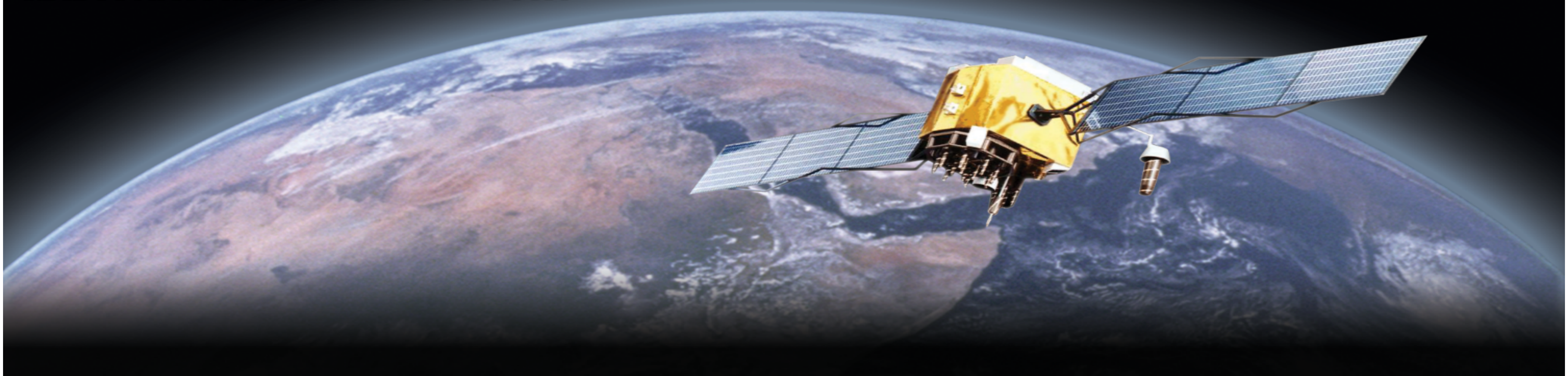
THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY



Precise Positioning for the Mass Market

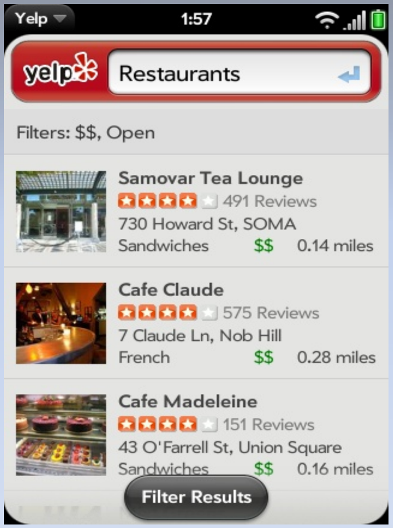
Todd Humphreys[1 2], Ken Pesyna[2], Daniel Shepard[1 2], Matthew Murrian[1], Collin Gonzalez[1], Tom Novlan[3]

[1]Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin

[2]Radiosense LLC [3]Samsung Research America

GNSS Futures IGS Workshop | February 9, 2016

Mass-Market GNSS Positioning Today



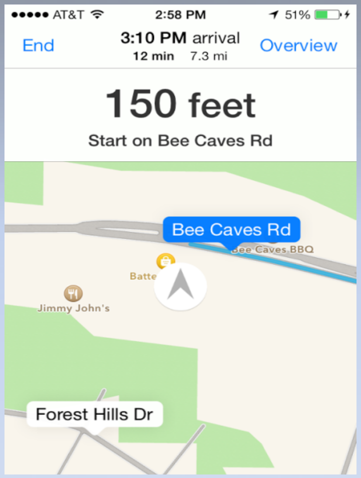
Filters: $$, Open

Samovar Tea Lounge
491 Reviews
730 Howard St, SOMA
Sandwiches $$ 0.14 miles

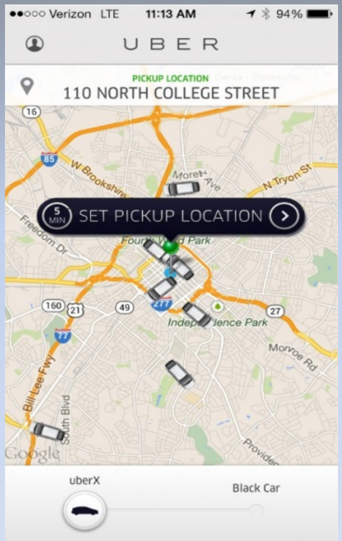
Cafe Claude
575 Reviews
7 Claude Ln, Nob Hill
French $$ 0.28 miles

Cafe Madeleine
151 Reviews
43 O'Farrell St, Union Square
Sandwiches $$ 0.16 miles

