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Evaluation of accuracy, integrity and availability of ARNS multi-constellation signals for aviation users in Australia

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Outline

- Current Status of GNSS Navigation in Aviation.
  - ADS-B, PBN (RNAV, RNP), SBAS, GBAS, (A)RAIM
- Multi-Frequency Multi-Constellation (MFMC) GNSS ARNS signals
  - GPS (L1, L5), Beidou (B1, B2), Galileo (E1, E5a, E5b)
- Error Treatment
  - Ionospheric error, DCBs, Antenna PCO, Troposphere
- Testing
  - Snapshot of current status
  - Application of DCB, Accuracy, Availability, Integrity
- Conclusions

Current Status of GNSS Navigation in Aviation

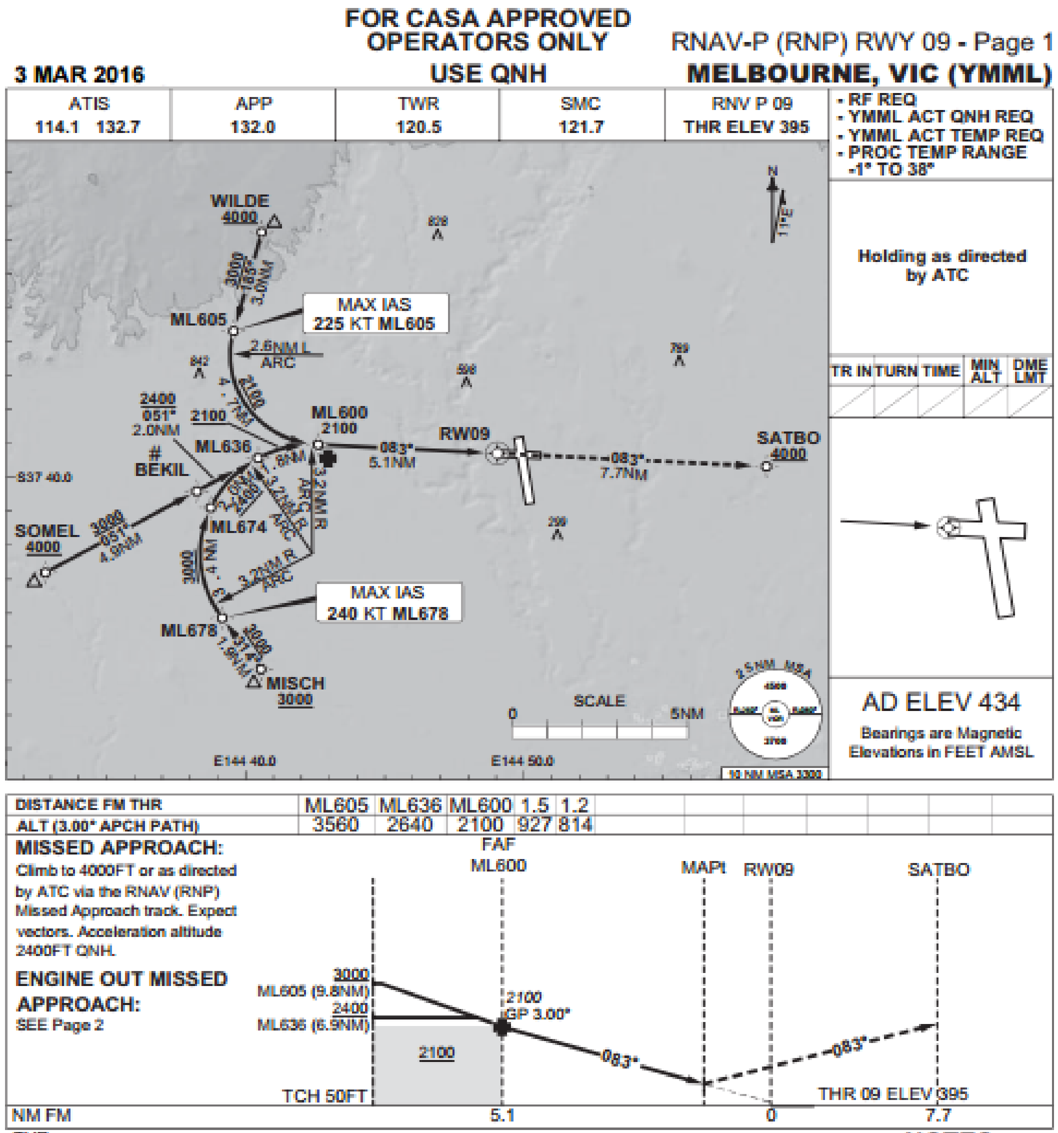
- Automatic Dependent Surveillance-Broadcast (ADS-B)
  - Aircraft position transmitted to ATC via communication link
  - Enables situational awareness of surrounding traffic to pilots
  - Several advantages over radar surveillance (e.g. cost, coverage, accuracy, maintenance).
  - Mandatory for IFR aircraft in Australia from 2 Feb 2017 (Civil Aviation Order 20.18)
  - Extended 3 years for private IFR aircraft (CASA)

ADS-B Ground Station at Broome, WA
Source: Airservices Australia

Current Status of GNSS Navigation in Aviation

- **Performance Based Navigation (PBN)**
  - Endorsed by ICAO for RNAV and RNP
  - **Area Nav. (RNAV):** navigation with aid of space based navaids (instead of DME, NDB, VOR).
    - CASA mandate for GNSS as primary means of navigation in Australia for IFR aircraft since 4 February 2016 → reduction in use of ground based navaids
  - **Required Nav. Position (RNP)**: equipment based navigation as well as performance monitoring of accuracy and integrity.
    - Uses RAIM algorithms inside receiver for monitoring. Alert issued if performance criteria not met
    - e.g. RNP 0.1 = 0.1NM accuracy 95% confidence
    - Enables precise and repeatable flight paths (curved approaches with reduced distance, fuel and flight time)
    - Avoids airborne holding, diversions and even cancellations.

