the measurement.

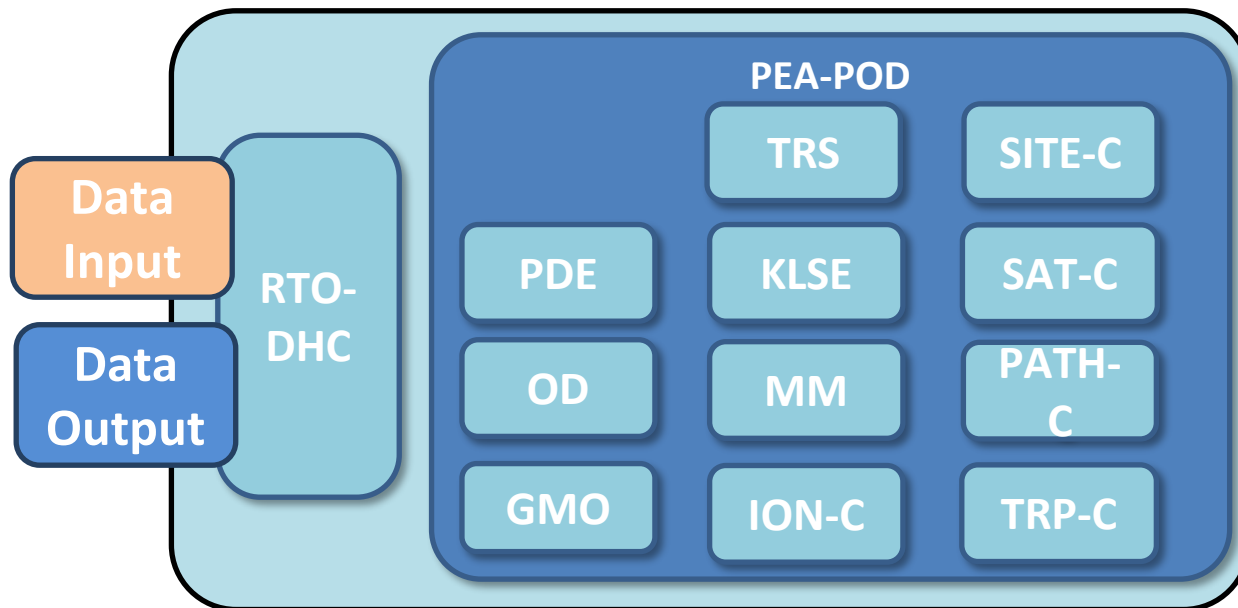
A Kalman filter is used to combine the design matrix and measurements to generate 'optimal' estimates of the observables.

Additional processing such as reverse smoothing, outlier rejection, and ambiguity resolution is performed before the results of the computation are output in various formats such as SINEX and SP3 files, and RTCM/IGS streams.

¹ *a priori* - relating to or denoting reasoning or knowledge which proceeds from theoretical deduction rather than from observation or experience.

Ginan: functional model

PEA – Parameter Estimation Algorithm
 POD – Precise Orbit Determination
 Ginan = PEA + POD



KEY	
PEA-POD	- Parameter Estimation Algorithm - Precise Orbit Determination
RTO-DHC	- Real-Time Offline Data Handling and Communications
PDE	- Pre-Processing & Data Editing
OD	- Orbit Determination
GMO	- Generation of Messages and Outputs
TRS	- Time and Reference System
KLSE	- Kalman Filter and Least Squares Estimator
MM	- Measurement Model
ION-C	- Ionospheric Corrections
TRP-C	- Tropospheric Corrections
SITE-C	- Site Corrections
SAT-C	- Satellite Corrections
PATH-C	- Path Corrections

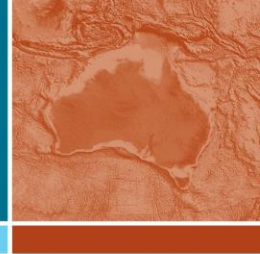
You know where you are with Ginan





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