

測位航法学会 2020年度 次世代高精度衛星測位研究委員会

Technology Evolution of Multi-Constellation RTK



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RTK (1992 -> 2021)

Precise Positioning with GNSS

Type		RTK		PPP-RTK	PPP	
		RTK	NRTK		PPP-AR	PPP
Practical Product/Service		1992 ~ (Trimble 4000)	1998 ~ (SAPOS)	2015 ~ (Trimble RTX Fast)	2011 ~ (Trimble RTX)	1998 ~ (NavCom StarFire)
Correction Data		OSR (RTK RS)	OSR (VRS, FKP, MAC)	SSR (Orbit, Clock, STEC, ZTD, Code Bias, Phase Bias)	Orbit, Clock, Code Bias, Phase Bias, (VTEC)	Orbit, Clock, Code Bias
Typical Specs	Coverage	Local, BL ^{*3} < 10 km	Regional		Global	
	Accuracy (H-RMSE)	1 cm + 1 ppm	~ 2 cm	2 ~ 6 cm	2 ~ 5 cm	5 ~ 20 cm
	TTF	< 60 s ^{*1}	< 60 s ^{*1}	< 60 s ^{*1}	15 min ^{*2}	30 min ^{*2}

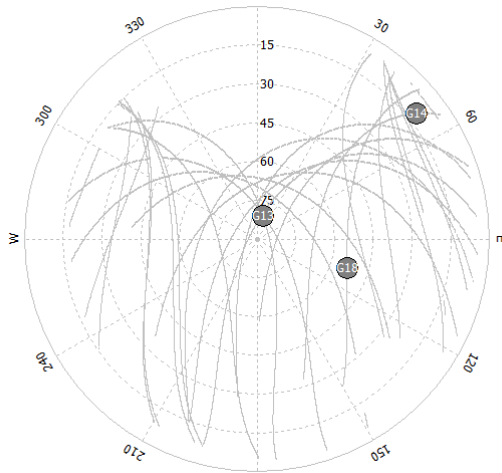
*1 RTK Initialization Time, *2 PPP Convergence Time *3 Baseline Length

Evolution of RTK (1992 -> 2021)

- **RTK-GPS -> Multi-Constellation RTK**
 - GPS, GLONASS, BDS2 (2012), Galileo (2016), QZSS (2018), BDS3 (2020), NavIC (?)
 - Dual Freq. (L1+L2) -> Triple/Quad Freq. (L1+L2+L5...)
- **Algorithm Improvement**
 - LAMBDA (1994), TCAR (1998), GLO IFB (2007), PAR (2011), FF-RT (2013) ...
 - RTKLIB (2009 ~) as an Open Source RTK S/W
- **Format and Protocol Standardization**
 - RTCM2.1 (1994), CMR (1996), RTCM3.0 (2004), RTCM3.2 (2013)
 - NTRIP (2003) over mobile Internet
- **RTK Receiver and Antenna Cost Reduction**
 - Trimble, Topcon, Hexagon (Leica/NovAtel), JAVAD, BDStar, UniStrong, CHCNav ...
 - u-blox M8P (2016)/F9P (2018), Septentrio mosaic (2019) ...
- **Expanded RTK Correction Services (in Japan)**
 - NRTK: Jenoba (2002), NGDS (2002) based on GSI GEONET
 - RTK RS: NTT Docomo (2019), Softbank (2019)/ALES (2020)

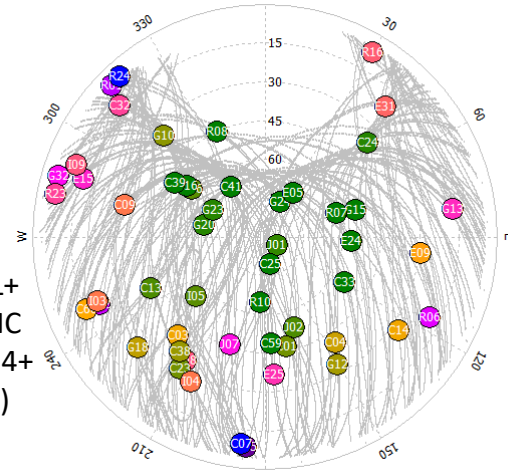
RTK-GPS -> RTK-GNSS (1992 -> 2021)

1992-11-01 NAGANO [1]



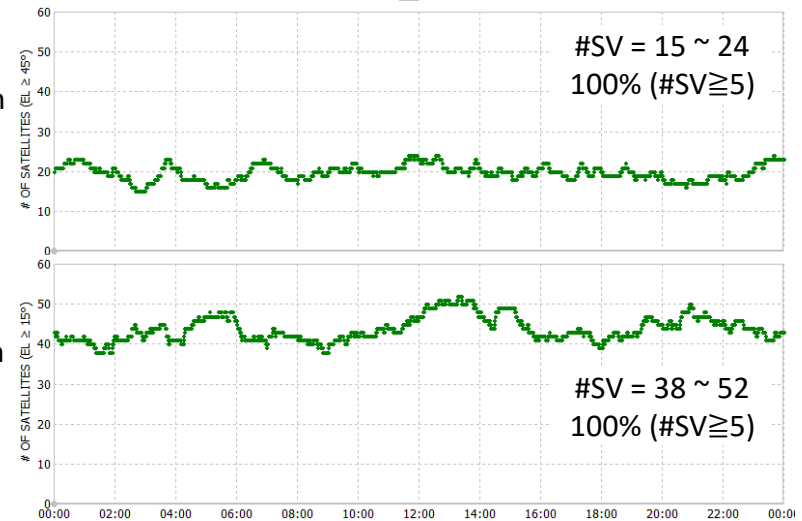
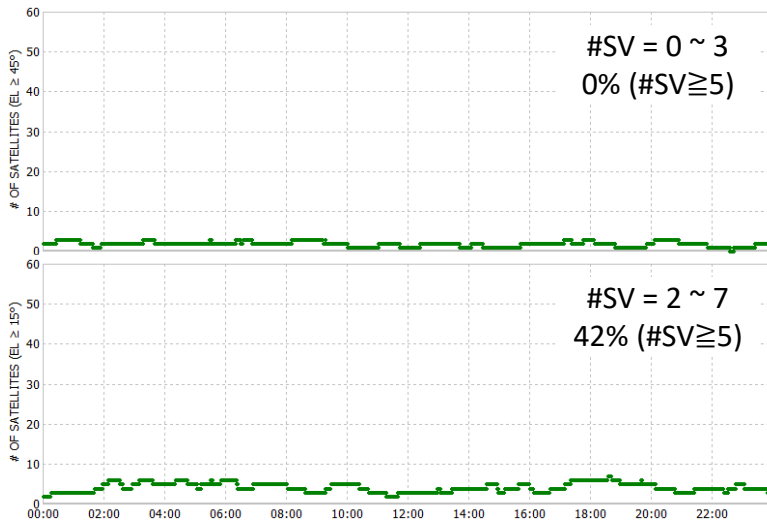
GPS
(#SV = 19)

2021-01-31 YAMANASHI



GPS+GLO+GAL+
QZS+BDS+NavIC
(#SV = 31+22+24+
4+43+7 = 131)

of Visible Satellites



[1] IGS USUD, <https://gdc.cddis.eosdis.nasa.gov/gps/data/daily>

RTK Receiver (1992 -> 2021)

Trimble 4000 SSE [1]



