農業食料工学会セミナー2016

オープンソースRTKソフトウェア RTKLIBの開発と応用

Development and Application of OSS RTK software RTKLIB

Tokyo Univ. of Marine Science and Technology
Tomoji TAKASU

2016-12-20 @Tokyo, Japan

自己紹介

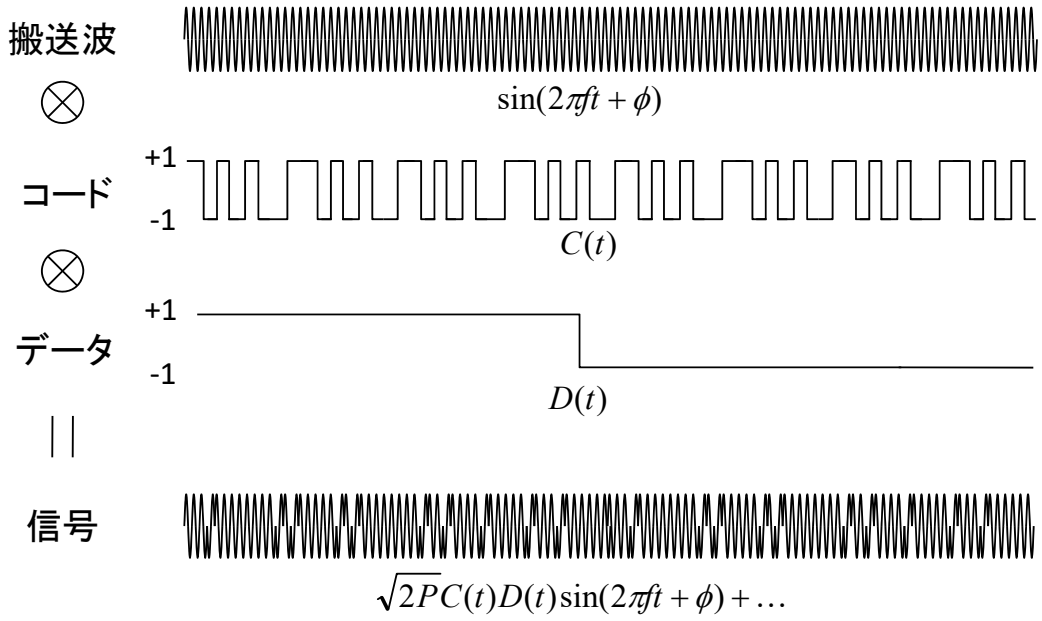
- ソフトウェア・エンジニア
  - 宇宙開発分野：衛星搭載、地上系 等
  - 得意分野：解析系 …
  - コードは20年以上書いている …
- 現在の所属と仕事
  - 東京海洋大学客員研究員 (10年)
    GPS/GNSS精密測位技術
    衛星軌道の精密決定
  - ライトハウステクノロジー・アンド・コンサルティング (4年)
    実用準天頂衛星 (QZSS) システム開発

内容

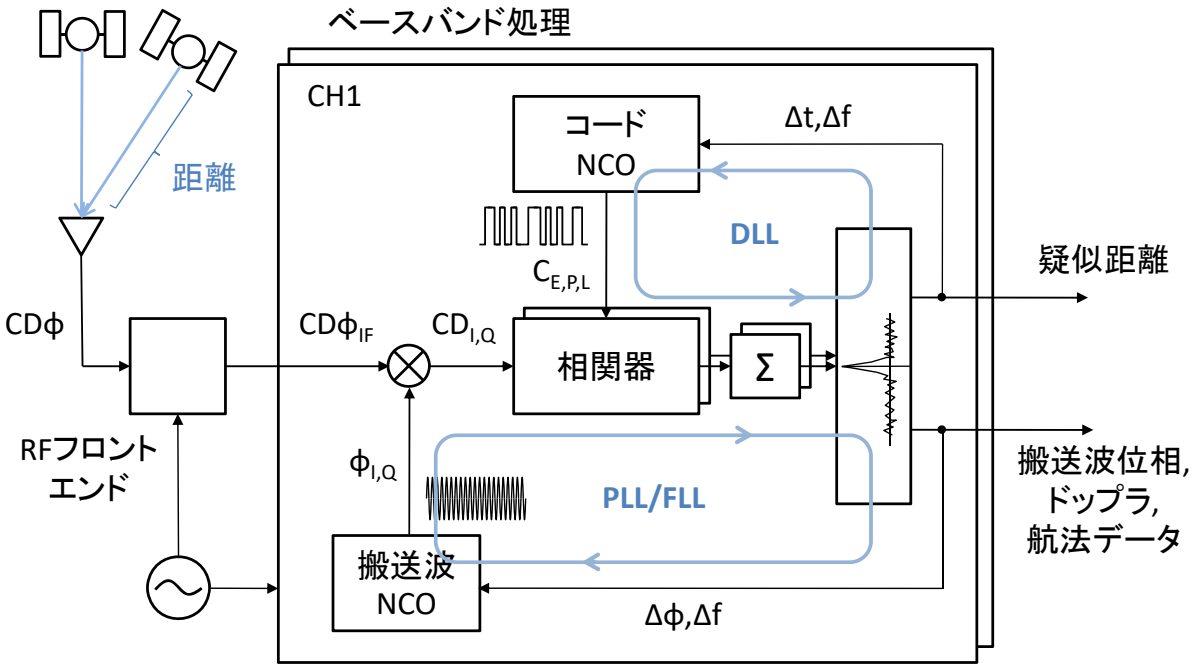
- RTK-GPS/GNSS とは
- RTKLIBの開発
- 低価格RTK
- RTKLIBの応用

RTK-GPS/GNSSとは

GPS/GNSS信号の構造



GPS/GNSS受信機の内部



コード測位：搬送波測位

	標準測位(コード測位)	高精度測位(搬送波測位)
観測量	疑似距離 (コード)	搬送波位相 + 疑似距離
受信機ノイズ	30 cm	3 mm
マルチパス	30 cm - 30 m	1 - 3 cm
感度	高感度 (C/N0<15dBHz)	低感度 (C/N0>35dBHz)
連続性	-	サイクルスリップ
アンビギュイティ	-	推定/AR
受信機価格	安価 (~$100)	高価 (~$20,000)
精度 (RMS)	3 m (H), 5 m (V) (単独) 1 m (H), 2 m (V) (DGPS)	5 mm (H), 1 cm (V) (静止) 1 cm (H), 2 cm (V) (RTK)
応用	航法, 時刻, ...	測量, 地図, ...

受信機/航法処理

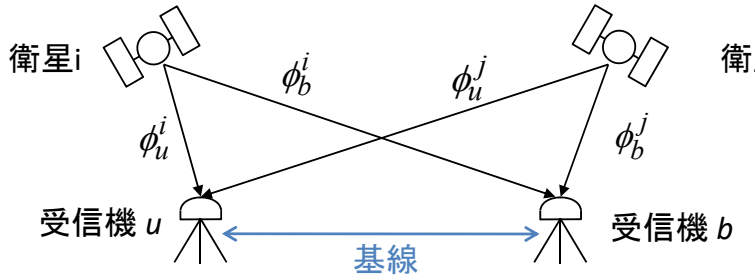
- 受信機処理
  - 信号捕捉　　：ドップラ/コード位相探索
  - コード追尾　　：DLL (Delay Lock Loop)
  - 搬送波追尾　　：PLL/FLL (Phase/Freq Lock Loop)
  - 航法データ再生 (エフェメリス,...)
  - 疑似距離、搬送波位相生成
- 航法処理
  - 測位アルゴリズム (単独, DGPS, SBAS, RTK, ...)
  - 座標変換
  - 入出力メッセージ処理 (NMEA, RTCM, ...)