RNAV-P (RNP) Approach: YMML RWY09



Current Status of GNSS Navigation in Aviation

- **SBAS**
  - Timely provision of correction and integrity information to aviation users in real-time
  - Regional atmospheric corrections, satellite orbit & clock errors and integrity messages via communication satellites
  - EGNOS (Europe), WAAS (US), MSAS (Japan) and NAVIC (India), Korea under development
  - Not available in Australia.
- **GBAS**
  - Mini-network of ground sensors at the airport vicinity
  - Calculate and transmit corrections and integrity information to aircrafts
  - Limited coverage area (e.g. certified for 23NM radius in Sydney)
  - Advantageous over ILS: serves multiple runways, available in all weather, low maintenance
  - Requires compatible avionic equipment on board aircraft
  - Enables CAT 1 Approach (CAT II/III pending regulatory certification)
  - Operational in Sydney (Melbourne under development).

Current Status of GNSS Navigation in Aviation (2)

Advanced (A)RAIM

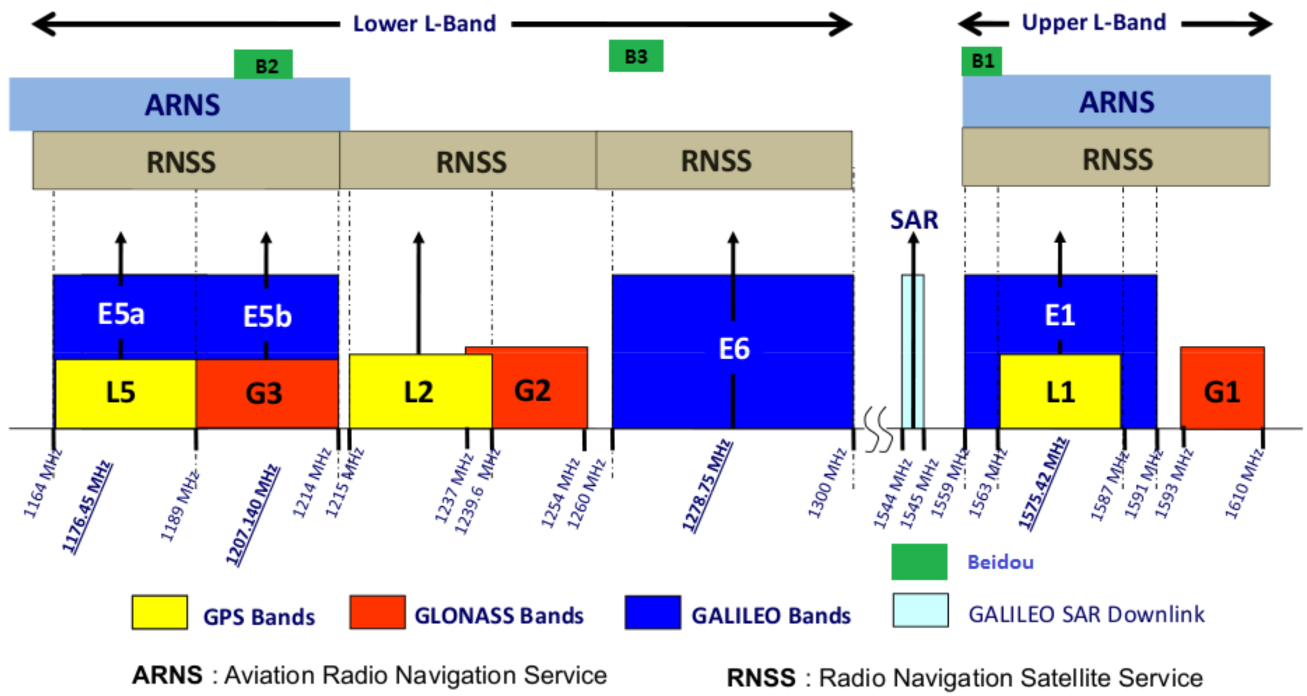
- Horizontal as well as vertical integrity monitoring
- Enables Localiser Performance with Vertical Guidance with decision height of 200ft (LPV-200)
- Similar to CAT I performance
- **Enabled** by Multi-frequency and Multi-constellation (MFMC) GNSS