Signal tracking: 18 (9 + 9) CH
(GPS: L1C/A, L1P, L2P,
AS on: L1P/L2P cross-correlation)
Fast Static, **RTK**
Protocol: NMEA, RTCM SC-104
cm accuracy (up to 10 km)
Price: \$270,000 [3]

Septentrio mosaic-X5 [2]



Signal tracking: 448 CH
(GPS: L1C/A, L1P(Y), L2C, L2P(Y), L5,
GLONASS: L1C/A, L2C/A, L2P, L3 CDMA,
BDS: B1I, B1C, B2a, B2I, B3,
Galileo: E1, E5a, E5b, E5 AltBOC,
QZSS: L1C/A, L2C, L5, NavIC: L5,
SBAS: L1C/A, L5, L-band)
RTK, RAIM, PPP SECORX, Moving base RTK
Protocol: SBF, NMEA, RINEX, RTCM2/3, CMR/CMR+
Max update rate: 100 Hz
Horizontal accuracy: 0.6 cm + 0.5 ppm
Initialization time: 7 s
Price: \$985 (Development Kit) [4]

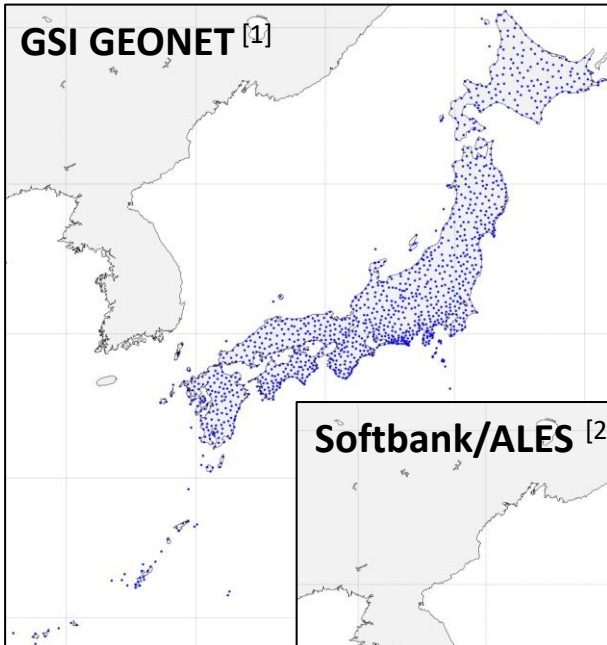
[1] Trimble, Series 4000 Receiver Reference, Rev. A, 1995

[2] Septentrio, mosaic-X5: Compact, multi-constellation GNSS receiver Datasheet, 2020

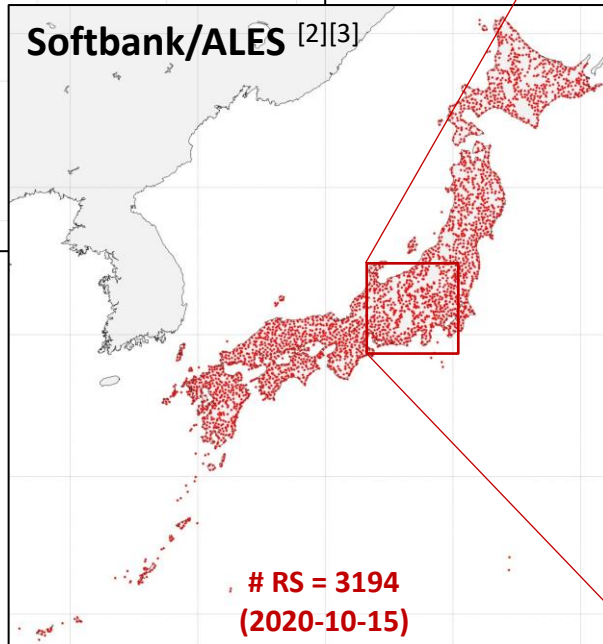
[3] 岡本, RTK測位の実力とその活用事例, FOSS4G 2018 TOKYO, 2018

[4] <https://www.digikey.com/en/products/detail/septentrio-inc/410331P3161/12503899>

RTK RS (Reference Station) (2021)

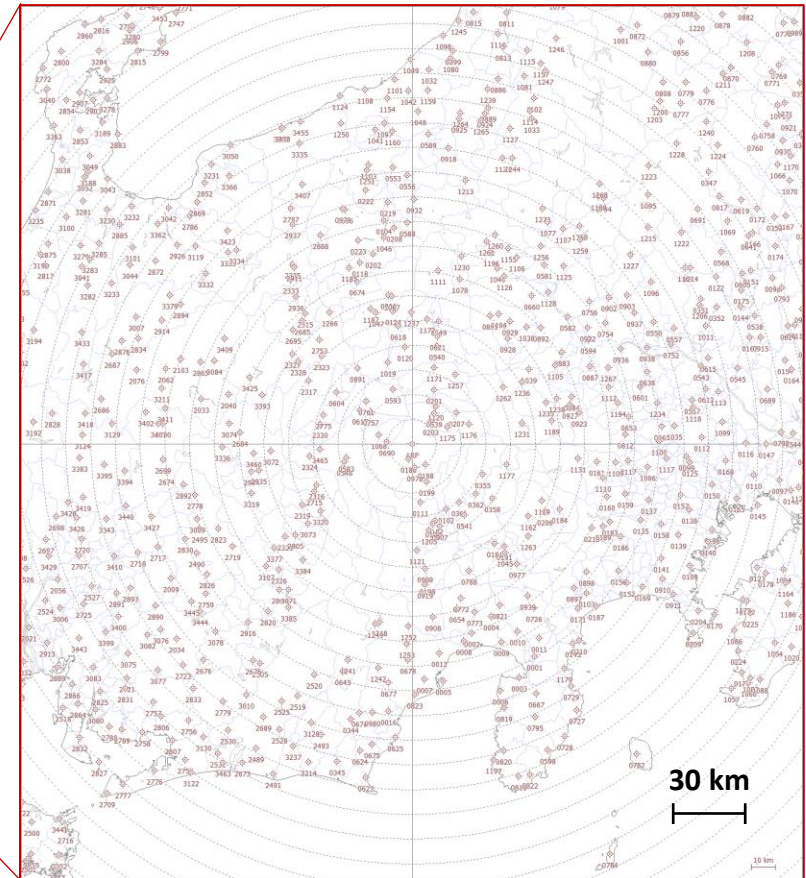


RS = 1322
(2020-11-14)



RS = 3194
(2020-10-15)