二重位相差

$$\Phi_{ub}^{ij} \equiv \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j))$$
$$= \rho_{ub}^{ij} + c(dt_{ub}^{ij} - dT_{ub}^{ij}) - I_{ub}^{ij} + T_{ub}^{ij} + \lambda B_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_\Phi$$
$$= \rho_{ub}^{ij} - I_{ub}^{ij} + T_{ub}^{ij} + \lambda N_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_\Phi$$
$$dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0,\ dT_{ub}^{ij} = dT_{ub}^{i} - dT_{ub}^{j} \approx 0$$
$$B_{ub}^{ij} = (\phi_{u,0} - \phi_0^i + N_u^i) - (\phi_{b,0} - \phi_0^i + N_b^i) - (\phi_{u,0} - \phi_0^j + N_u^j) + (\phi_{b,0} - \phi_0^j + N_b^j) = N_{ub}^{ij}$$

（短基線+同一アンテナ）

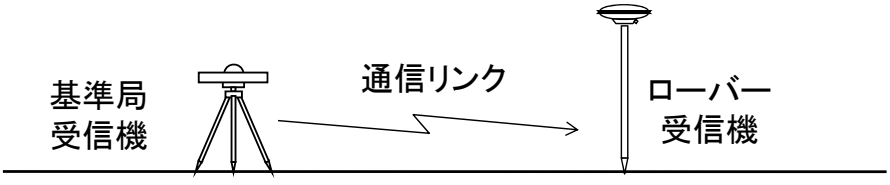
$$\Phi_{ub}^{ij} \approx \rho_{ub}^{ij} + \lambda N_{ub}^{ij} + \varepsilon_\Phi$$
$$I_{ub}^{ij} = I_{ub}^{i} - I_{ub}^{j} \approx 0, T_{ub}^{ij} = T_{ub}^{i} - T_{ub}^{j} \approx 0, d_{ub}^{ij} = d_{ub}^{i} - d_{ub}^{j} \approx 0$$



Memo for Misra & Enge:
http://gpspp.sakura.ne.jp/diary200608.htm

RTK (real-time kinematic)

- 基線解析による精密測位技術
  - ローバアンテナ位置のリアルタイム算出
  - 通信リンク
  - OTF（オンザフライ）整数アンビギュイティ決定
  - 精度: 1 cm + 1ppm x 基線長（水平RMS）
  - 応用: 測地測量, 建設機械制御, 精密農業等



RTK with RTKLIB例 (1)

RTKNAVI RTKPLOT RTKPLOT (GE View)

Receiver:

CSG Shop
u-blox NEO-M8T card

ONDA
V919 Air CH
9.7"
(2048x1536)
ATOM X5-8300,
RAM 4GB,
Flash 64GB

Com Link to base-station: Y-mobile WiFi Router

RTK with RTKLIB例 (2)

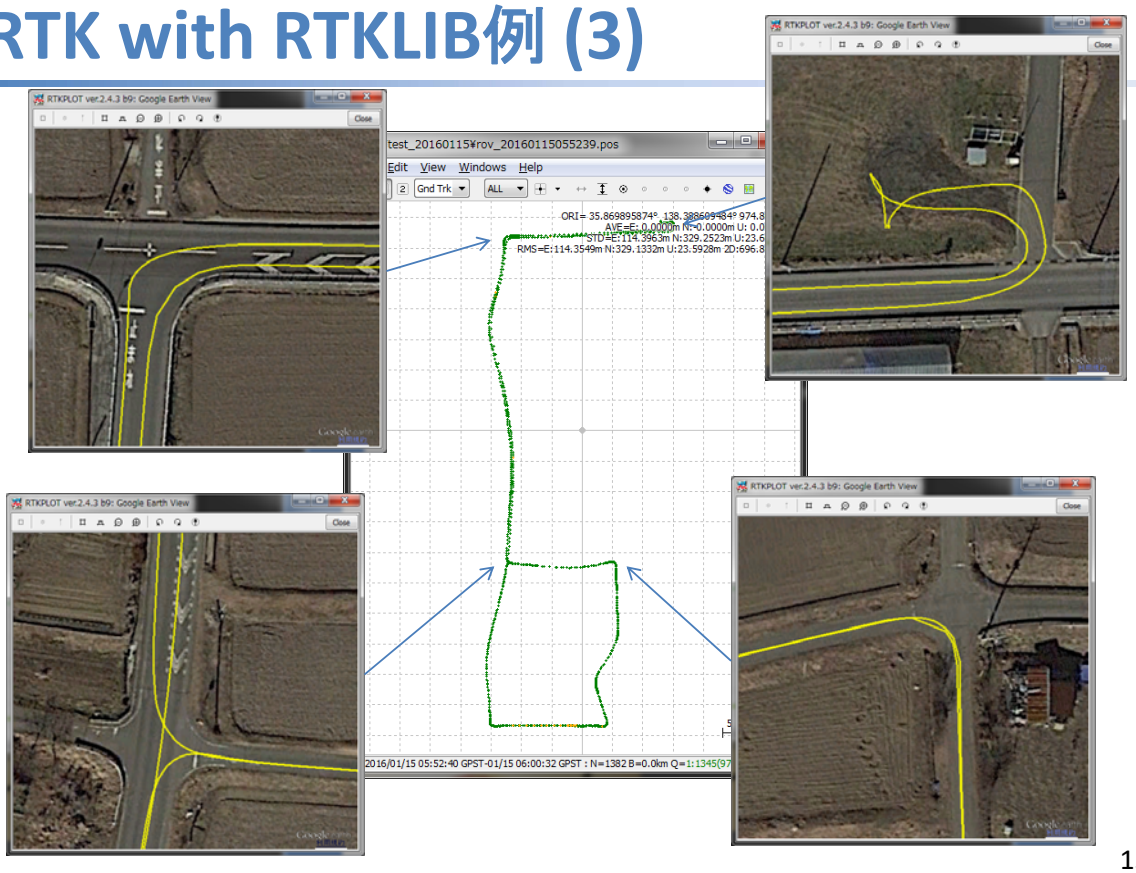
Receiver:
CSG Shop
u-blox NEO-M8T card

Antenna:

Tallysman
TW4721

Tallysman
TW2400

RTK with RTKLIB例 (3)



RTK応用

Geodetic Survey

Construction Machine Control

Precision Agriculture

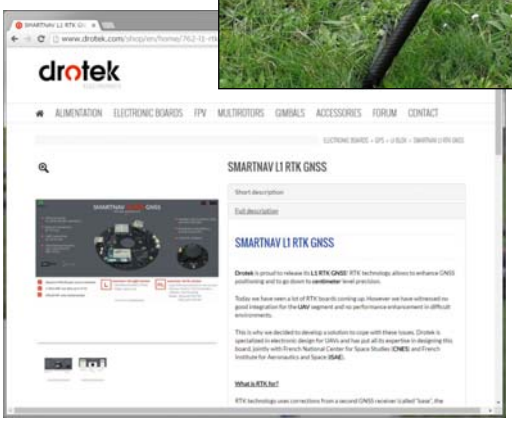
ITS (Intelligent Transport System)

Mobile Mapping System

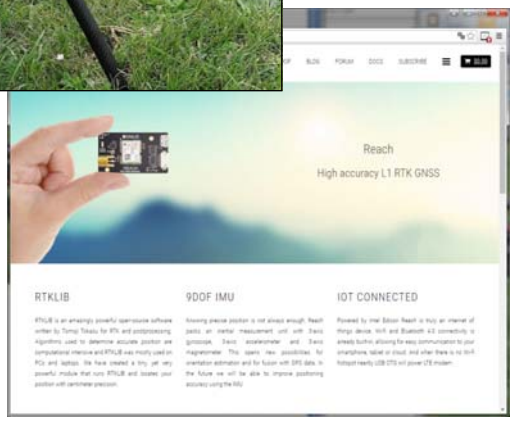
Sports

http://www.trimble.com, http://www.leica-geosystems.com, http://www.gpsworld.com

UAV (Drone)



http://www.drotek.com

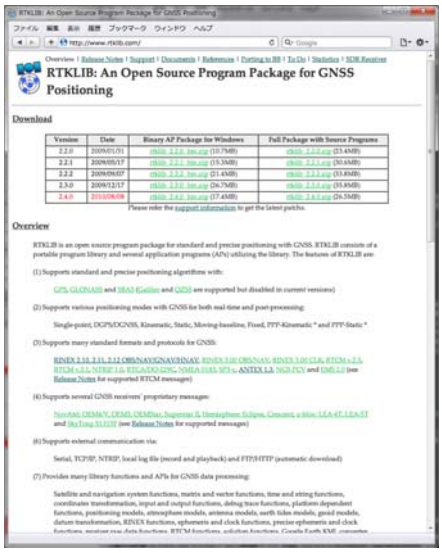


http://www.emlid.com

RTKLIBの開発

RTKLIB

- **An Open Source Software Package for GNSS Positioning**
  - Has been developed since 2006
  - The latest version 2.4.2 p11 distributed under BSD license
- **Portable APIs and Useful APs**
  - "All-in-one" package for Windows
  - CLI APs for any environments