Location-based Searches



Driving Directions



Location Sharing

Fitness Tracking

Where It’s Going

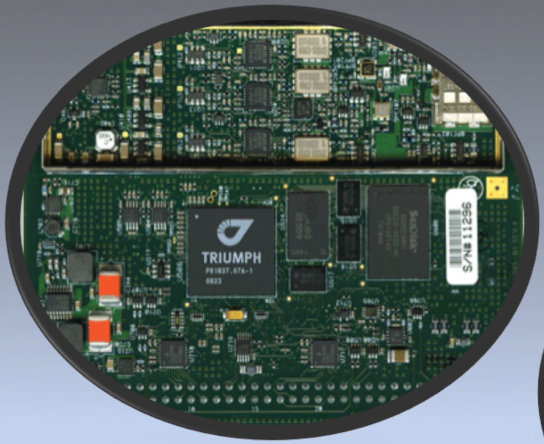
Virtual Reality

Augmented Reality

Large-scale
Mapping

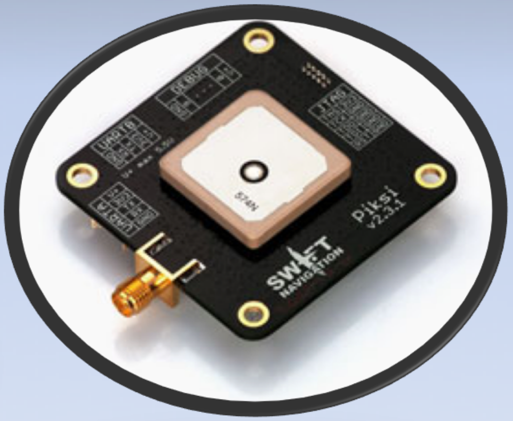
Autonomous
Driving