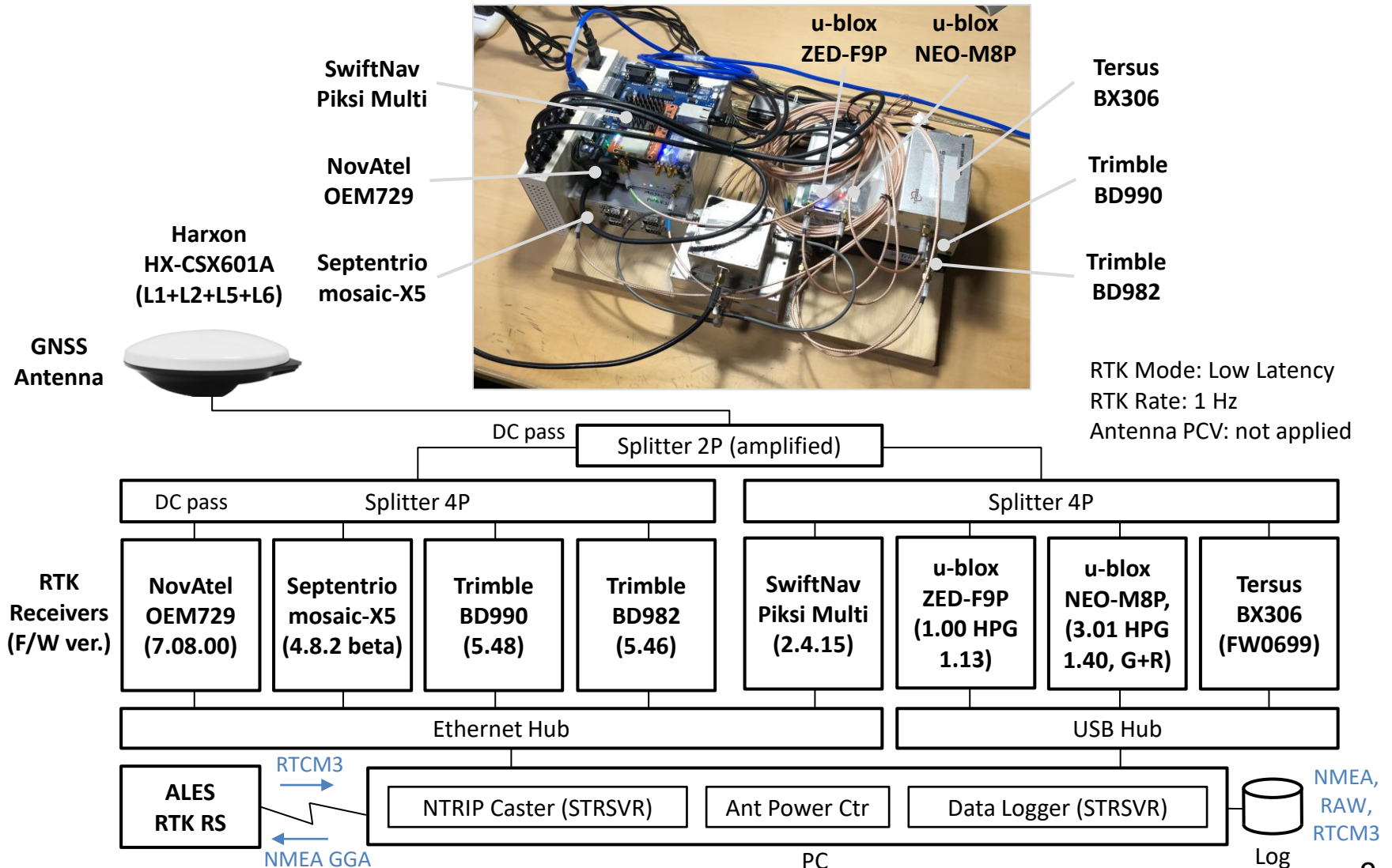
Receiver: Septentrio AsteRx SB Galileo: E1, E5a, E5b, E5 AltBOC
Antenna: Unknown QZSS: L1C/A, L2C, L5
GPS: L1C/A, L2P(Y), L2C, L5 BDS: B1I, B2I (PRN1-37)
GLONASS: L1C/A, L2C/A, L2P RTCM 3.1/3.2, NTRIP



[1] <https://terras.gsi.go.jp>, [2] <https://www.softbank.jp/biz/iot/service/ichimill>, [3] <https://ales-corp.co.jp>

RTK Performance (2021)