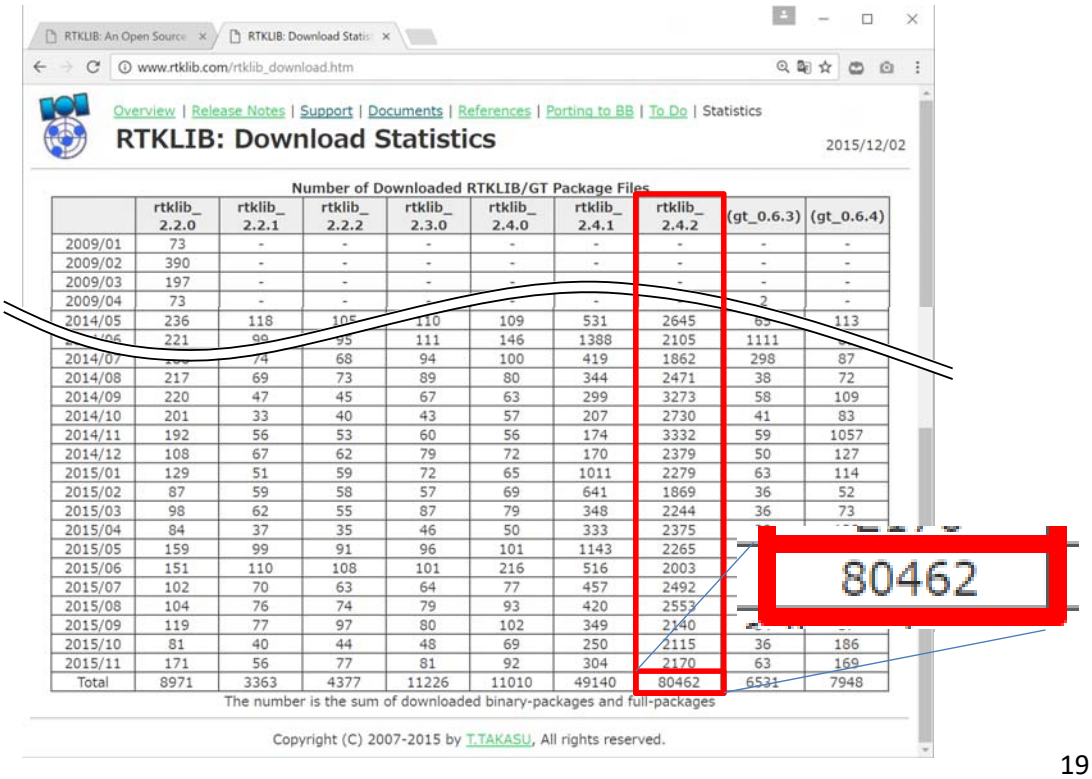


http://www.rtklib.com
https://github.com/tomojitakasu/RTKLIB
https://github.com/tomojitakasu/RTKLIB_bin

RTKLIB: History

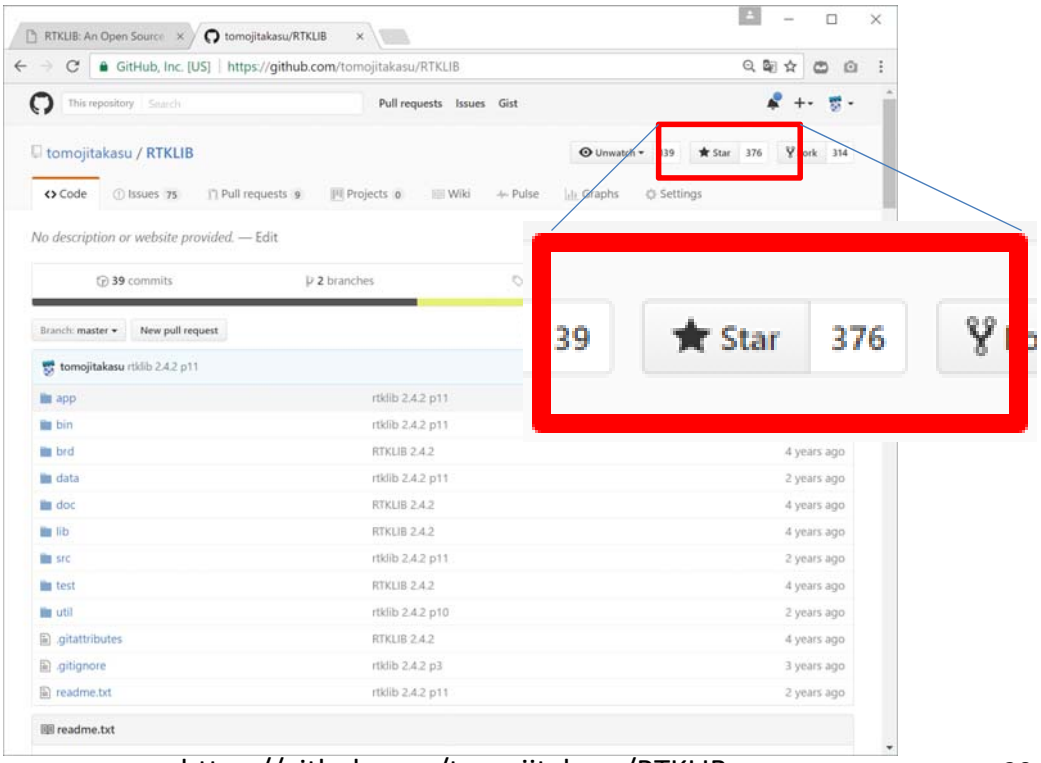
- 2006/04 0.0.0 First version for RTK+C program lecture
- 2007/01 1.0.0 Simple post processing AP
- 2008/07 2.1.0 Add APs, support medium-range
- 2009/01 2.2.0 Start to distribute as **Open Source S/W**
- 2009/05 2.2.1 Support RTCM, NRTK, many receivers
- 2009/12 2.3.0 Support GLONASS, several receivers
- 2010/08 2.4.0 PPP and Long-baseline RTK (<1000 km)
- 2011/06 2.4.1 Support QZSS, JAVAD receiver, …
- 2013/04 2.4.2 Support Galileo, Enable BeiDou, …
  Hosting at GitHub, BSD License
- 2015/03 2.4.2 p11 The newest patch
- **2016/12 2.5.0 New version release (planned)**

Downloads



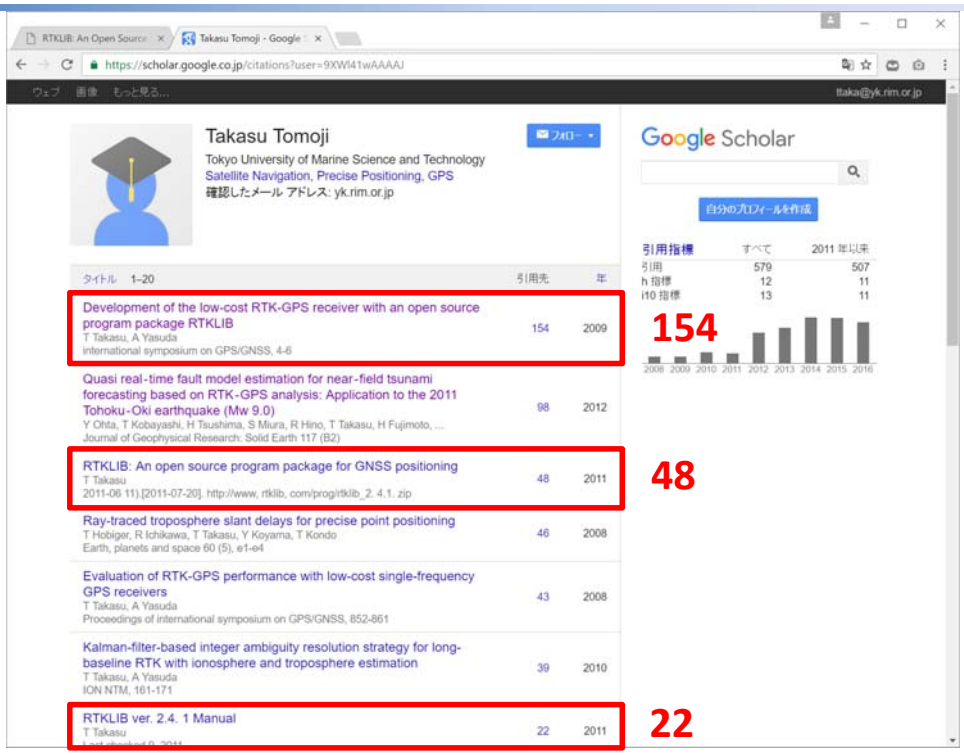
	rtklib_ 2.2.0	rtklib_ 2.2.1	rtklib_ 2.2.2	rtklib_ 2.3.0	rtklib_ 2.4.0	rtklib_ 2.4.1	rtklib_ 2.4.2	(gt_0.6.3)	(gt_0.6.4)
2009/01	73	-	-	-	-	-	-	-	-
2009/02	390	-	-	-	-	-	-	-	-
2009/03	197	-	-	-	-	-	-	-	-
2009/04	73	-	-	-	-	-	-	-	-
2014/05	236	118	105	110	109	531	2645	69	113
2014/06	221	99	95	111	146	1388	2105	1111	87
2014/07	103	74	68	94	100	419	1862	298	87
2014/08	217	69	73	89	80	344	2471	38	72
2014/09	220	47	45	67	63	299	3273	58	109
2014/10	201	33	40	43	57	207	2730	41	83
2014/11	192	56	53	60	56	174	3332	59	1057
2014/12	108	67	62	79	72	170	2379	50	127
2015/01	129	51	59	72	65	1011	2279	63	114
2015/02	87	59	58	57	69	641	1869	36	52
2015/03	98	62	55	87	79	348	2244	36	73
2015/04	84	37	35	46	50	333	2375		
2015/05	159	99	91	96	101	1143	2265		
2015/06	151	110	108	101	216	516	2003		
2015/07	102	70	63	64	77	457	2492		
2015/08	104	76	74	79	93	420	2553		
2015/09	119	77	97	80	102	349	2140		
2015/10	81	40	44	48	69	250	2115	36	186
2015/11	171	56	77	81	92	304	2170	63	169
Total	8971	3363	4377	11226	11010	49140	80462	6531	7948