Disruption of the RTK-Capable RX Market



~$13k

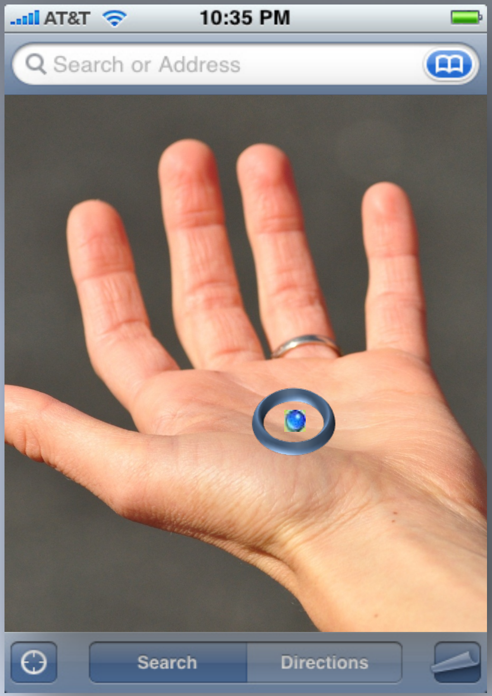
~$600

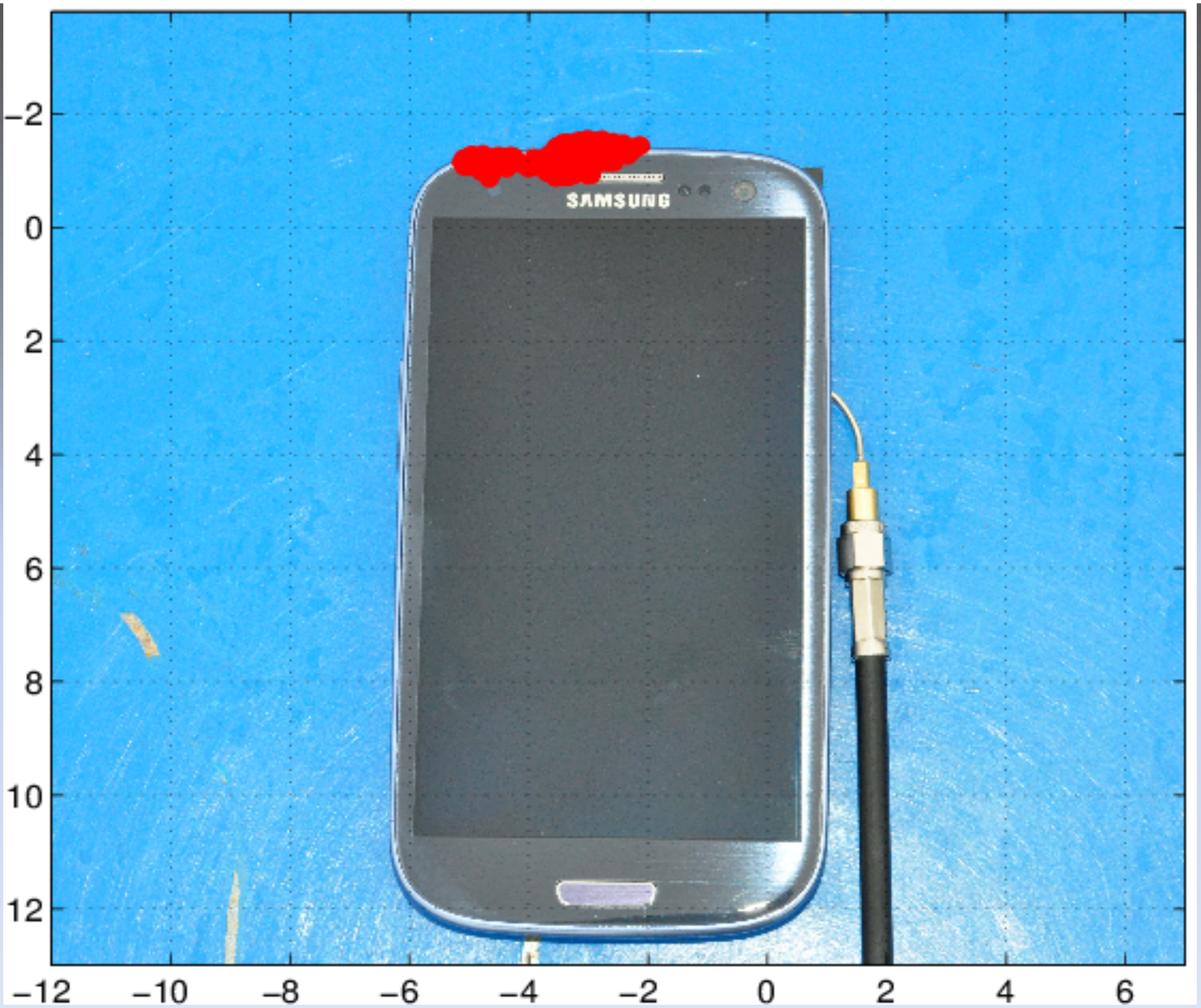


~$500

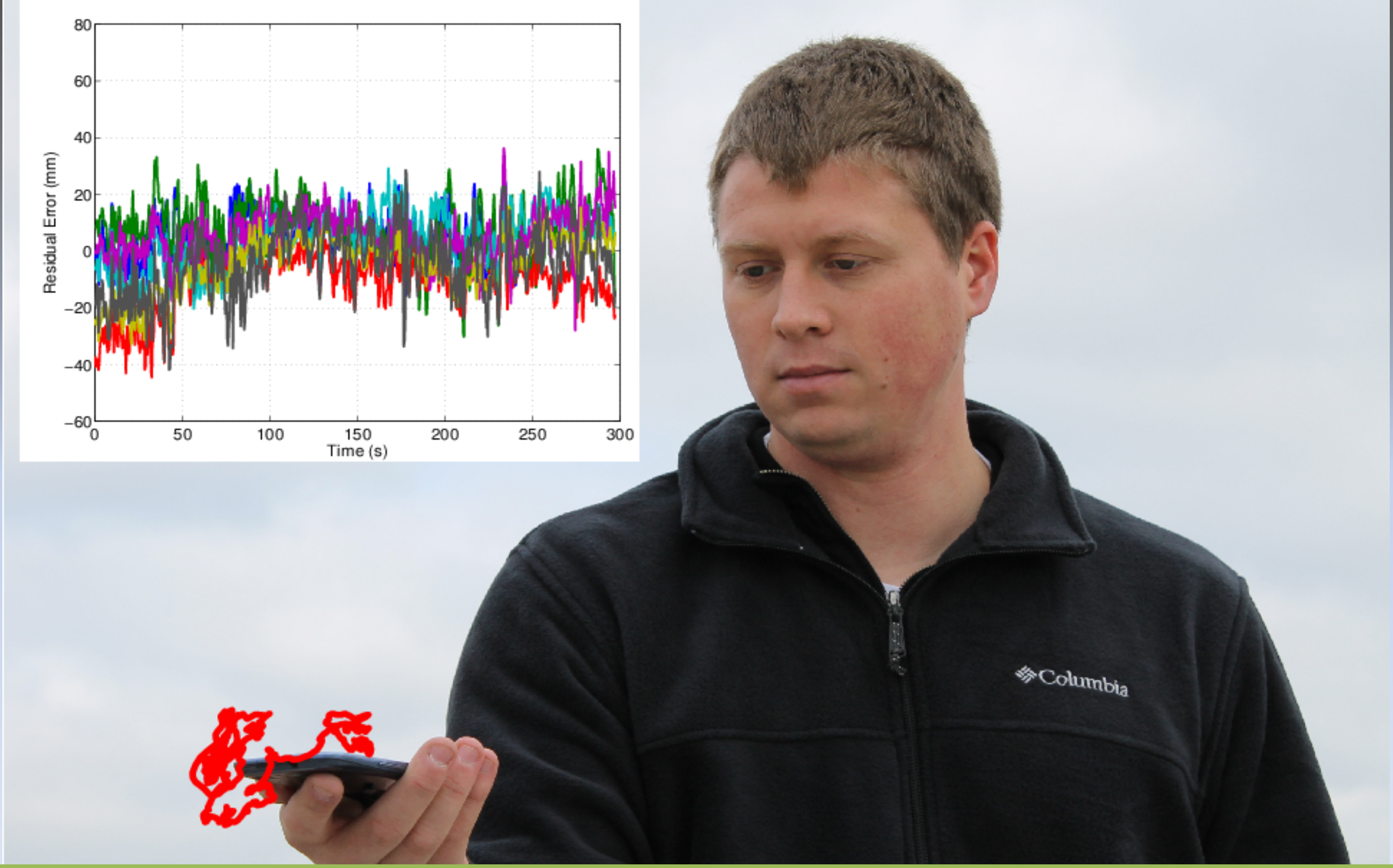
~$150


AT&T
10:35 PM
Search or Address
North Santa Cruz Avenue / Olive Street
© 2011 Google
Search
Directions