Test Configuration



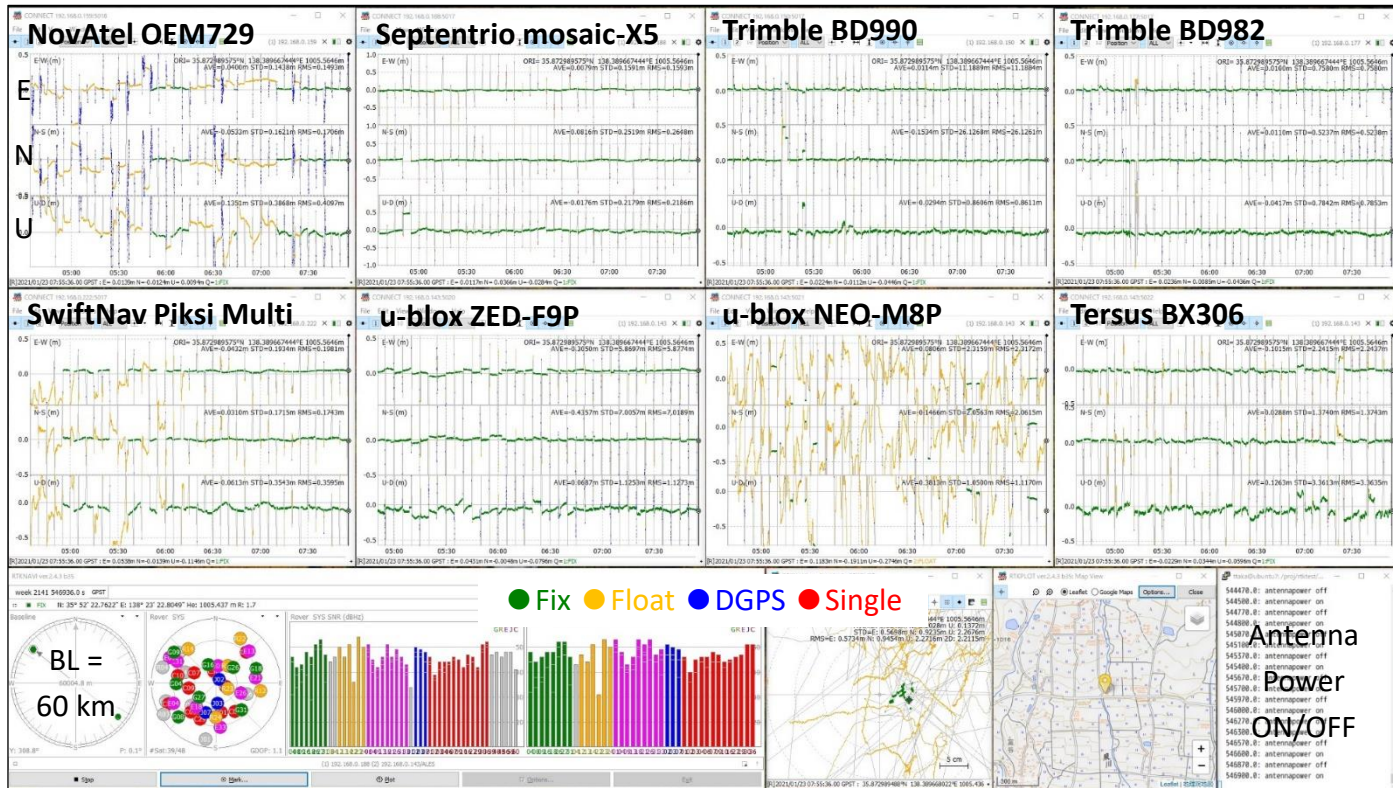
Target RTK Receivers

RTK Receiver	# of CH	Max Rate (Hz)	Supported Signals																								OEM Price													
			GPS					GLONASS					Galileo				QZSS				BDS					NavIC SBAS														
			L1		L2		L5	L1		L2		L3	E1	E5		E6	L1		L2		L5	L6	B1		B2			B3	L5	S	L1		L5	L						
			CA	PY	C	PY		C	CA	P	CA			P	a		b	ab	E6	CA			C	S	C	I					C	I			a	b	ab	CA	L5	
NovAtel OEM729	555	100	Y	-	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y _{*1}	Y	Y	Y	Y	Y	-	Y	Y	-	Y	Y	Y	\$900 _{*5 *8}		
Septentrio mosaic-X5	448	100	Y	Y	-	Y	Y	Y	Y	-	Y	Y	Y	Y	Y	Y	Y	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-	-	Y	Y	-	Y	Y	Y	\$985 _{*7}			
Trimble BD990	336	50	Y	-	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y _{*1}	Y	Y	Y	Y	Y	-	Y	Y	-	Y	Y	Y	\$999 _{*5}		
Trimble BD982	220	50	Y	-	-	Y	Y	Y	Y	-	Y	-	Y	Y	Y	Y	Y	-	Y	-	Y	Y	Y	-	Y _{*3}	-	Y _{*3}	-	-	-	-	-	-	-	Y	Y	Y	\$1150 _{*5}		
SwiftNav Piksi Multi	44	20	Y	-	-	-	Y	-	Y	-	Y	-	Y	Y	-	Y	-	-	Y	-	-	Y	-	-	Y _{*4}	-	Y _{*4}	-	-	-	-	-	-	-	Y	-	-	\$695 _{*7}		
u-blox ZED-F9P	184	20	Y	-	-	-	Y	-	Y	-	Y	-	-	Y	-	Y	Y	-	-	Y	-	Y	-	-	Y _{*4}	-	Y _{*4}	-	-	-	-	-	-	-	Y	-	-	\$199 _{*6}		
u-blox NEO-M8P	72	8	Y	-	-	-	-	Y	-	-	-	-	-	-	-	-	-	-	-	Y	-	-	-	-	Y _{*2 *3}	-	-	-	-	-	-	-	-	-	-	-	-	\$149 _{*6}		
Tersus BX306	384	20	Y	-	-	Y	Y	-	Y	-	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	Y _{*3}	-	Y _{*3}	-	-	-	-	-	-	-	-	-	-	-	\$1850 _{*7}	
ALES RTK RS	-	1	Y	-	-	Y	Y	Y	Y	-	Y	Y	-	-	Y	Y	Y	Y	Y	Y	-	-	Y	Y	-	Y _{*4}	-	Y _{*4}	-	-	-	-	-	-	-	-	-	-	-	\$347/year

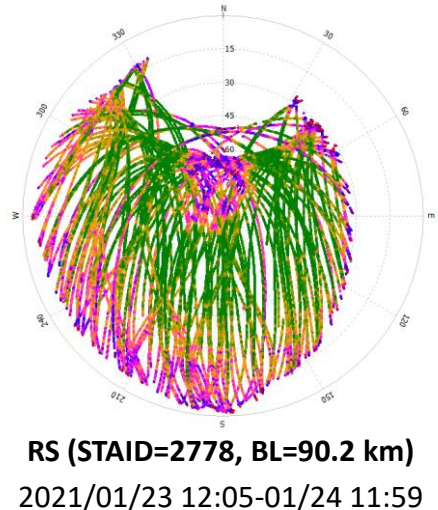
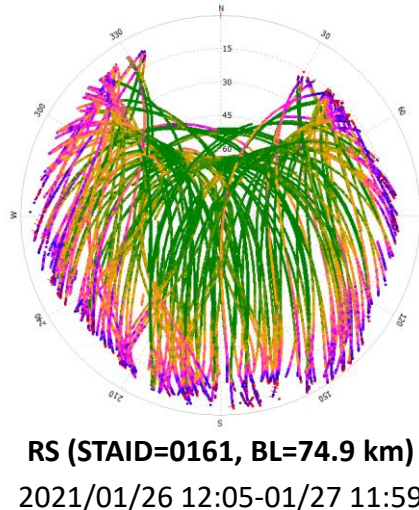
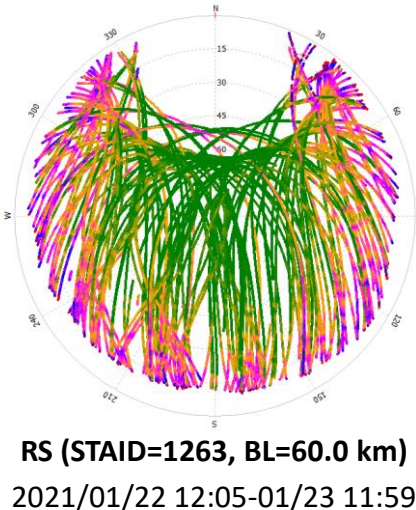
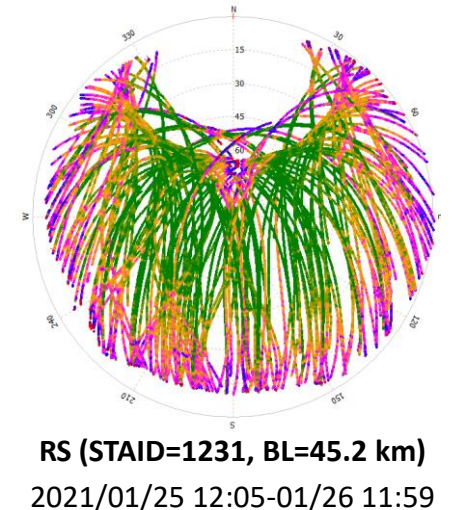
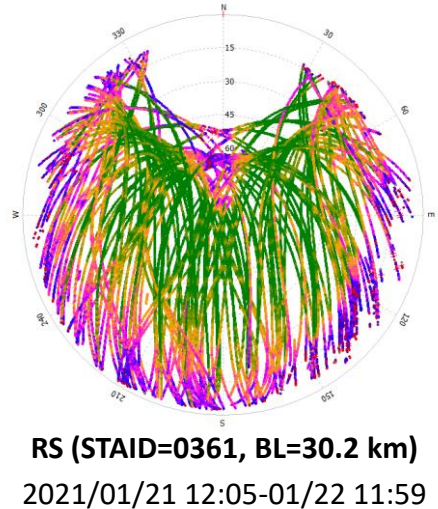
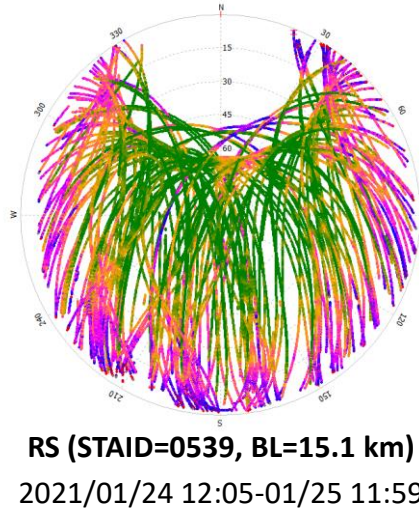
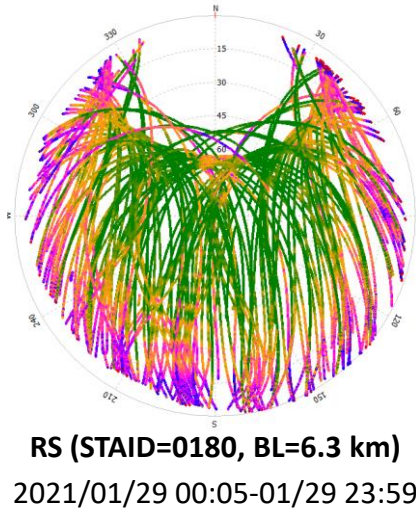
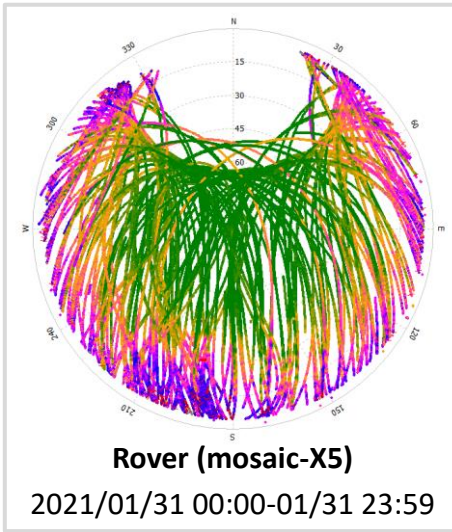
Y: Support, *1 L6 pilot signal only, *2 Exclusive use, *3 PRN1-30, *4 PRN1-37, *5 Discount In China, *6 Receiver Module, *7 Receiver Kit, *8 Max Rate 5Hz