GitHub



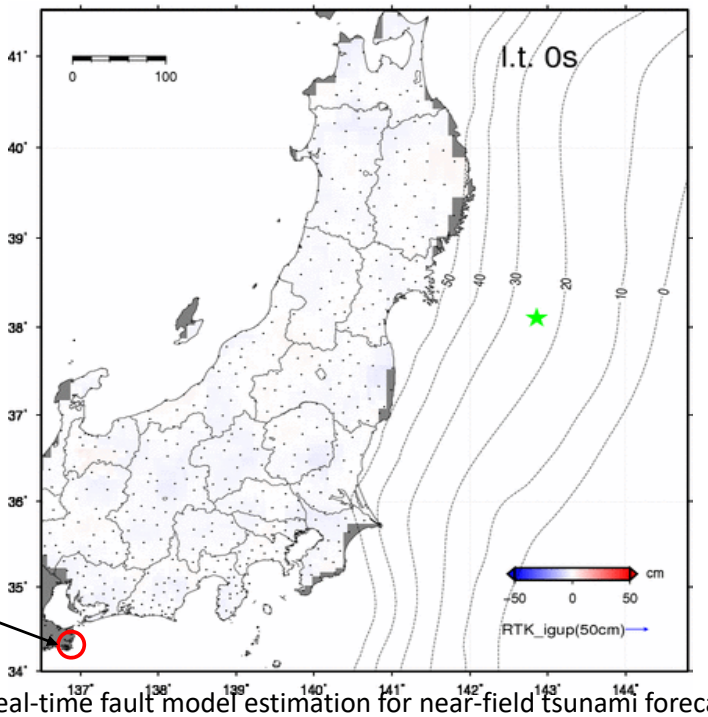
https://github.com/tomojitakasu/RTKLIB

Google Scholar



https://scholar.google.co.jp/citations?user=9XWl41wAAAAJ

RTKLIB応用例



RTK
基準点

Y. Ohta et al., Quasi real-time fault model estimation for near-field tsunami forecasting base on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0), JGR-solid earth, 2012

地理院REGARD

電子基準点リアルタイム解析システム（REGARD）プロトタイプの開発
Development of a prototype of GEONET Real-time Analysis System: REGARD

地理地殻活動研究センター　川元智司
Geography and Crustal Dynamics Research Center　Satoshi KAWAMOTO
測地観測センター　檜山洋平・古屋智秋・佐藤雄大
Geodetic Observation Center
Yohei HIYAMA, Tomoaki FURUYA and Yudai Sato
東北大学大学院理学研究科附属地震・噴火予知研究観測センター　太田雄策
Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University
Yusaku OHTA

ことが可能である．Ohta et al.（2012）は，東北地方太平洋沖地震のリアルタイムにおける状況を想定してGEONETデータを用いてRTK-GNSS解析を行い，地震発生後3分の時点で得られた地殻変動データからM_w8.7の断層モデルを推定可能であることを示した．

これらの成果を踏まえ，東北地方太平洋沖地震後，国土地理院は東北大学と共同でリアルタイムGNSS解析システム「Real-time GEONET analysis system for Rapid Deformation monitoring（REGARD）」の開発を開始した．REGARDは，GEONETのデータをリアルタイムで解析することにより地震時地殻変動を抽出し，地震後3分以内に自動で断層モデル及び地震規模の推定を行うことを目指す．

いる1Hz変位時系列から，逐次地殻変動を抽出し，それから単一矩形断層モデル及びすべり分布モデルの2種類を推定する．断層モデル推定は，1分毎，5分間繰り返した後動作を停止する．推定された断層モデルは，電子メールで関係する国土地理院職員に送信される（図-2）．

本システムは，「リアルタイム測位サブシステム」，「イベント検知サブシステム」，「断層モデル推定サブシステム」の三つのサブシステムからなり，それぞれ，リアルタイム測位による変位時系列の計算，巨大地震発生の検出，自動断層モデル推定による地震規模計算を担う（図-3）．

リアルタイム測位サブシステムは，電子基準点からのリアルタイムデータを処理し，1Hz変位時系列を算出する．測位エンジンにはRTKLIB 2.4.1（Takasu, 2011）を使用し，単一の固定局を用いた解析基線

国土地理院時報 (2016, 128集)

低価格RTK

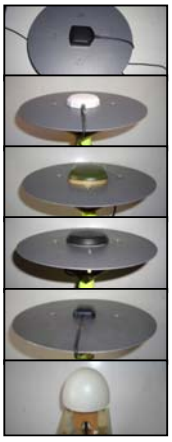
1周波受信機の評価

- Raw antenna/receiver performance
  - Antenna phase center stability
  - Carrier-phase multipath
  - Code multipath
- RTK-GPS performance
  - Positioning accuracy (RMS errors)
  - Ratio of correct AR (ambiguity resolution)
  - TTFF (time to first fix) with AR
- Various antenna/receiver combinations

Antennas

Low-cost

u-blox	ANN-MS	$31
AeroAntenn	AT575	$200
AntCom	AG15A2-XS-3	$194
MicroPlus	2335TB	$47
Pioneer	GPS-M1ZZ Ant	?
Trimble	Bullet III	$125



Geodetic-grade (for reference)

NovAtel	GPS-702-GG	$995

Receivers

Low-cost

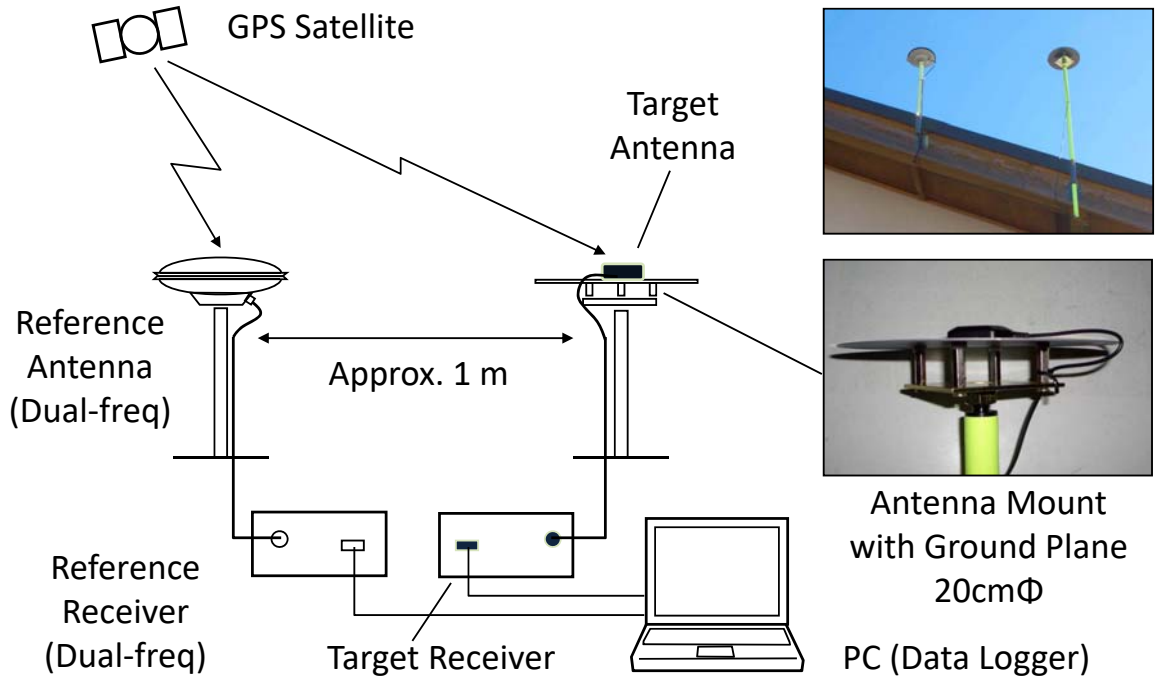
u-blox	AEK-4T	$179*1
u-blox	EVK-5H*2	$99 *1
NovAtel	Superstar II	$165
Hemisphere	Crescent	$285

Geodetic-grade (for reference)