AT&T
10:35 PM
Search or Address
Search
Directions

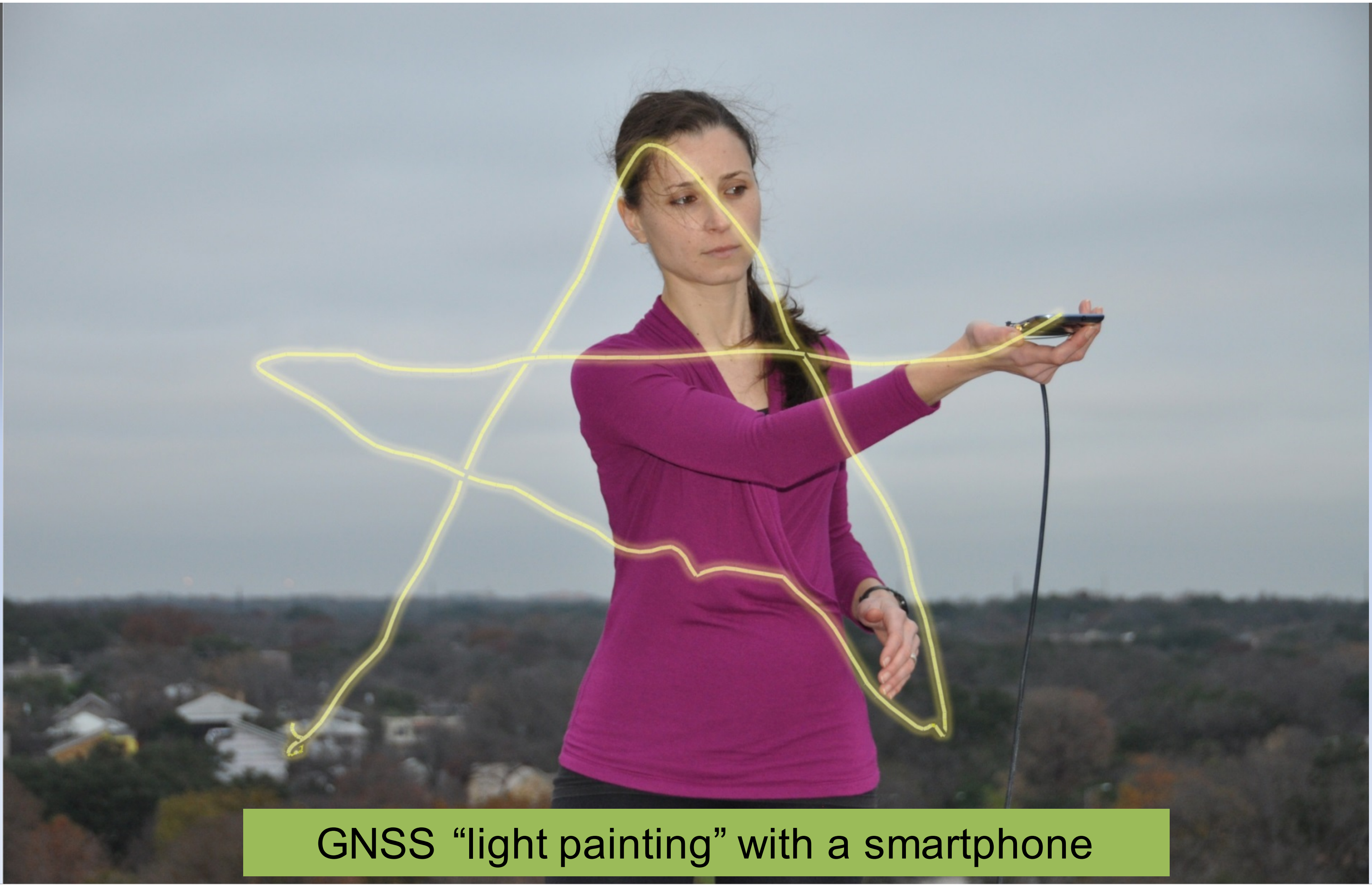


Dec. 2014: First successful RTK positioning solution with a smartphone antenna

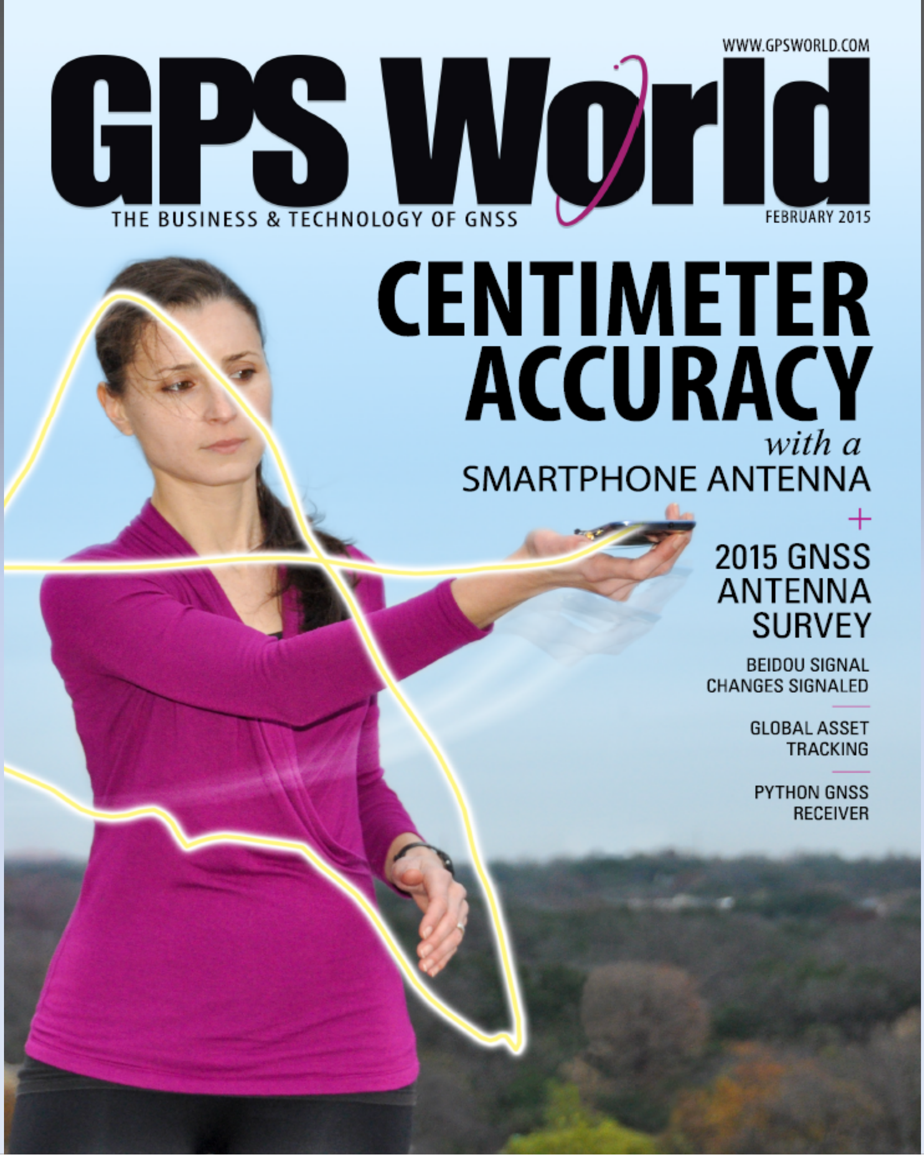


Handheld RTK result with some signals passing through Ken’s body

One of Picasso’s famous light paintings



GNSS “light painting” with a smartphone



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GPS World

THE BUSINESS & TECHNOLOGY OF GNSS

FEBRUARY 2015

CENTIMETER ACCURACY *with a* SMARTPHONE ANTENNA

+

2015 GNSS ANTENNA SURVEY

BEIDOU SIGNAL CHANGES SIGNALED