Static RTK Test (Open Sky)

- **Rover:** Stationary, open sky, RF {on (270s) + off (30s)} x 287 cycles (24H)
- **RS:** ALES, BL = 6 km, 15 km, 30 km, 45 km, 60 km, 75 km, 90 km
- **Evaluation:** RMSE, TTFF (95%), Miss-Fix Rate



Rover/RS Data Quality



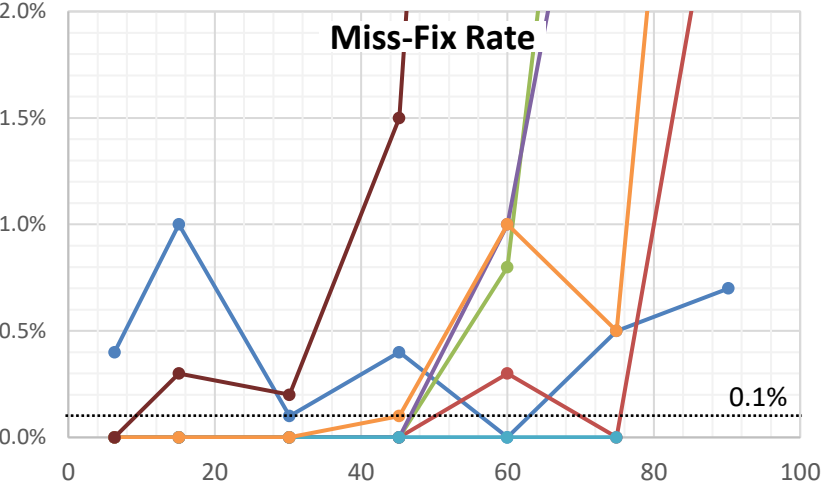
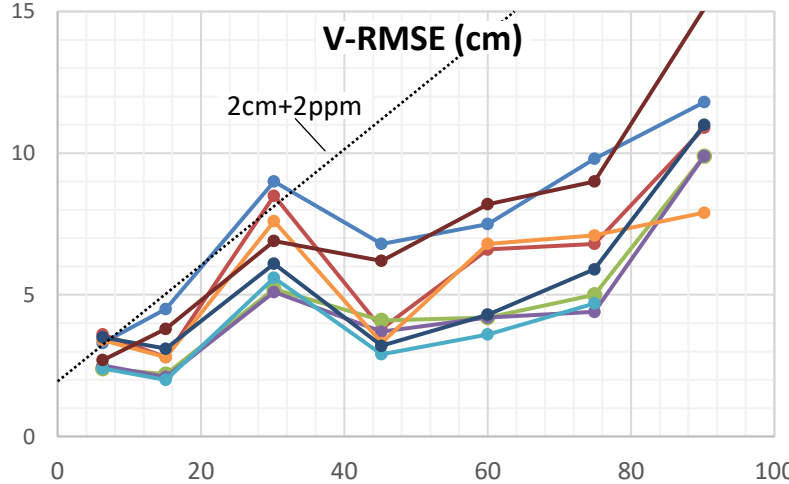
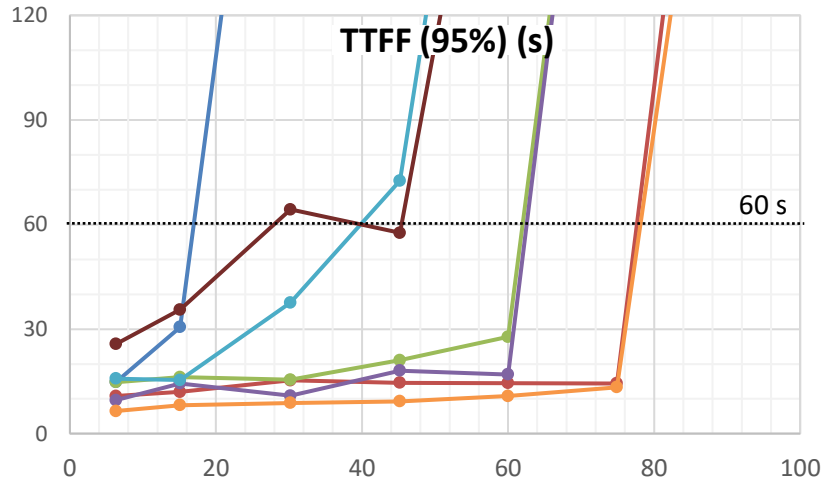
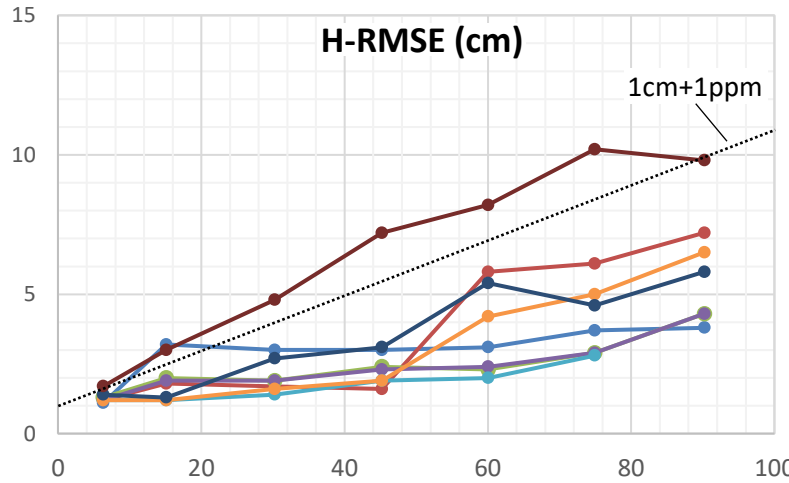
L1 C/N0: ...45...40...35...30...25 <25 (dBHz)

Static RTK Test Result (1/2)