Aircraft Phase of Flight	Accuracy		Integrity			Maximum Probabilities of Failure	
	2σ or 95%		Alert Limits		Time to Alert	Integrity	Continuity
	Vertical	Horizontal	Vertical	Horizontal			
NPA, Initial Approach, Departure	N/A	0.22–0.74km	N/A	1.95–3.7km	10–15 s	$10^{-7}/hr$	$10^{-4}/hr$
LNAV/ VNAV	20m	220m	50m	556m	10 s	$\mathbf{1.2 \times 10^{-7}/150\ s}$	$\mathbf{4.8 \times 10^{-4}/15\ s}$
LPV		***16m***		***40m***			
APV I			35m				
APV II	8m		20m		***6 s***		
LPV-200	***4m***		***35m***				
Precision Approach CAT I			***10m***				
Precision Approach CAT II/ III	< 2.9m	< 6.9m	5.3m	< 17m	< 2s	$< 10^{-9}/150\ s$	$< 4 \times 10^{-6}/15s$

MFMC GNSS ARNS signals

- **ARNS**
  - Aeronautical Radionavigation Service band
  - Protected for safety of life applications

- GPS
  - L1: 1572.42MHz
  - L5: 1176.45MHz
- **Beidou**
  - B1: 1561.098MHz
  - B2: 1207.14MHz
- **Galileo**
  - E1: 1575.42MHz
  - E5a: 1176.45MHz
  - E5b: 1207.14MHz



Source: http://www.navipedia.net/index.php/GNSS_signal

Error Treatment

Ionosphere Error

- Use dual frequency iono-free combination
- GPS: $P^{o_G} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2} P_{L1}^{o_G} - \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2} P_{L\%}^{o_G} = 2.260604 \cdot P_{L1}^{o_G} - 1.260604 \cdot P_{L5}^{o_G}$
- Beidou: $P^{p_C} = \frac{f_{B1}^2}{f_{B1}^2 - f_{B2}^2} P_{B1}^{p_C} - \frac{f_{B2}^2}{f_{B1}^2 - f_{B2}^2} P_{B2}^{p_C} = 2.487168 \cdot P_{B1}^{p_C} - 1.487168 \cdot P_{B2}^{p_C}$
- Galileo: Triple frequency combination (Deo and El-Mowafy 2016)

$$P^{q_E} = 2.314925 \cdot P_{E1}^{q_E} - 0.836269 \cdot P_{E5a}^{q_E} - 0.478656 \cdot P_{E5b}^{q_E}$$

Differential Code Bias (DCB)

- Hardware biases in the satellite and receiver due to frequency diff.
- Future NAV messages with broadcast inter-signal corrections (ISCs) as part of Civil NAV (CNAV)
- IGS DCBs used in this study (produced by DLR under the Multi-GNSS Experiment M-GEX))

Error Treatment (2)

Antenna Phase Centre Offset (PCO)

- Normally not required for aviation users (broadcast orbits referenced to satellite antenna phase centre)
- Required if using IGS orbits (used in this study)
- GPS offsets available in ANTEX file (applicable for L1-L2)
- Galileo and Beidou use M-GEX recommended values (taken from satellite drawings)
- Large variation for Beidou IGSO satellites (up to 3.9m) found in Dilssner et al. (2014)

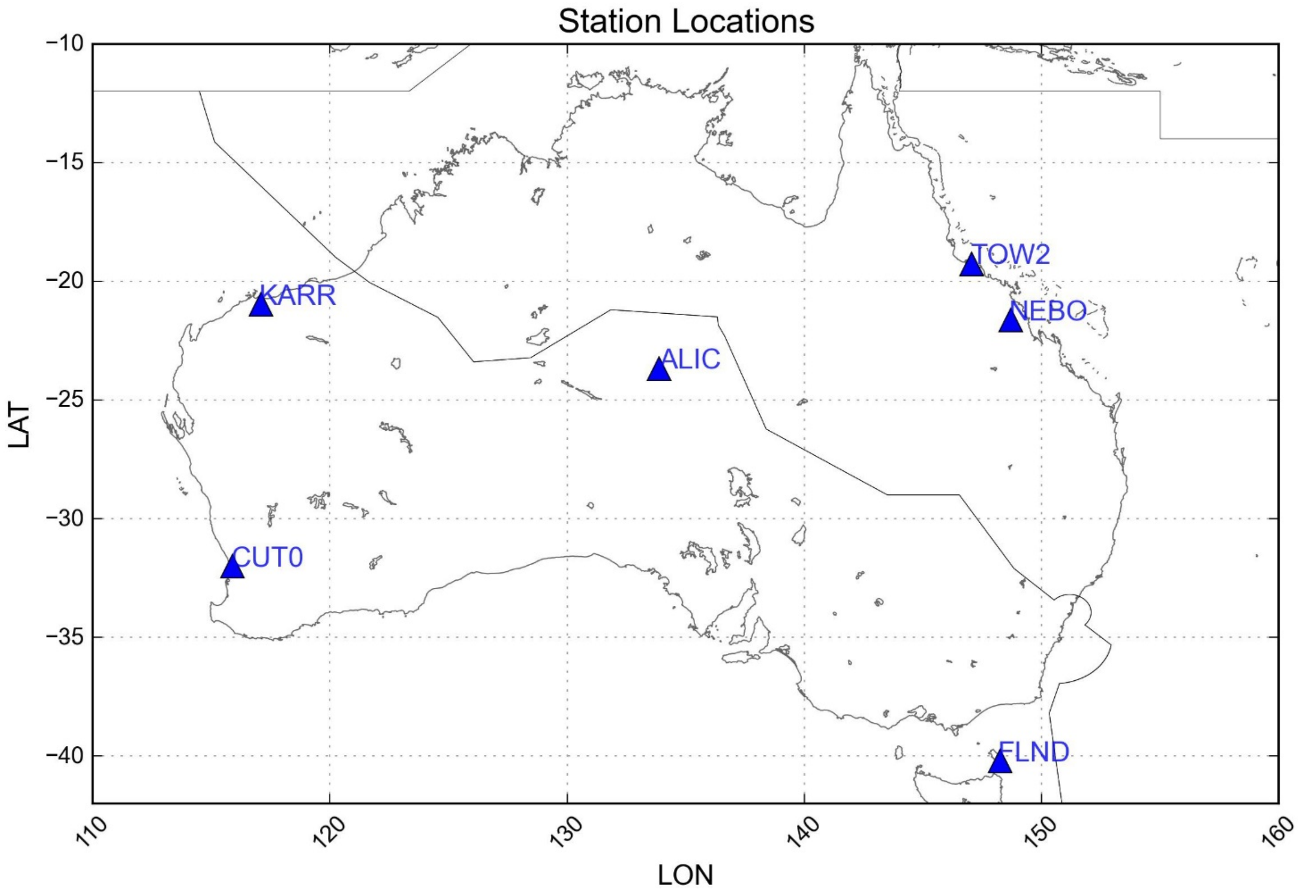
GNSS	PRNS	x-offset	y-offset	z-offset
Galileo IOV	E11, E12, E19, E20	-0.2	0.0	+0.6
Galileo FOC	E18, E14, E26, E22, E24, E30, E08, E09, E01, E02	+0.15	0.0	1.0
Beidou	All	+0.6	0.0	1.1