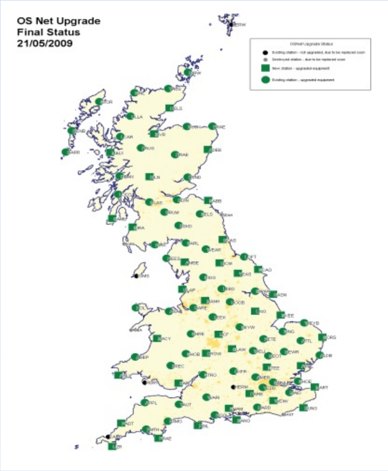
GLOBAL ASSET TRACKING

PYTHON GNSS RECEIVER

Work Proceeding on Two Fronts

Reference Network

Q: If we shift focus from network cost to end-user performance, i.e., time to reliable fix despite significant blockage and multipath at mobile device, how does this alter network layout?



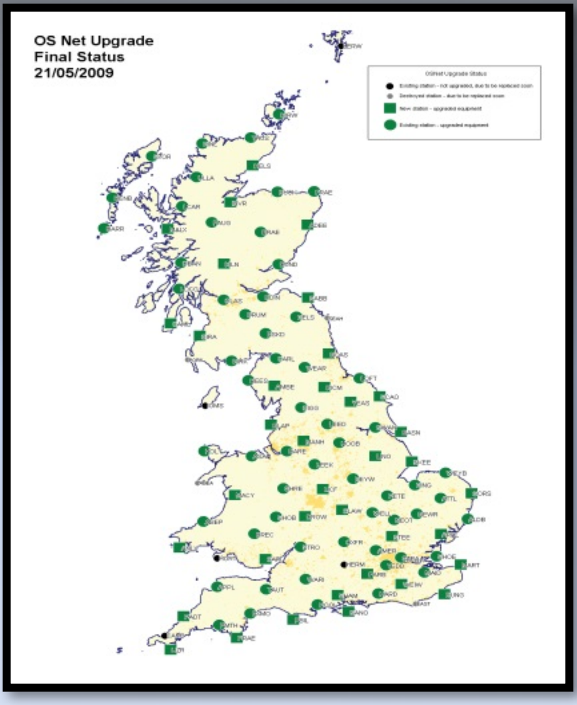
Existing permanent reference network: 70-100 km inter-station spacing

Mobile Device

Q: How must we modify existing low-cost mobile devices – handsets, VR headsets, intelligent vehicle sensors – to enable these to achieve cm-accurate positioning?