NovAtel	OEMV-3	$7,995

*1 module only, *2 F/W version 3.00

Configuration of Experiment

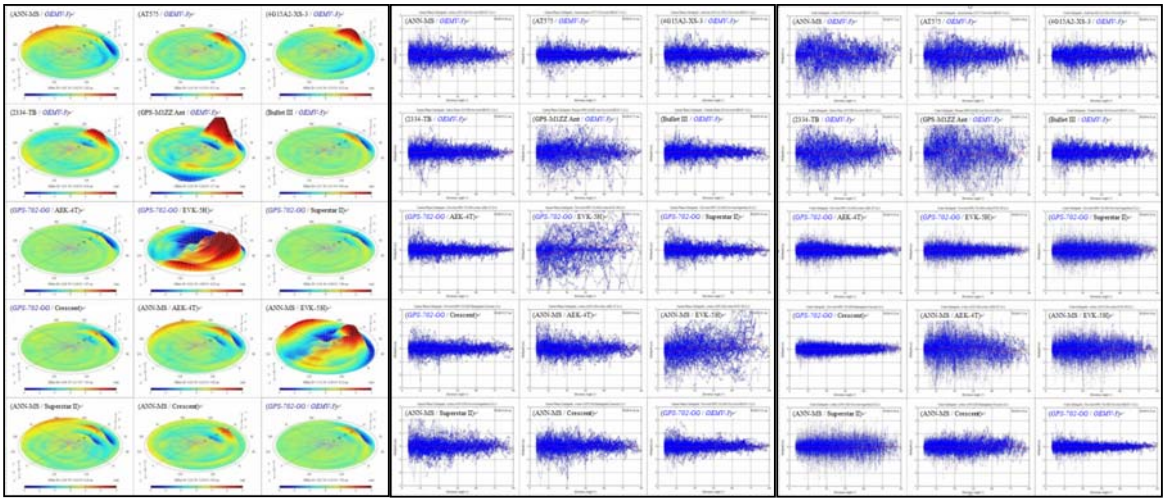


Results of Experiment (1)

Antenna PCV

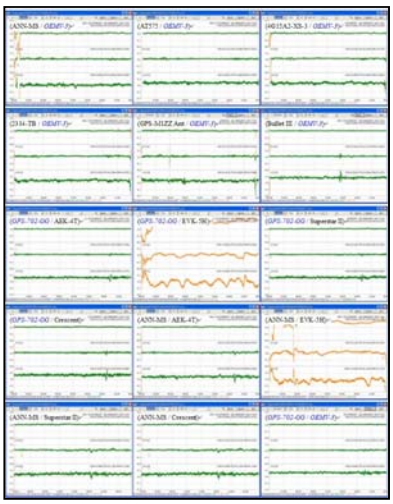
Carrier-phase Multipath

Code Multipath

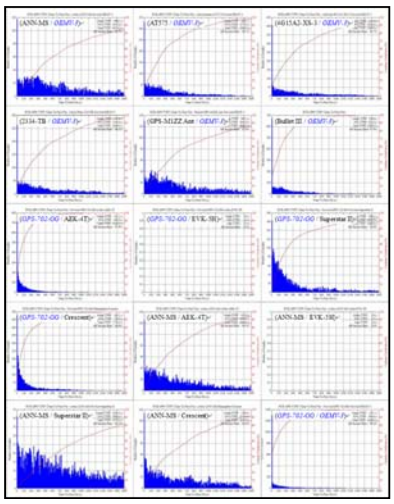


Results of Experiment (2)

RTK-GPS Positioning Accuracy

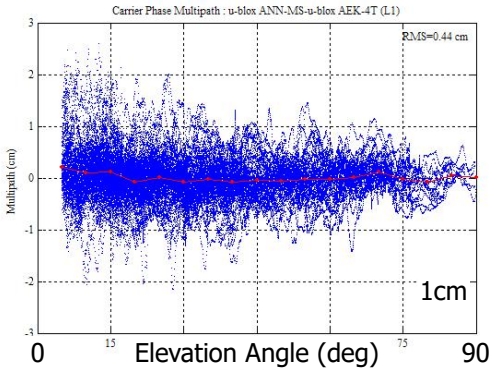


RTK-GPS TTFF with AR



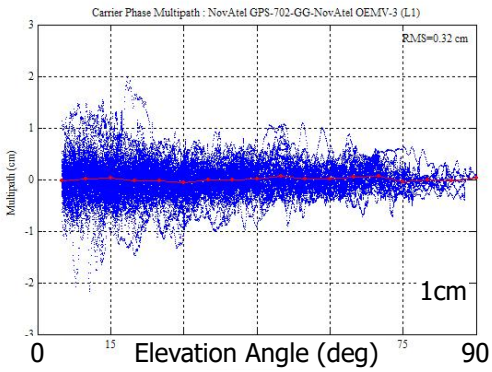
Carrier-phase Multipath

Low-cost
Antenna/Receiver
(ANN-MS/AEK-4T)



RMS=0.44cm

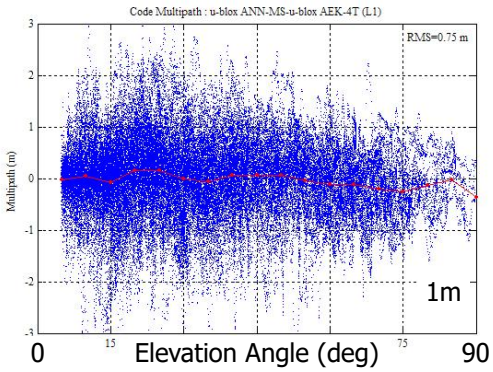
Geodetic-grade
Antenna/Receiver
(GPS-702-GG/OEMV-3)



RMS=0.32cm

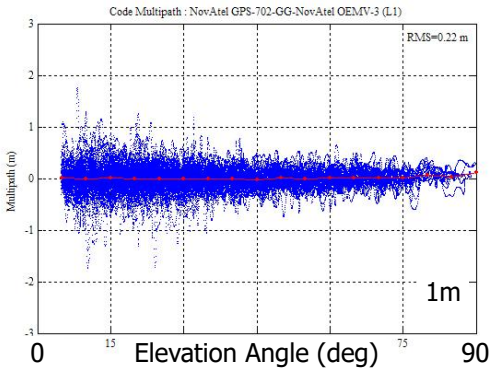
Code Multipath

Low-cost
Antenna/Receiver
(ANN-MS/AEK-4T)



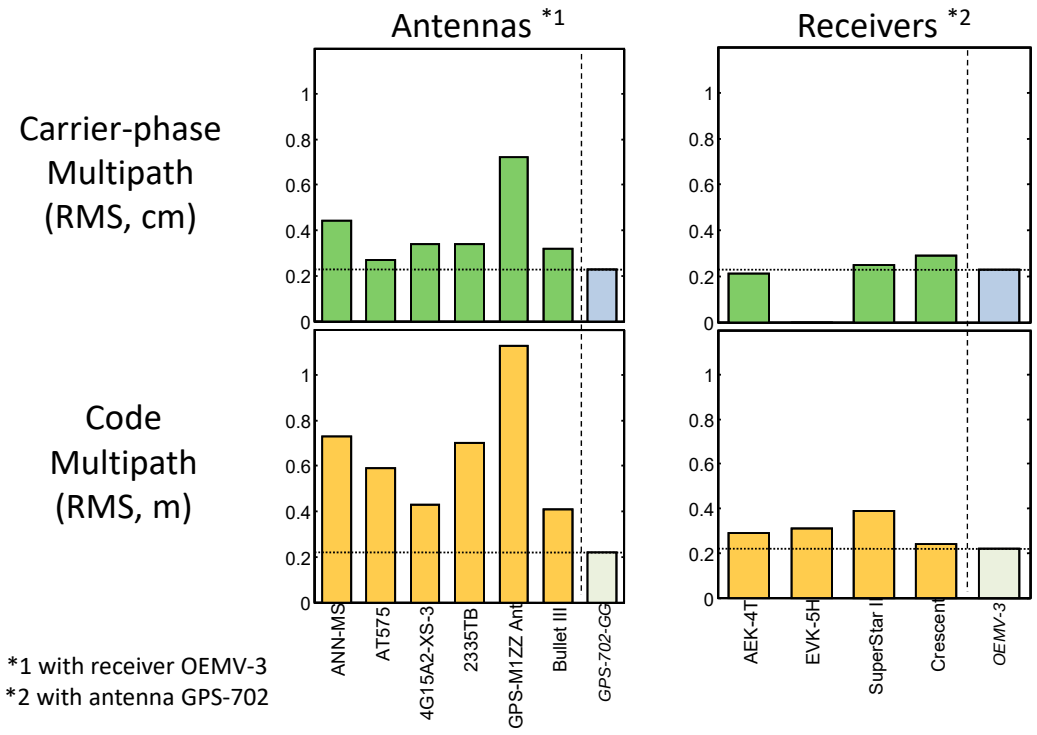
RMS=0.75m

Geodetic-grade
Antenna/Receiver
(GPS-702-GG/OEMV-3)