Test Case	1-A		1-B		1-C		1-D		1-E		1-F		1-G	
RS STAID	0180		0539		0361		1231		1263		0161		2778	
BL	6.3 km		15.1 km		30.2 km		45.2 km		60.0 km		74.9 km		90.2 km	
	RMSE	TTFF	RMSE	TTFF	RMSE	TTFF	RMSE	TTFF	RMSE	TTFF	RMSE	TTFF	RMSE	TTFF
NovAtel OEM729	1.1cm	14.8s	3.2cm	30.6s	3.0cm	>270s	3.0cm	>270s	3.1cm	>270s	3.7cm	>270s	3.8cm	>270s
	3.3cm	0.4%	4.5cm	1.0%	9.0cm	0.1%	6.8cm	0.4%	7.5cm	0.0%	9.8cm	0.5%	11.8cm	0.7%
Septentrio mosaic-X5	1.2cm	10.8s	1.8cm	12.0s	1.7cm	15.3s	1.6cm	14.6s	5.8cm	14.5s	6.1cm	14.4s	7.2cm	>270s
	3.6cm	0.0%	2.8cm	0.0%	8.5cm	0.0%	3.8cm	0.0%	6.6cm	0.3%	6.8cm	0.0%	10.9cm	3.0%
Trimble BD990	1.3cm	14.8s	2.0cm	16.2s	1.9cm	15.5s	2.4cm	21.1s	2.3cm	27.8s	2.9cm	>270s	4.3cm	>270s
	2.4cm	0.0%	2.2cm	0.0%	5.2cm	0.0%	4.1cm	0.0%	4.2cm	0.8%	5.0cm	5.1%	9.9cm	14.1%
Trimble BD982	1.2cm	9.6s	1.9cm	14.4s	1.9cm	10.9s	2.3cm	18.1s	2.4cm	17.0s	2.9cm	>270s	4.3cm	>270s
	2.5cm	0.0%	2.1cm	0.0%	5.1cm	0.0%	3.7cm	0.0%	4.2cm	1.0%	4.4cm	3.7%	9.9cm	16.3%
SwiftNav Piksi Multi	1.2cm	15.8s	1.2cm	15.4s	1.4cm	37.6s	1.9cm	72.6s	2.0cm	>270s	2.8cm	>270s	-	>270s
	2.4cm	0.0%	2.0cm	0.0%	5.6cm	0.0%	2.9cm	0.0%	3.6cm	0.0%	4.7cm	0.0%	-	-
u-blox ZED-F9P	1.2cm	6.5s	1.2cm	8.2s	1.6cm	8.8s	1.9cm	9.3s	4.2cm	10.8s	5.0cm	13.3s	6.5cm	235.6s
	3.4cm	0.0%	2.8cm	0.0%	7.6cm	0.0%	3.3cm	0.1%	6.8cm	1.0%	7.1cm	0.5%	7.9cm	6.0%
u-blox NEO-M8P	1.4cm	>270s	1.3cm	>270s	2.7cm	>270s	3.1cm	>270s	5.4cm	>270s	4.6cm	>270s	5.8cm	>270s
	3.5cm	3.4%	3.1cm	2.3%	6.1cm	5.5%	3.2cm	4.2%	4.3cm	4.5%	5.9cm	6.5%	11.0cm	4.0%
Tersus BX306	1.7cm	25.7s	3.0cm	35.6s	4.8cm	64.3s	7.2cm	57.6s	8.2cm	224.6s	10.2cm	183.6s	9.8cm	>270s
	2.7cm	0.0%	3.8cm	0.3%	6.9cm	0.2%	6.2cm	1.5%	8.2cm	9.1%	9.0cm	3.6%	15.1cm	17.1%

RMSE = upper: horizontal, lower: vertical (fix), TTFF = upper: TTFF (95%), lower: miss-fix rate, Red: TTFF (95%) > 60s, miss-fix rate > 0.1%

Static RTK Test Result (2/2)

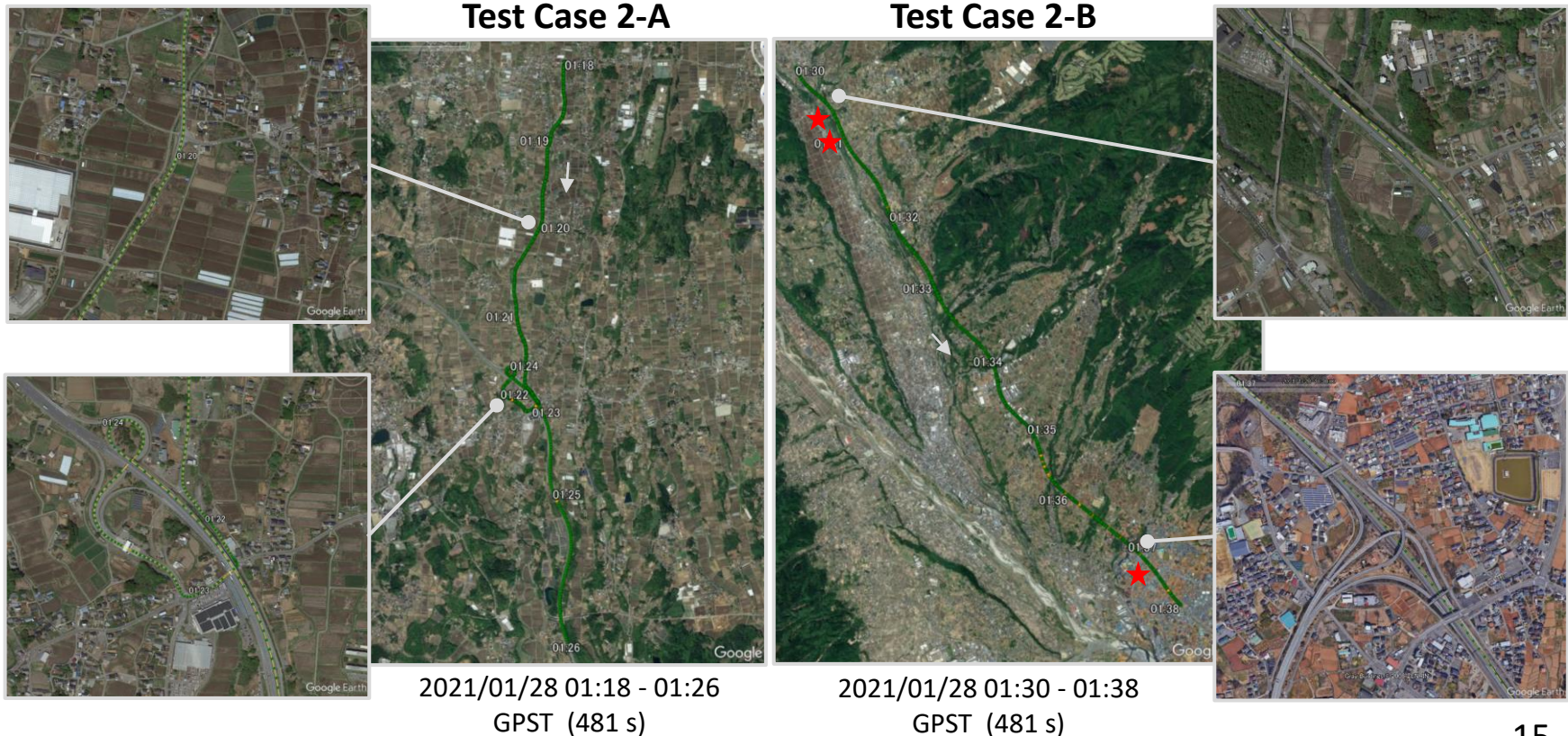


- NovAtel OEM729
- Trimble BD990
- SwiftNav Piksi Multi
- u-blox NEO-M8P
- Septentrio mosaic-X5
- Trimble BD982
- u-blox ZED-F9P
- Tersus BX306

Dynamic RTK Test 1 (Open Sky)