Troposphere

- Available for SBAS (e.g. UNB3 model for WAAS)
- GPT2 empirical model used in this study (suitable for implementing in receiver memory)

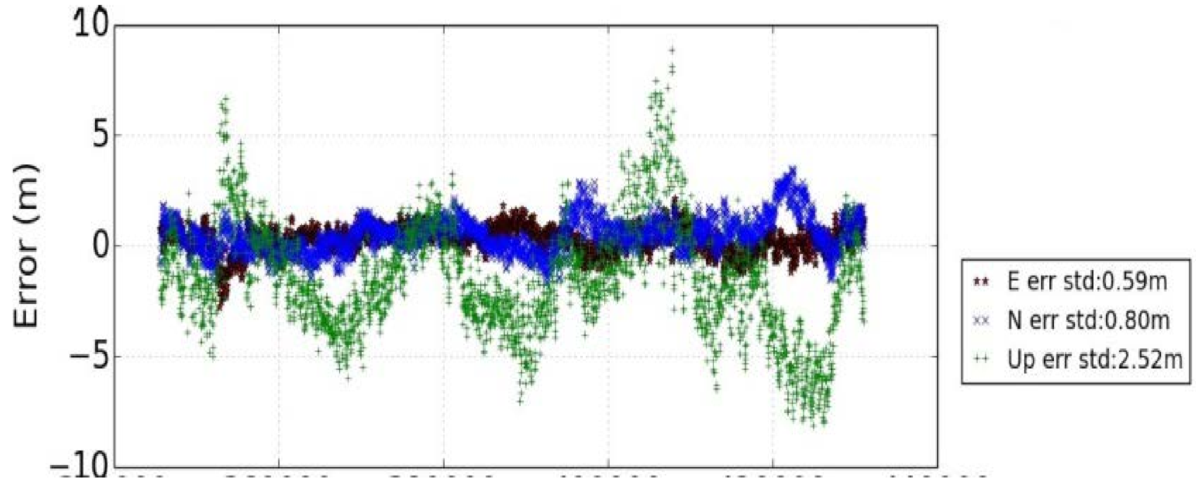
Testing and evaluation

- **Six CORS stations**
  - Distributed Australia wide
  - RINEX 3.02 data, 14 April 2016
  - Provides test case for aviation users
  - IGS M-GEX
    - CUT0
  - ARGN/AuScope
    - ALIC
    - NEBO
    - FLND
    - TOW2
    - KARR