RMS=0.22m

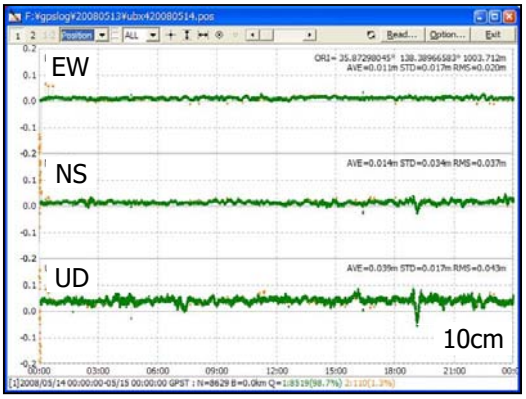
Comparison of Antennas/Receivers



*1 with receiver OEMV-3
*2 with antenna GPS-702

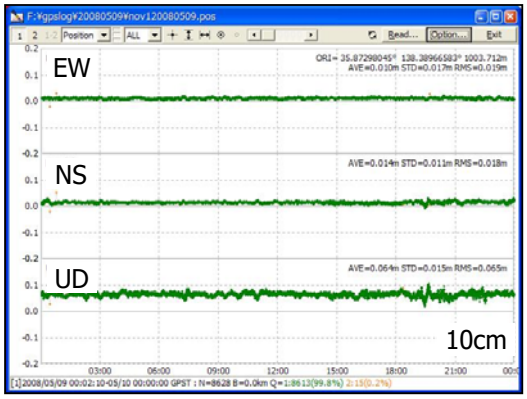
RTK-GPS Positioning Accuracy

Low-cost Antenna/Receiver (ANN-MS/AEK-4T)



RMS Error (cm):
E 0.39, N 0.59, U 1.08
Fixing-ratio: 98.7%

Geodetic-grade Antenna/Receiver (GPS-702-GG/OEMV-3)

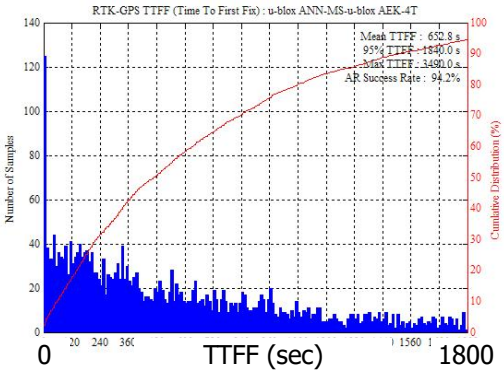


RMS Error (cm):
E 0.26, N 0.36, U 0.77
Fixing-ratio: 99.8%

● Fix
● Float

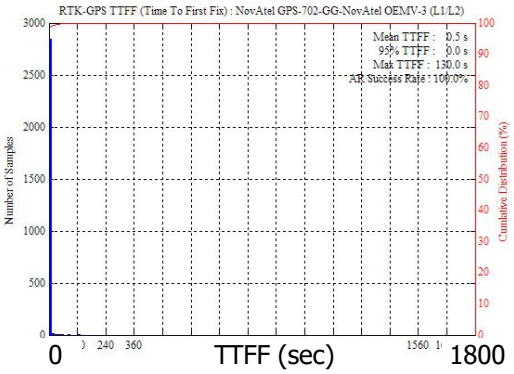
TTFF with AR

Low-cost
Antenna/Receiver
(ANN-MS/AEK-4T)



Mean: 652.8 s
95%: 1840.0 s
Max: 3490.0 s

Geodetic-grade
Antenna/Receiver (L1/L2)
(GPS-702-GG/OEMV-3)

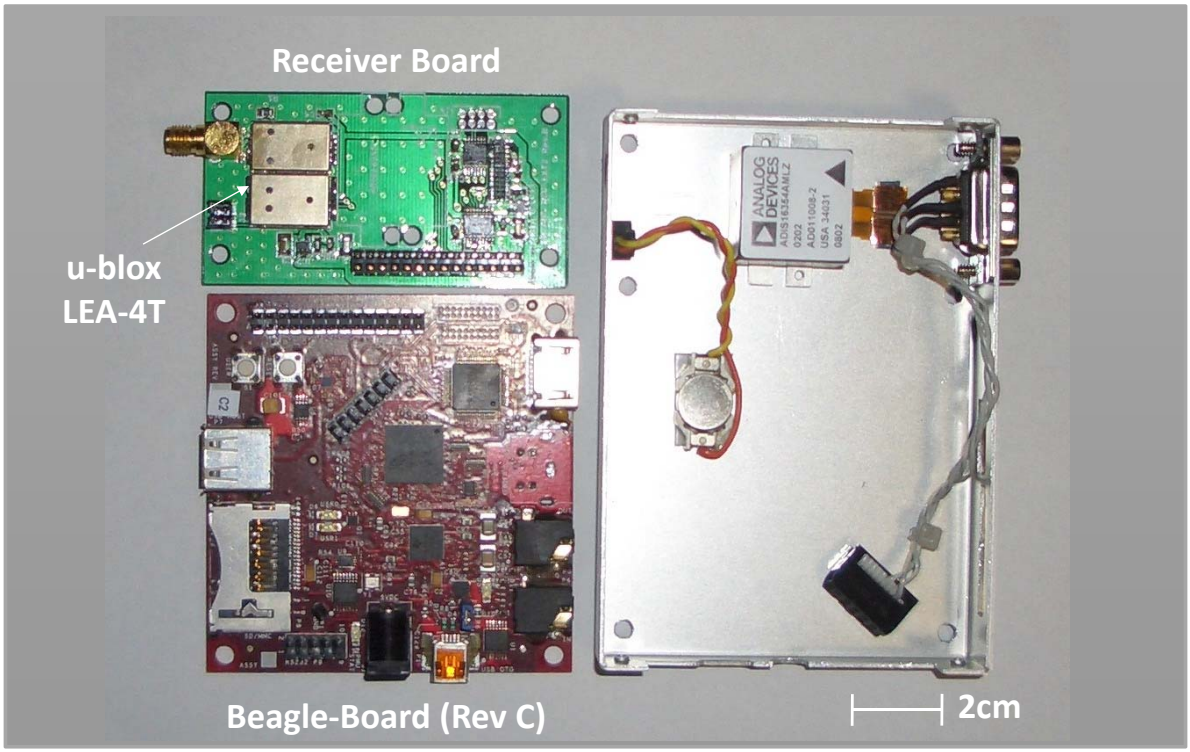


Mean: 0.5 s
95%: 0.0 s
Max: 130.0 s

Low-Cost Receiver with RTKLIB

- **Objectives**
  - To demonstrate and verify the low-cost RTK-GPS receiver without PC
  - To evaluate production cost, CPU load, memory usage, power consumption, RTK performance, etc.
  - To provide a platform for various RTK applications
- **Porting RTKLIB to Embedded CPU**
  - Needs powerful CPU for many floating point operations
  - Needs various peripherals for rover-base station communications like WiFi LAN, Bluetooth, modem devices

Hardware



Selection of Receiver Module

Vendor	Receiver Board/Module	B/M *1	# of CH	Max Raw Rate	Sample Price
NovAtel	SuperStar II	B	12ch	1Hz	$165
NovAtel	OEMStar *2	B	14ch	10Hz	2009/4Q
Magellan	AC12	M	12ch	1Hz	$106
SiRF	SiRF star II	C	12ch	1Hz	$57
GARMIN	GPS 15L/15H	M	12ch	1Hz	$60
u-blox	LEA-4T	M	16ch	10Hz	$179
u-blox	LEA-5T	M	50ch	2Hz	$179
u-blox	LEA-6T	M	50ch	?	2010/1Q
Hemisphere	Crescent	B	12ch	10Hz	$285
SkyTraq	S1315F	M	12ch	20Hz	$25

*1 B: OEM Board, M: Module, C: Chip, *2 Supports GLONASS

Parts List and Price

No	Parts	Specs	Provider	#	Price
1	Beagle-Board	OMAP3530, 256+256MB RAM/Flash	Digi-key	1	$149
2	LEA-4T	16ch, Single-Freq Receiver Module	u-blox	1	$179
3	Extension Board	3" x 1.2", double-side	Silver Circuit	1	$18
4	TPS79933DDCR	IC LDO Reg 200mA 3.3V TSOT-23-5	TI	1	$1
5	TPS79930DDCT	IC LDO Reg 200mA 3.0V TSOT-23-5	TI	1	$1
6	TXS0108E	IC 8bit Non-Inv Transtr 20TSSOP	TI	1	$2
7	TXS0104E	IC 4bit Non-Inv Transtr 14TSSOP	TI	1	$2
8	Connectors	SMA, D-Sub-9P, Header-28P-M/F	-	1s	$20
9	Chip Cap, Reg.	-	-	1s	$2
10	Case YM-115	115 x 80 x 20 mm	Takachi	1	$6
11	Screws, Spacers	-	-	1s	$3
12	SD Card	2GB	-	1	$20
	Total	-	-	-	$403
OP1	ADIS16354	6-Axis MEMS-IMU, 1.7g, 300deg/s	ADI	1	$720
OP2	CLM-112-02	24P 1mm-pitch sockets	Samtech	1	$7