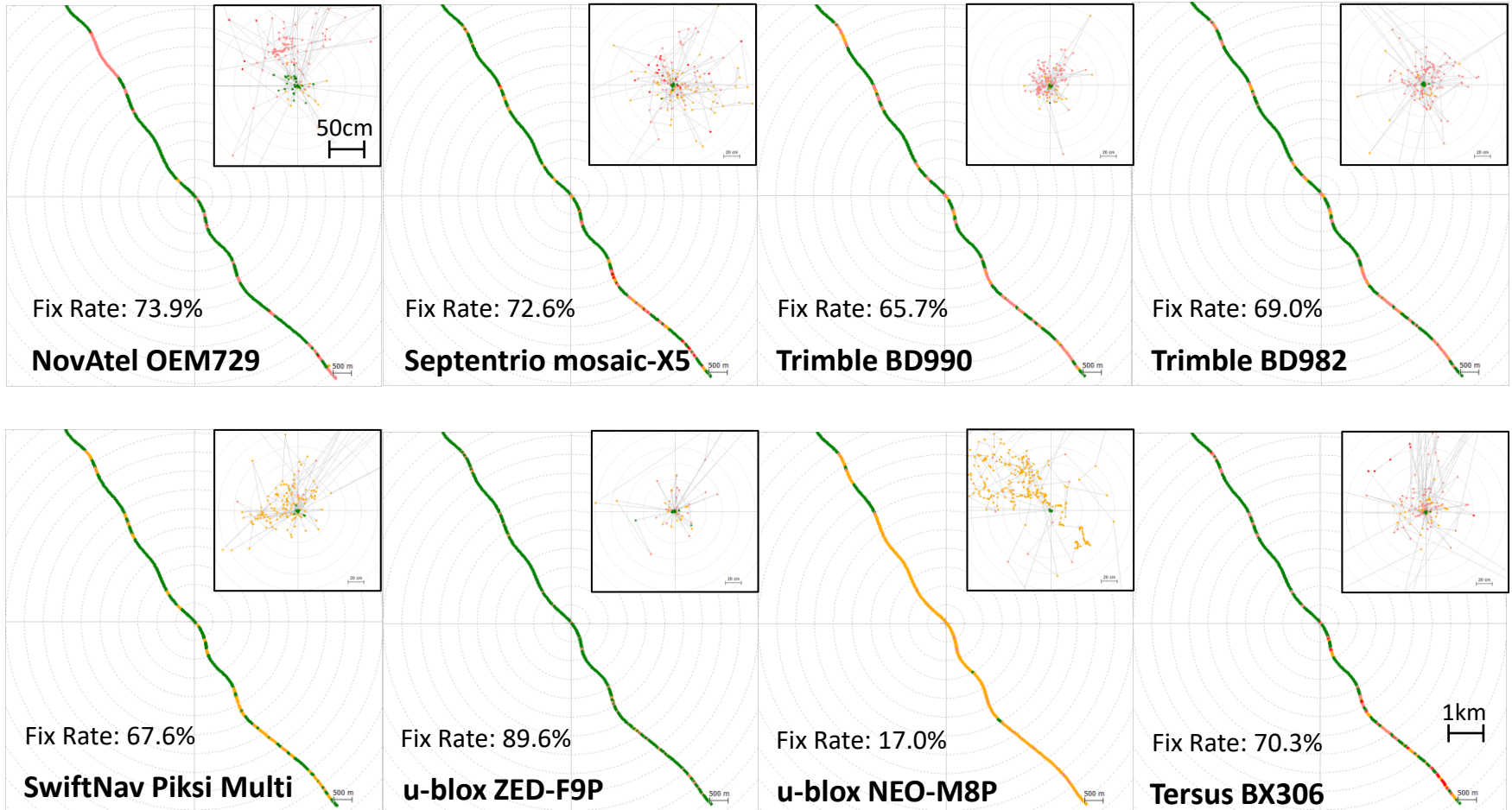
- **Rover:** Driving along open-sky roads (country and Chuo highway)
- **RS:** ALES, BL = 0 ~ 7 km (auto hand-over to the nearest RS)
- **Evaluation:** RMSE, Fix Rate (ref: PPK and combined solutions)

★ : RS Hand-Over



Dynamic RTK Test 1 Result (1/2)

Test Case 2-B, BL = 0.1 - 6.7 km (with RS hand-over)



● Fix ● Float ● DGPS ● Single

Dynamic RTK Test 1 Result (2/2)

Test Case	2-A		2-B	
RS STAID	0180		0978, 0188, 0199, 0102	
BL	1.9 - 5.4 km		0.1 - 6.7 km (with hand-over)	
	RMSE	Fix Rate	RMSE	Fix Rate
NovAtel OEM729	0.7 cm	93.8%	10.3 cm	73.9%
	1.6 cm		8.6 cm	
Septentrio mosaic-X5	0.8 cm	95.2%	1.6 cm	72.6%
	1.8 cm		1.7 cm	
Trimble BD990	1.0 cm	95.0%	1.7 cm	65.7%
	1.2 cm		1.4 cm	
Trimble BD982	0.8 cm	94.6%	1.5 cm	69.0%
	1.1 cm		1.6 cm	
SwiftNav Piksi Multi	0.6 cm	94.8%	1.4 cm	67.6%
	1.1 cm		1.7 cm	
u-blox ZED-F9P	0.8 cm	97.3%	3.1 cm	89.6%
	1.4 cm		2.8 cm	
u-blox NEO-M8P	0.9 cm	62.6%	65.5 cm	17.0%
	2.0 cm		54.0 cm	
Tersus BX306	15.4 cm	49.7%	1.3 cm	70.3%
	86.4 cm		6.2 cm	

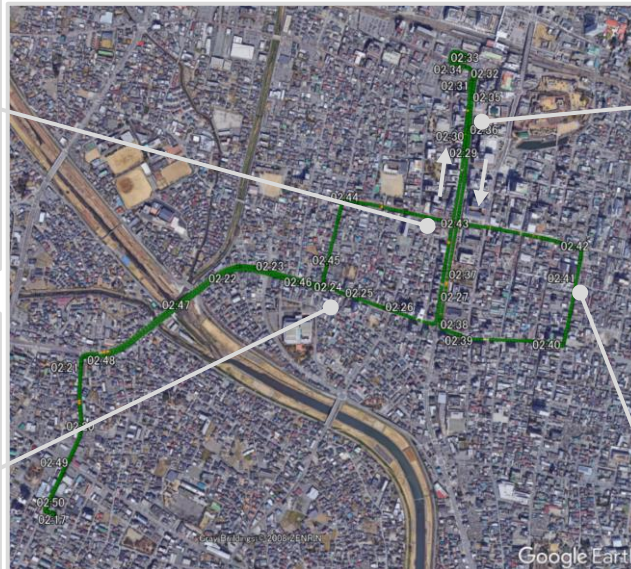
RMSE = upper: horizontal, lower: vertical (fixed solutions), **Bold = Best and second best**

Dynamic RTK Test 2 (Urban)

- **Rover:** Driving along urban streets around Kofu station
- **RS:** ALES, BL = ~3 km, ~14 km, ~30 km, ~60 km (w/o RS hand-over)
- **Evaluation:** RMSE, Fix Rate (ref: PPK and combined solutions)



Test Case 3-A, 3-B, 3-C, 3-D



3-A: 2021/01/28 02:15 - 02:51 GPST (2139 s)