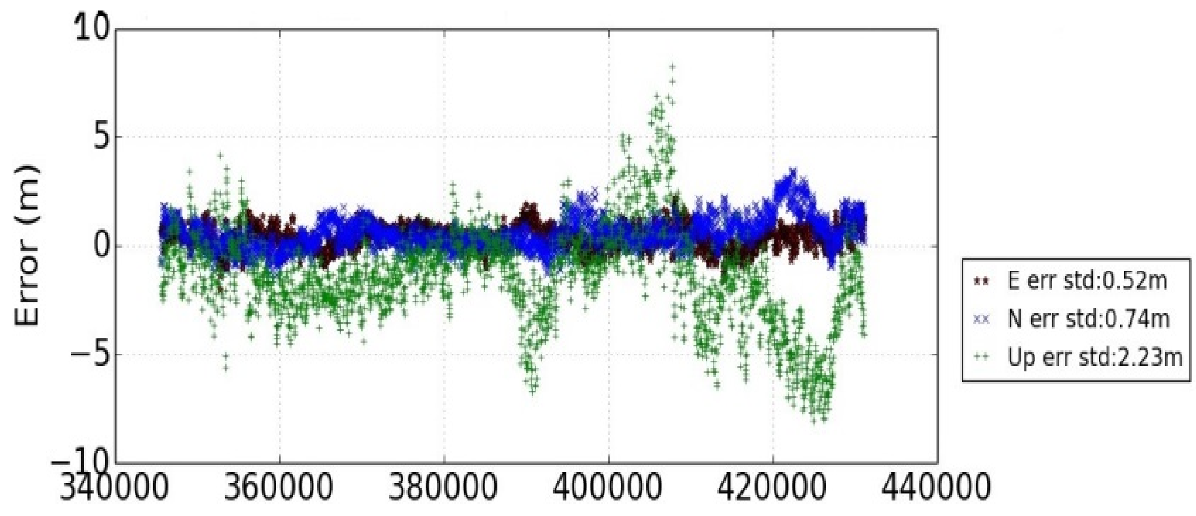
Impact of DCB - ALIC

Without DCB correction

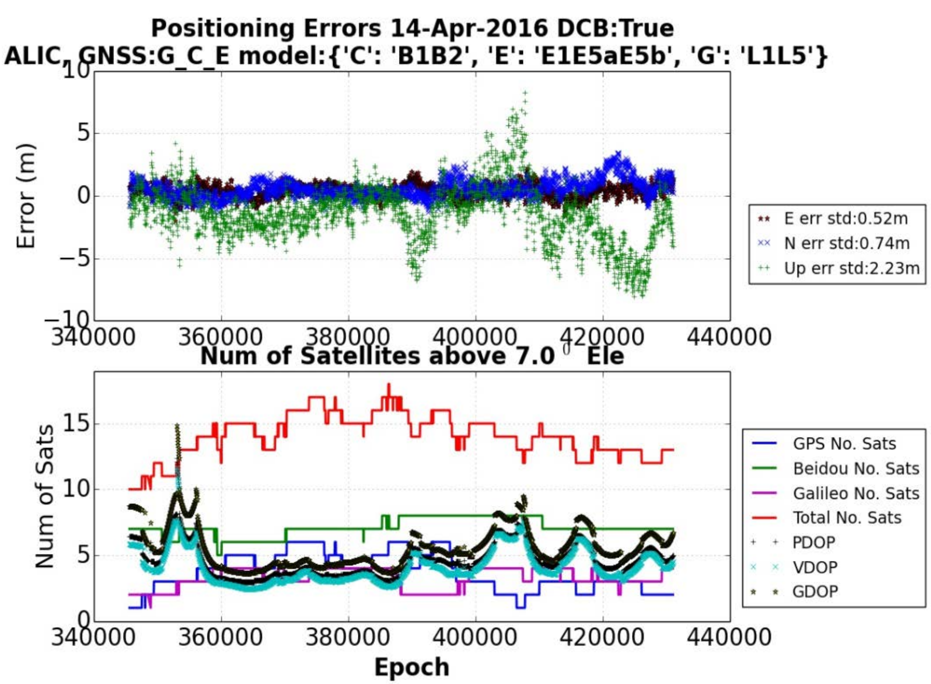


With DCB correction

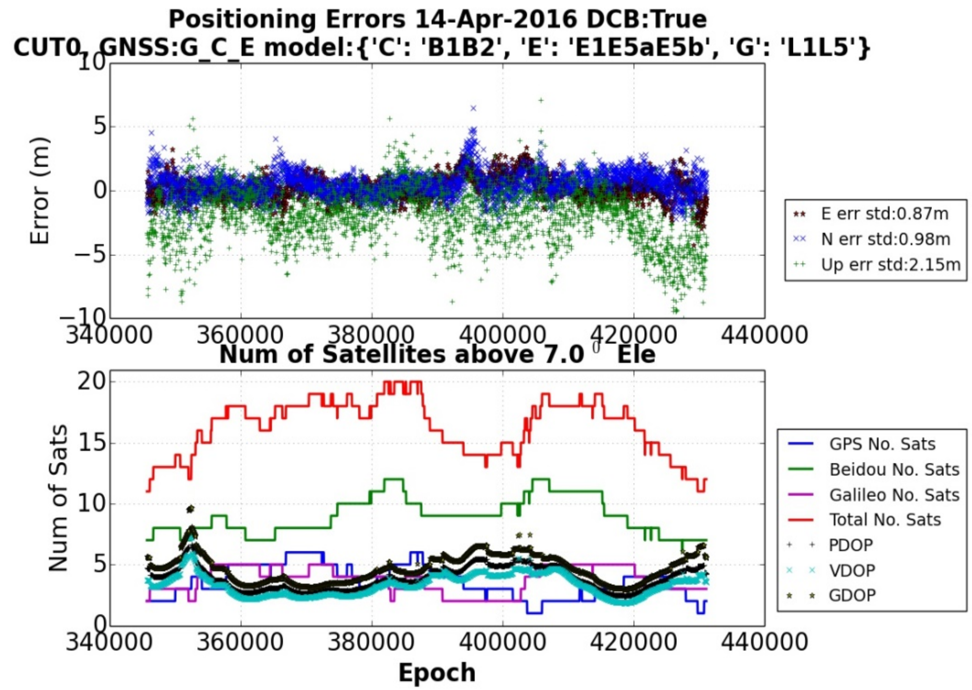
- Improvement in Std. by 12% (East), 8% (N) & 12% (Up)