Software Configuration

- **Operating System**
  - Kernel: Linux 2.6.29-OMAP1+Patchs
  - Root FS: Ubuntu 9.04 for ARM on SD-Card
  - Peripherals: USB LAN, USB WiFi, USB Modem,...
- **Cross-compiler**
  - ARM-gcc 4.2.1
  - Compiler options
    -O3 -mfpu=neon -mfloat-abi=softfp -ffast-math
- **LIBC: glibc 2.9, libc6-vfp**
  - Optimized floating-point library for ARM co-processor

RTKRCV

- **Console AP for real-time positioning**
  - Newly implemented for Beagle-Board-based RTK receiver
  - Portable to many targets like Windows, Linux, Mac OS X
  - Will be incorporated into RTKLIB ver.2.3.0
- **Features**
  - Various receivers, input/output formats, stream types, positioning options are supported same as RTKNAVI
  - No GUI but support TELNET login from remote console to set options, control and monitor the receiver
  - TCP/IP stack and device drivers are provided by OS

CPU Load and Memory Usage

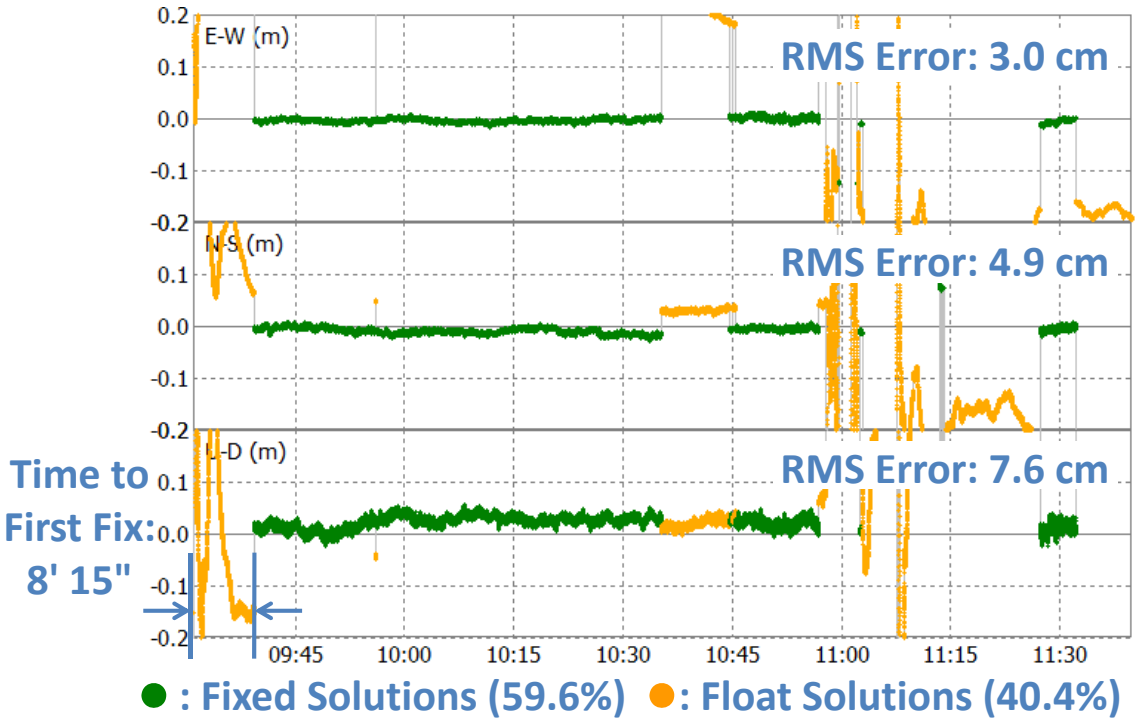
- 10 Hz update of RTK-GPS solutions
- Receiving RTCM v.3 via NTRIP with E-Mobile HSDPA modem
- Logging all raw measurement data and solutions to SD card

```
$ top

top - 00:08:24 up 24 min,  1 user,  load average: 0.16, 0.24, 0.18
Tasks:  46 total, 1 running, 45 sleeping,  0 stopped,  0 zombie
Cpu(s): 24.3%us, 1.3%sy, 0.0%ni,73.4%id, 0.7%wa, 0.3%hi, 0.0%si, 0.0%st
Mem:   239616k total,   30476k used,  209140k free,     3540k buffers
Swap:       0k total,       0k used,       0k free,    12492k cached

 1876 ubuntu    20   0 11896 2344 1256 S 25.1  1.0   4:13.09 rtkrcv
 1894 ubuntu    20   0  2492 1160  936 R  0.7  0.5   0:00.16 top
    1 root      20   0  2860 1896  572 S  0.0  0.8   0:01.49 init
    2 root      15  -5     0    0    0 S  0.0  0.0   0:00.00 kthreadd
    3 root      15  -5     0    0    0 S  0.0  0.0   0:00.07 ksoftirqd/0
    4 root      RT  -5     0    0    0 S  0.0  0.0   0:00.00 watchdog/0
    5 root      15  -5     0    0    0 S  0.0  0.0   0:00.04 events/0
    6 root      15  -5     0    0    0 S  0.0  0.0   0:00.05 khelper
...
```

Positioning Error and Fixing Ratio

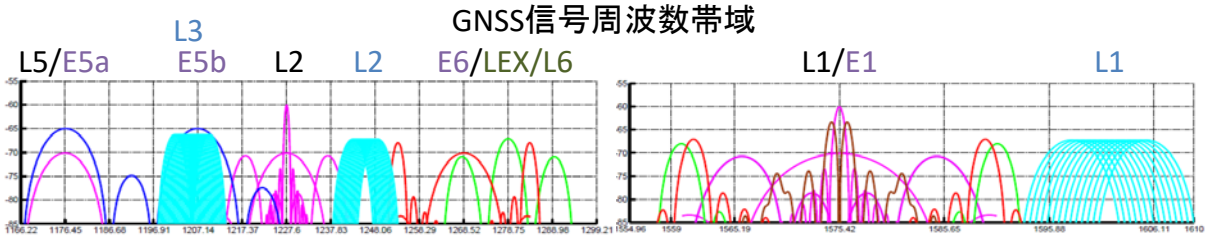


GNSS衛星及び信号帯域

GNSS衛星の数

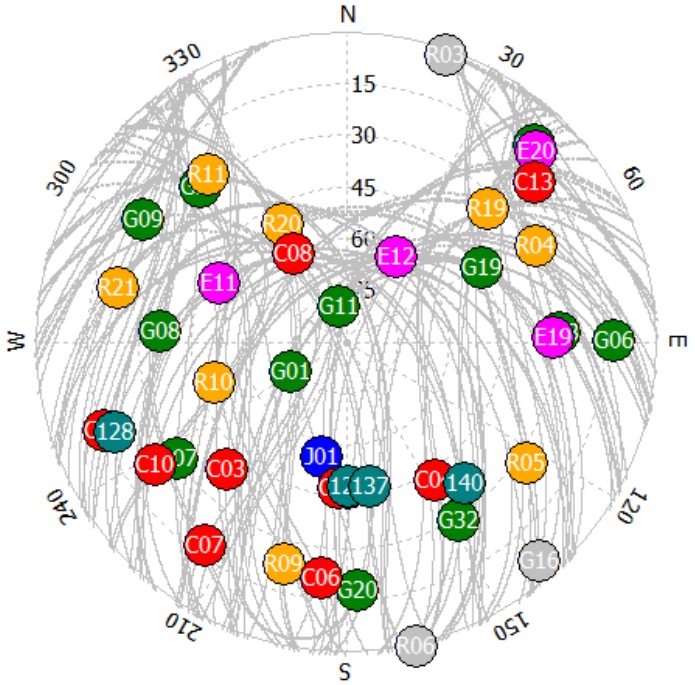
システム	2010	2014	2017	2020
GPS	31	31	32	32
GLONASS	23 (+2)	24 (+3)	24 (+3)	24 (+3)
Galileo	0	4	18	27 (+3)
BeiDou	6	16	35	35
QZSS	1	1	4	7
IRNSS	0	1	7	7
SBAS	7	8	11	11
合計	68	86	134	149