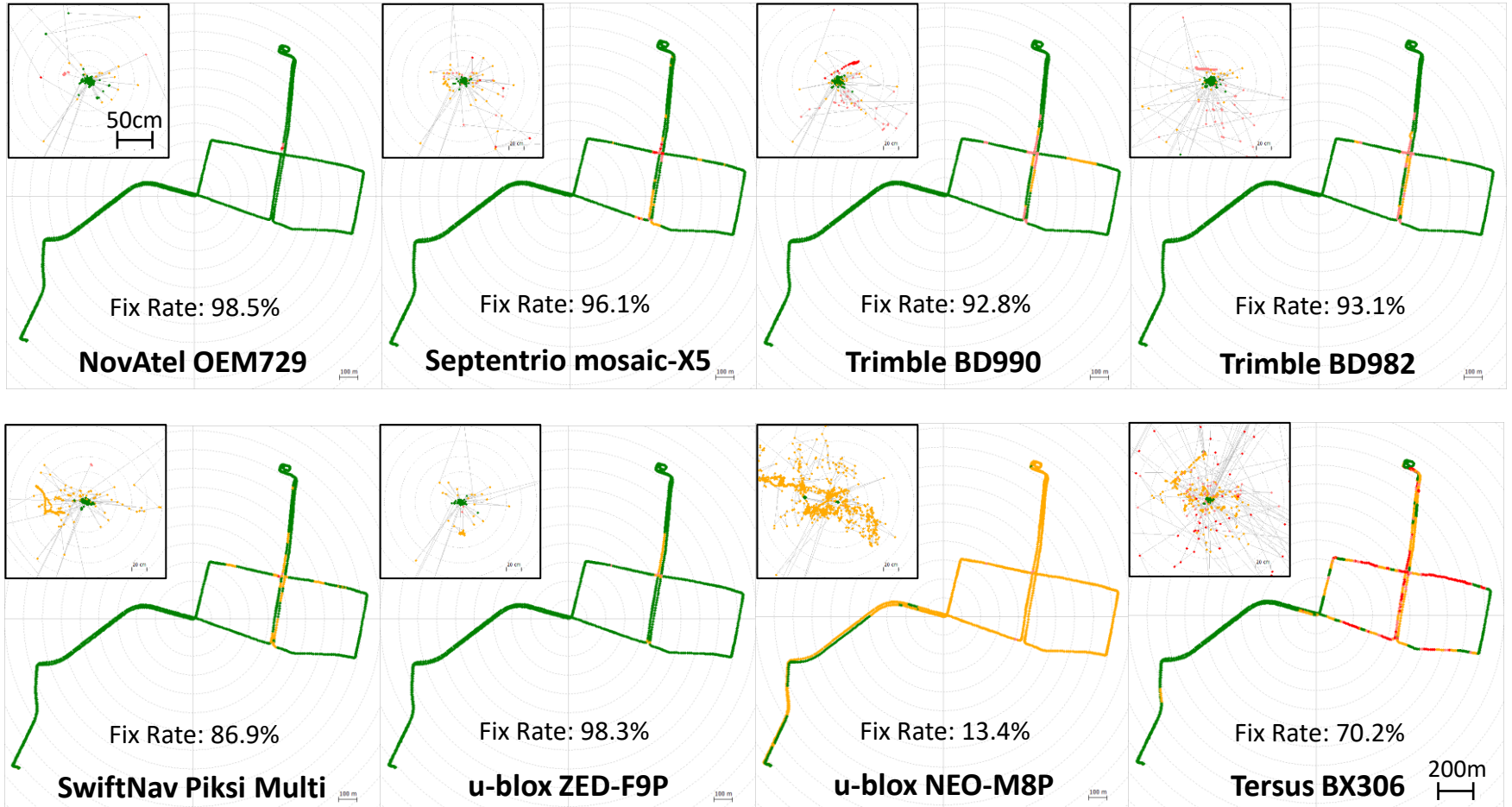
3-B: 2021/01/28 02:51 - 03:29 GPST (2278 s)

3-C: 2021/01/28 03:30 - 04:02 GPST (1919 s)

3-D: 2021/01/28 04:03 - 04:37 GPST (2062 s)

Dynamic RTK Test 2 Result (1/2)

Test Case 3-A, BL = 2.3 - 4.2 km (w/o RS hand-over)



● Fix ● Float ● DGPS ● Single

Dynamic RTK Test 2 Result (2/2)

Test Case	3-A		3-B		3-C		3-D	
RS STAID	0361		1205		1045		2324	
BL	2.3 - 4.2 km		13.3 - 15.4 km		29.0 - 30.2 km		59.5 - 61.1 km	
	RMSE	Fix Rate	RMSE	Fix Rate	RMSE	Fix Rate	RMSE	Fix Rate
NovAtel OEM729	4.3 cm	98.5%	5.9 cm	91.3%	21.3 cm	94.5%	16.8 cm	97.4%
	3.7 cm		14.0 cm		23.6 cm		36.2 cm	
Septentrio mosaic-X5	1.3 cm	96.1%	2.7 cm	97.1%	3.1 cm	96.1%	6.1 cm	88.6%
	2.6 cm		5.6 cm		6.4 cm		9.2 cm	
Trimble BD990	1.9 cm	92.8%	25.9 cm	88.5%	14.3 cm	91.7%	16.3 cm	80.7%
	4.9 cm		236.7 cm		29.0 cm		34.9 cm	
Trimble BD982	8.2 cm	93.1%	2.4 cm	91.9%	3.6 cm	87.4%	5.5 cm	77.0%
	26.3 cm		6.9 cm		5.7 cm		12.0 cm	
SwiftNav Piksi Multi	1.7 cm	86.9%	4.0 cm	61.7%	3.8 cm	91.3%	3.4 cm	89.0%
	3.5 cm		16.1 cm		8.6 cm		8.0 cm	
u-blox ZED-F9P	1.3 cm	98.3%	2.2 cm	97.7%	2.0 cm	98.6%	9.9 cm	98.4%
	2.1 cm		5.8 cm		5.9 cm		8.9 cm	
u-blox NEO-M8P	77.8 cm	13.4%	182.9 cm	5.4%	220.4 cm	0.9%	-	0.0%
	156.4 cm		272.3 cm		57.3 cm		-	
Tersus BX306	6.0 cm	70.2%	13.9 cm	58.4%	5.6 cm	54.5%	9.3 cm	45.3%
	4.8 cm		19.9 cm		11.9 cm		8.1 cm	

RMSE = upper: horizontal, lower: vertical (fixed solutions), **Bold = Best and second best**

Summary and Future Work

- **RTK (1992 -> 2021)**
 - Multi-constellation RTK with all GNSS becomes common
 - Cost reduction of RTK receivers accelerated (< \$1,000)
 - Lower cost RTK correction service recently introduced in Japan
- **RTK Performance (2021)**
 - Static and dynamic RTK performance evaluated with various receivers
 - RTK performance much depends on selection of receivers
 - RTK over 50 km BL seems practical by some receivers
 - Performance degradation due to RS hand-over by some receivers
 - Need further evaluation of new RTK correction service quality
- **Future Work**
 - Improved RTK algorithms involved in next version RTKLIB
 - INS/RTK integration with MEMS-IMU (~ \$500, < 1.5 °/hr)
 - Need more reliable AR algorithms (miss-fix rate < 10⁻⁵)



Aceinna IMU3832A ^[1]
Bias Instability: 1.3 °/hr
ARW: 0.08 °/√hr

[1] <https://www.aceinna.com/inertial-systems/IMU>