Point Positioning Accuracy

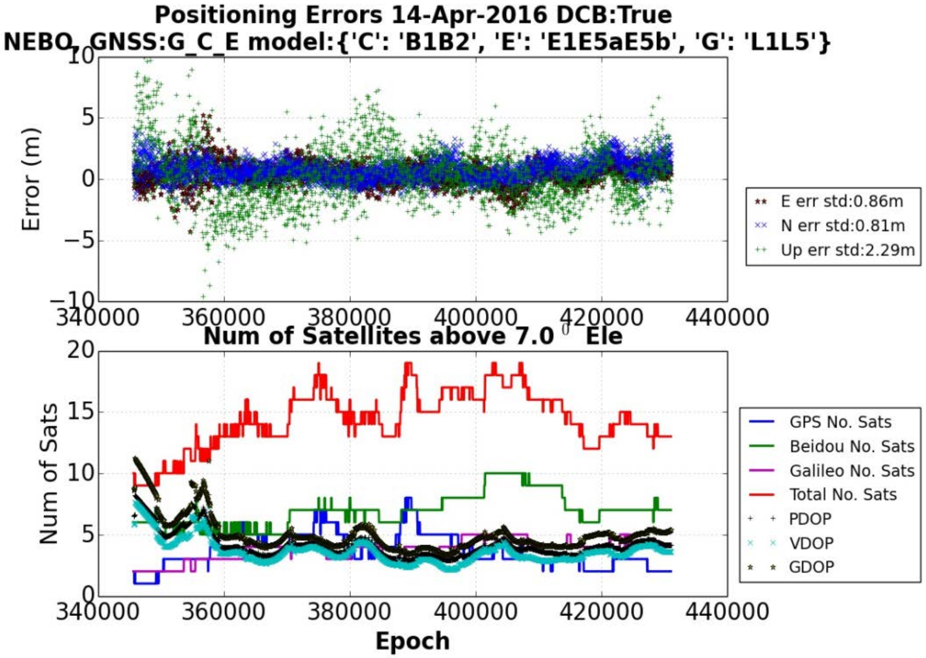


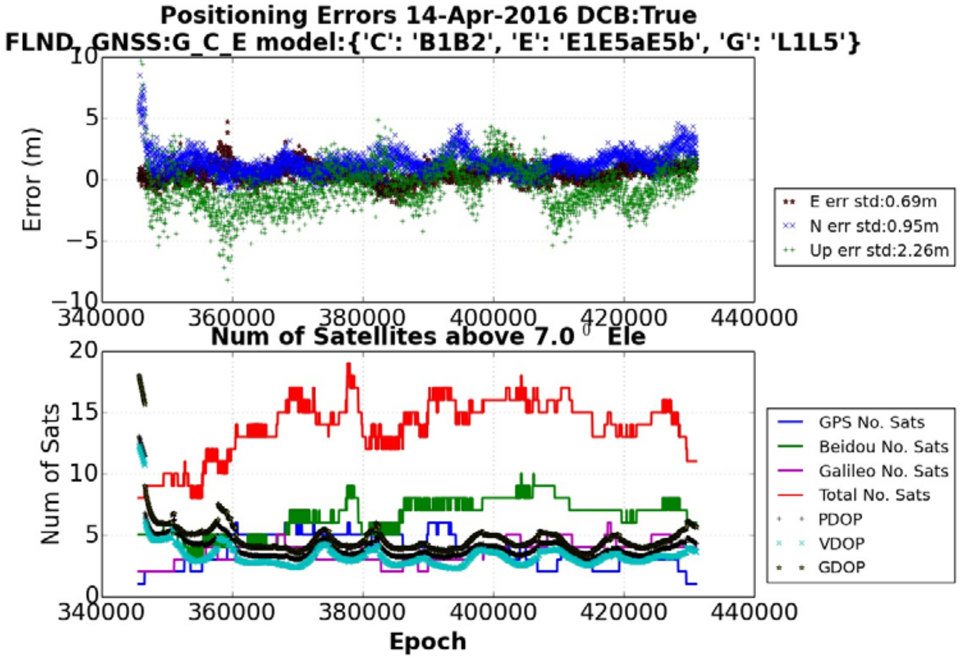
ALIC



CUT0

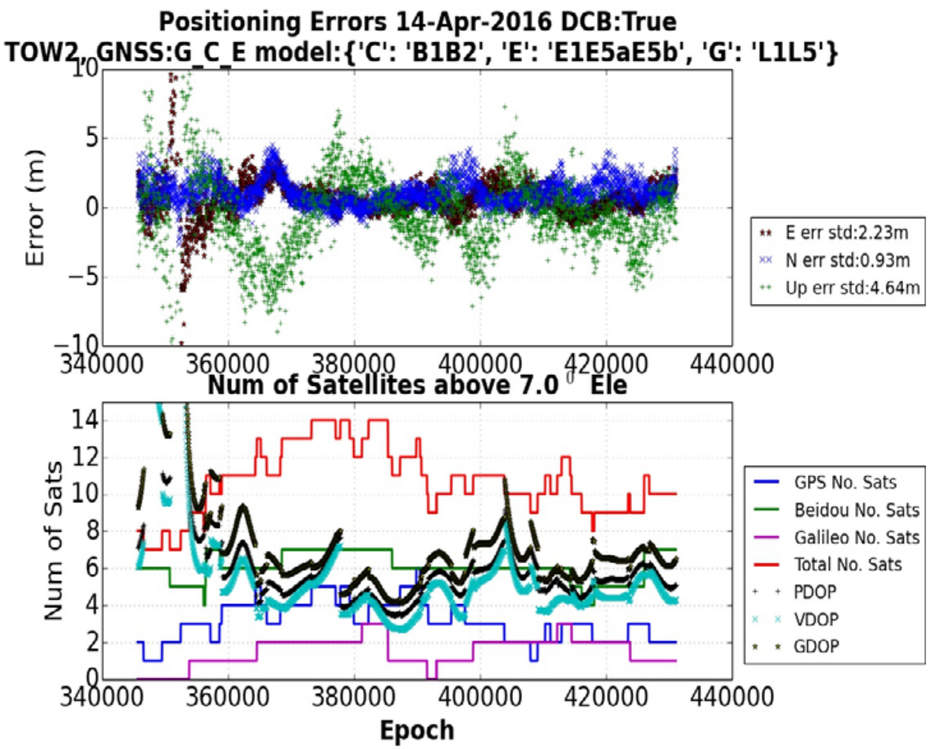
Point Positioning Accuracy (2)



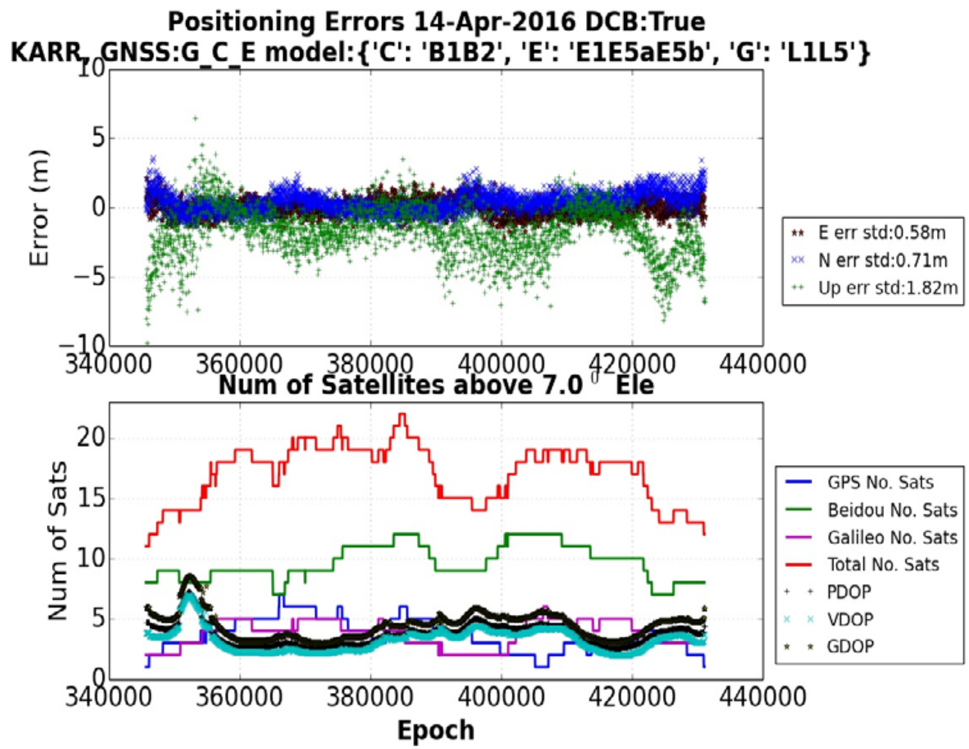


NEBO **FLND**

Point Positioning Accuracy (3)



TOW2



KARR

Summary of Accuracy

- LPV-200 horizontal requirements clearly met (2σ=16m)
- Vertical requirements (2σ=4m) fall short by ~0.5m

Station	Std E	Std N	Std Hor	Std Vert	RMS E	RMS N	RMS Hor	RMS Vert
ALIC	0.52	0.74	**0.58**	**2.23**	0.65	0.93	1.13	2.64
CUT0	0.87	0.98	**0.75**	**2.15**	0.89	1.12	1.43	2.86
NEBO	0.86	0.81	**0.73**	**2.29**	0.97	1.13	1.49	2.33
FLND	0.69	0.95	**0.88**	**2.26**	0.88	1.68	1.90	2.30
TOW2	2.23	0.93	**2.06**	**4.64**	2.38	1.45	2.78	4.70
KARR	0.58	0.71	**0.52**	**1.82**	0.58	0.82	1.01	2.47

Standard Deviation and RMS of positional error of with Multi-constellation ARNS data (GPS+Galileo+Beidou). All values are in units of metres (m).