GNSS信号周波数帯域



(Y.Yang, COMPASS: View on Compatibility and Interoperability, 2009)

東京上空のGNSS衛星配置



- GPS (12)
- GLONASS (8)
- Galileo (4)
- QZSS (1)
- BeiDou (10)
- SBAS (4)

Total (39)
(仰角>10度)

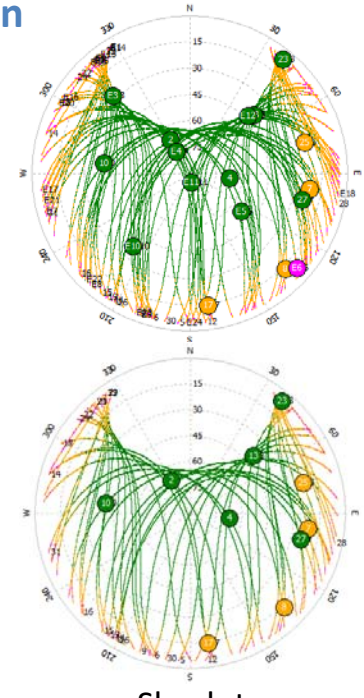
2013-06-12 10:20 GPST
RTKPLOTによるスカイプロット

Multi-GNSS-RTK

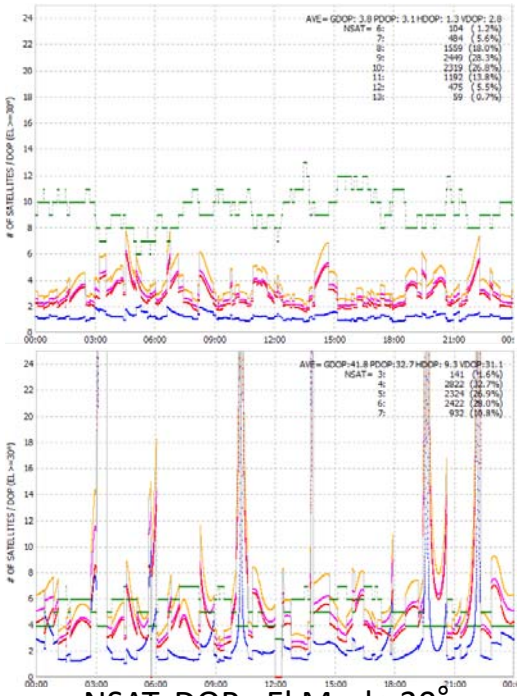
By Simulation

31GPS+
27 Galileo

31 GPS



Skyplot



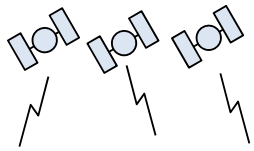
NSAT, DOP: El Mask>30°

GPS vs GPS+Galileo

RTK Performance: Baseline 13.3 km, Instantaneous AR

GPS	Galileo	El Mask=15°				El Mask=30°			
		Fixing Ratio	RMS Error (cm)			Fixing Ratio	RMS Error (cm)		
			E-W	N-S	U-D		E-W	N-S	U-D
L1	-	49.7%	4.6	8.1	19.0	23.3%	71.4	115.0	289
L1,L2	-	99.0%	1.4	1.3	1.9	87.6%	3.4	10.5	15.5
L1,L2,L5	-	99.0%	1.4	1.3	1.9	87.3%	3.4	10.5	15.6
L1	E1	98.8%	1.3	1.2	1.9	90.1%	1.2	2.1	2.7
L1,L2	E1	98.9%	1.4	1.2	1.7	98.7%	1.2	1.0	1.6
L1,L2,L5	E1,E5a, E5b	98.9%	1.5	1.3	2.0	98.9%	1.3	1.1	1.8

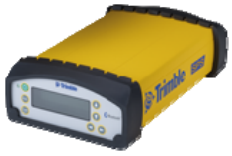
RTK (従来)



GPS

Antenna: ～¥400K

全部で
1式¥500万位



Receiver: ～¥2,000K

Antenna-Receiver: ～¥2,000K

Controller: ～¥500K

基準局

移動局

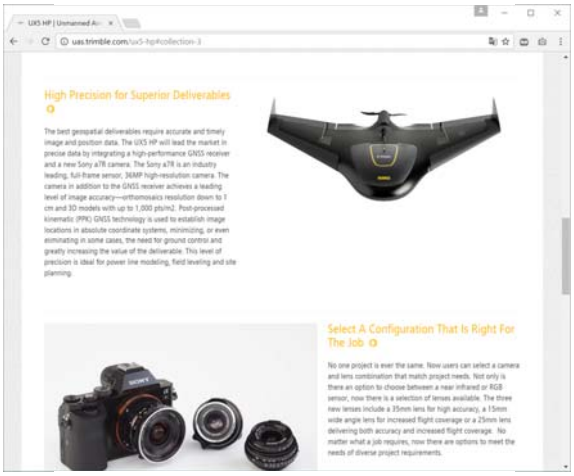
http://www.trimble.com

RTK with RTKLIB

RTKLIBの応用

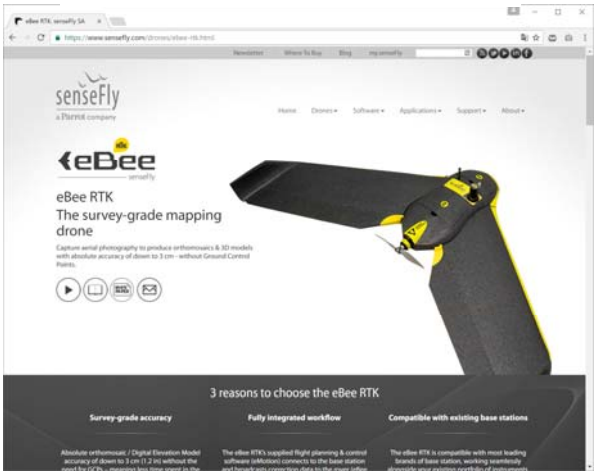
Mapping Drone

Trimble UX5 HP



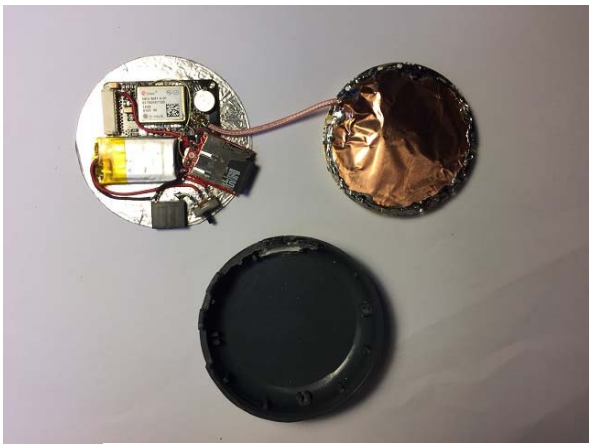
http://www.uas.trimble.com

Sensefly eBee RTK



https://www.sensefly.com

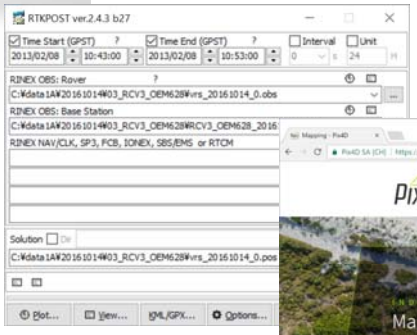
Mapping Drone用ロガー (試作)



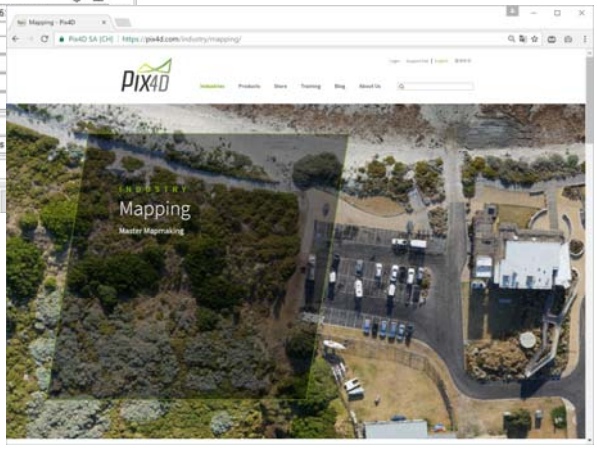
Tallysman TW2710
CSG-Shop u-blox NEO-M8T Card
OpenLog + Micro-SD
LiPo 3.7V 110mAH
Weight: 48 g, OPR: 1H40min

Mapping Drone

https://www.dji.com



RTKLIB (RTKPOST)



https://pix4d.com

サマリ

- RTK-GPS/GNSS とは
- RTKLIBの開発
- 低価格RTK
- RTKLIBの応用