Samsung Galaxy phone with internal <$1 Broadcom GNSS chip

Mass market (MM) use of cm-accurate positioning upends the conventional wisdom (CW) on network design



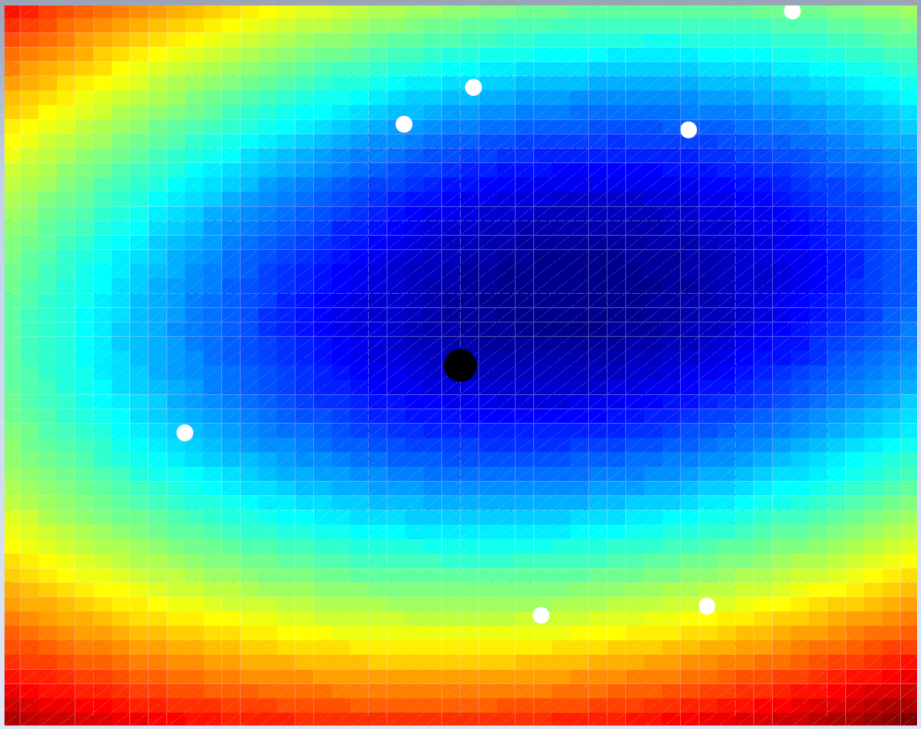
CW: Permanent reference stations cost \$50k for initial equipage+install and \$1k/yr to maintain, so network must be *sparse*.

MM: Cost of network is negligible when amortized across millions of users; performance is key, so network must be *dense*. Besides, adequate-quality reference stations can cost less than \$1k for equipage+install, \$100/yr maintenance.

University of Texas & Samsung
Centimeter-Accurate
Positioning System (CAMPS)
Dual-Frequency GPS/Galileo
Reference Station
Parts and assembly: ~\$1k

CW: Minimize number of stations while ensuring every user is within R km of a station; results in *uniformly-distributed network*.

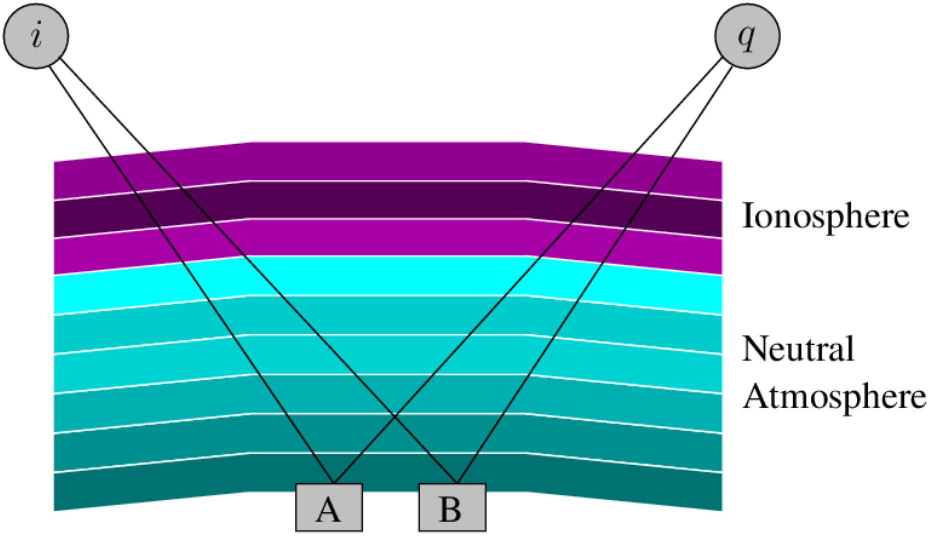
MM: Deploy stations *however necessary* to ensure P% of population experiences RMS corrections errors less than 2 mm; must take into account *population density* and *atmospheric spatial statistics.*