Summary of availability and geometry

Availability

Five satellites for fault detection, six for detection and isolation of faulty satellite

With MFMC, two satellites required from each constellation to be useful

GNSS Constellation(s)	Stations					
	ALIC	CUT0	NEBO	FLND	TOW2	KARR
GPS	30.3	27.5	30.4	34.3	11.2	27.9
Galileo	0.0	33.0	12.0	14.5	0.0	31.6
Beidou	**100**	**100**	**100**	86.4	97.3	**100**
GPS+Beidou	**100**	**100**	**100**	**100**	**100**	**100**
GPS+Galileo	95.6	96.6	94.4	93.6	54.4	95.3
GPS+Galileo+Beidou	**100**	**100**	**100**	**100**	**100**	**100**

Percentage availability of at least 5 ARNS satellites

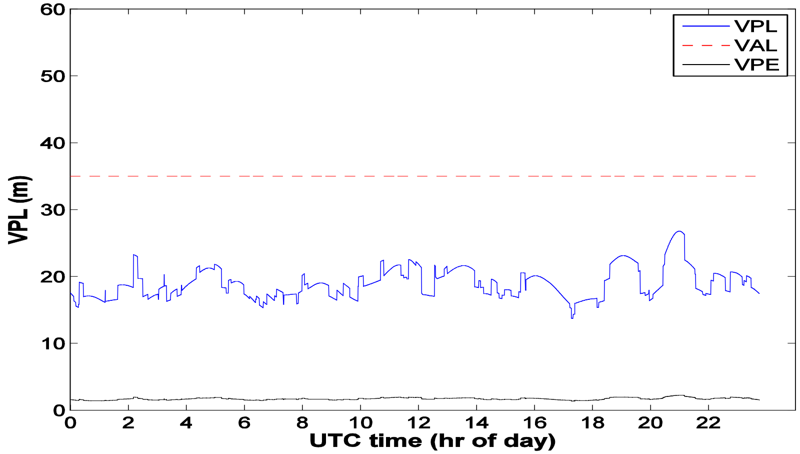
Geometry

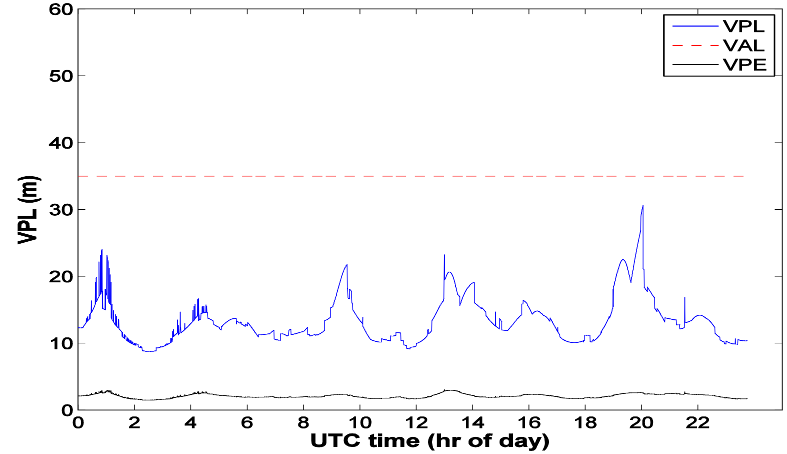
Average DOP and percentage of time DOPs < 5

Station	PDOP		VDOP		GDOP	
	Mean	< 5.0 (%)	Mean	< 5.0 (%)	Mean	< 5.0 (%)
ALIC	4.59	71.08	4.13	76.44	5.59	42.82
CUT0	3.89	89.12	3.36	97.33	4.71	60.55
NEBO	4.15	86.63	3.64	91.72	5.04	66.09
FLND	3.99	90.38	3.34	97.68	4.81	66.69
TOW2	6.91	32.57	6.07	55.67	8.39	9.06
KARR	3.72	95.30	3.26	96.07	4.50	69.15

Integrity Monitoring

- Integrity monitoring with Multiple Hypothesis Solution Separation (MHSS) Blanch et al., 2013
  - Use of real URA data from broadcast NAV message
  - **VPE** computed as difference between known and computed height
  - **VPL** bound with a confidence level derived from the integrity risk requirement
  - **ARAIM** availability by testing that VPL is bounded by a selected vertical alert limit (VAL) i.e. fraction of time when when VPL<VAL. (VAL = 35m for LPV-200)
  - If VPE>VPL: misleading information event
  - if VPE>VAL: hazardously misleading information event (El-Mowafy and Yang, 2016)





Integrity monitoring with *VPE*, *VPL* and *VAL* at stations CUT0 (left) and TOW2 (right) using GPS+Galileo+Beidou

Conclusions

- Evaluated accuracy and availability with MFMC GNSS data (with precise orbit and clock corrections, M-GEX DCBs & Antenna Offsets)
- GPT2 for Tropospheric model suitable for real-time implementation
- Positional accuracy and availability at west coast stations (CUT0, KARR) better than other stations.
- LPV-200 horizontal criteria is met easily. However the vertical accuracy achieved falls short by ~0.5m
- Beidou dominant solution (100% coverage at all except FLND, TOW2 → outside coverage area)
- Beidou recommended satellite phase antenna offsets by IGS M-GEX have large differences from calibrated values
- Tests with integrity monitoring a typical day showed 100% availability where the computed VPE < VPL < VAL
- Four Galileo satellites recently launched will improve results