$$\nu = c_x dx + c_y dy + c_z dz + c_0$$

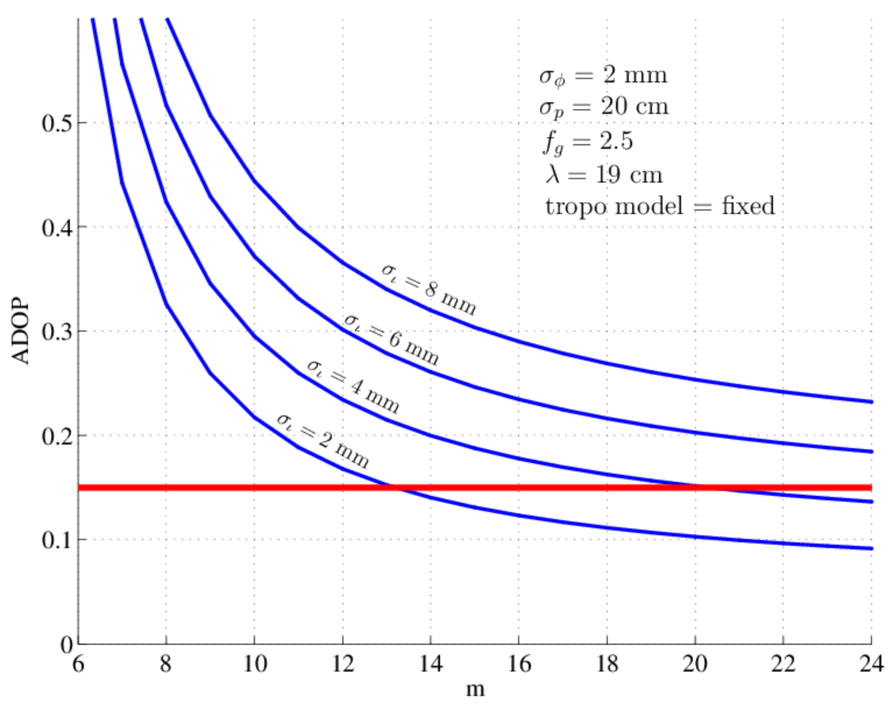
Standard deviation of network corrections for a linear DD iono + tropo model and iid multipath + thermal noise errors at each of 8 reference stations whose locations are known

Red = high, blue = low

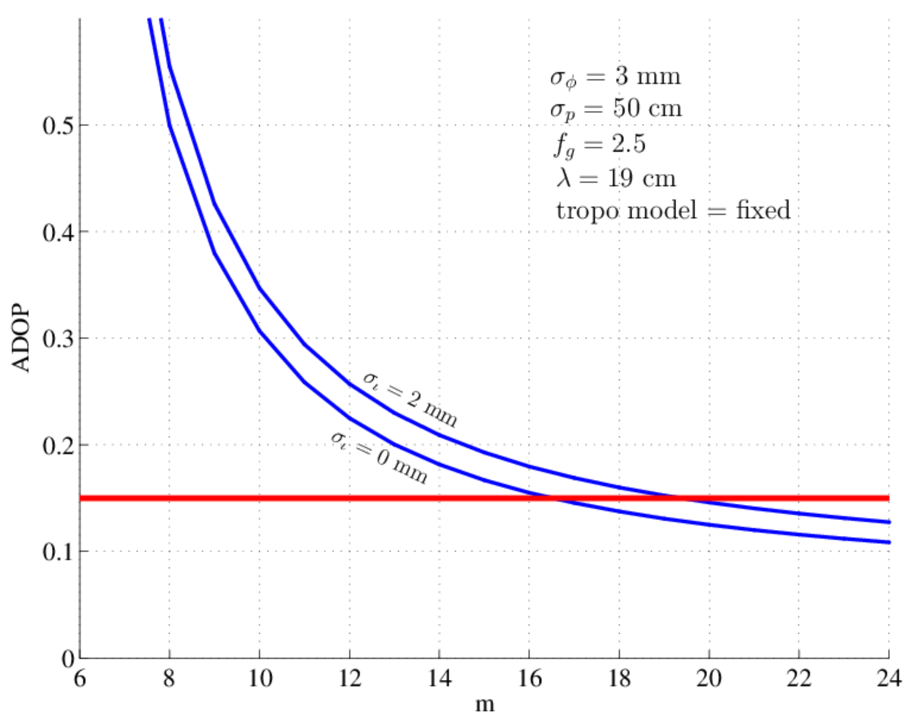


$$\rho^{iq}_{\mathrm{AB}} = r^{iq}_{\mathrm{AB}} + I^{iq}_{\mathrm{AB}} + T^{iq}_{\mathrm{AB}} + w^{iq}_{\rho,\mathrm{AB}}$$

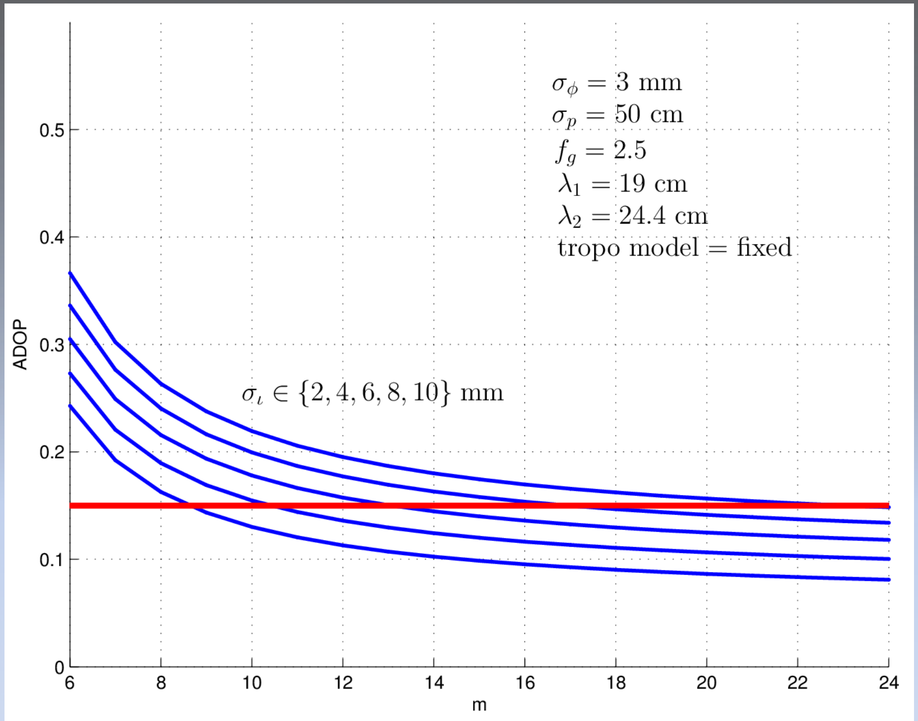
$$\lambda\phi^{iq}_{\mathrm{AB}} = r^{iq}_{\mathrm{AB}} - I^{iq}_{\mathrm{AB}} + T^{iq}_{\mathrm{AB}} + \lambda N^{iq}_{\mathrm{AB}} + \lambda w^{iq}_{\phi,\mathrm{AB}}$$



Dense network benefits: (1) iono+tropo DD errors can be made negligible, and (2) master station multipath attenuated



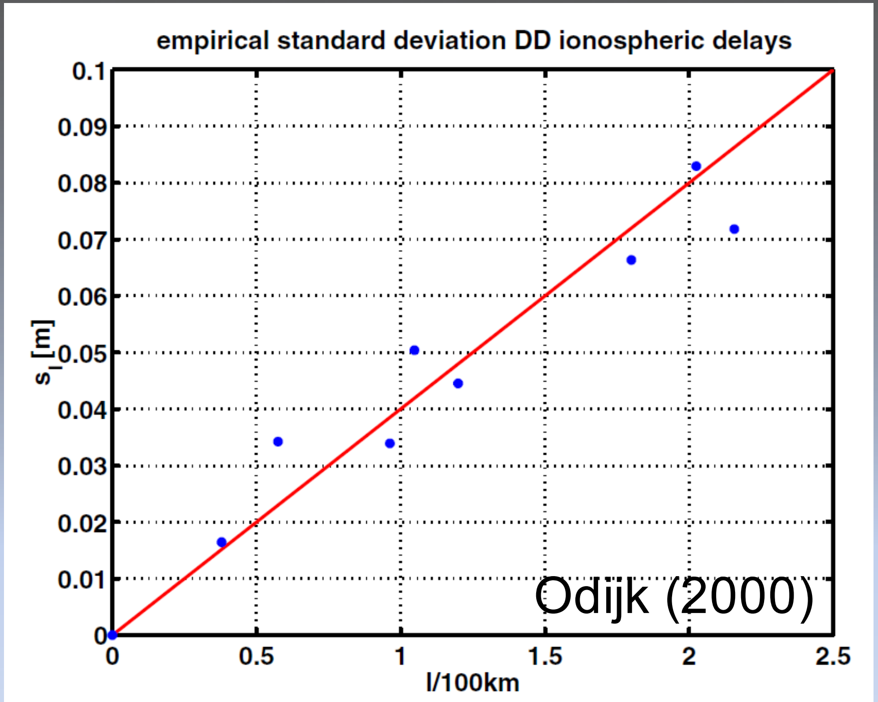
Reality check for single-frequency RTK with network-provided corrections: For low-cost antennas in realistic multipath environments, a dense network can't ensure reliable single-epoch fixing.



Adding a second frequency helps tremendously: for RMS corrections errors of 2 mm (attainable with < 20 km inter-station spacing), reliable single-epoch fixing is possible with only m = 9 satellites.

Q: What is functional relationship between network density and the size of RMS errors in the DD iono + tropo corrections?

(In other words, how dense must our reference network be to achieve 2 mm RMS corrections errors?)



Odijk (2000)

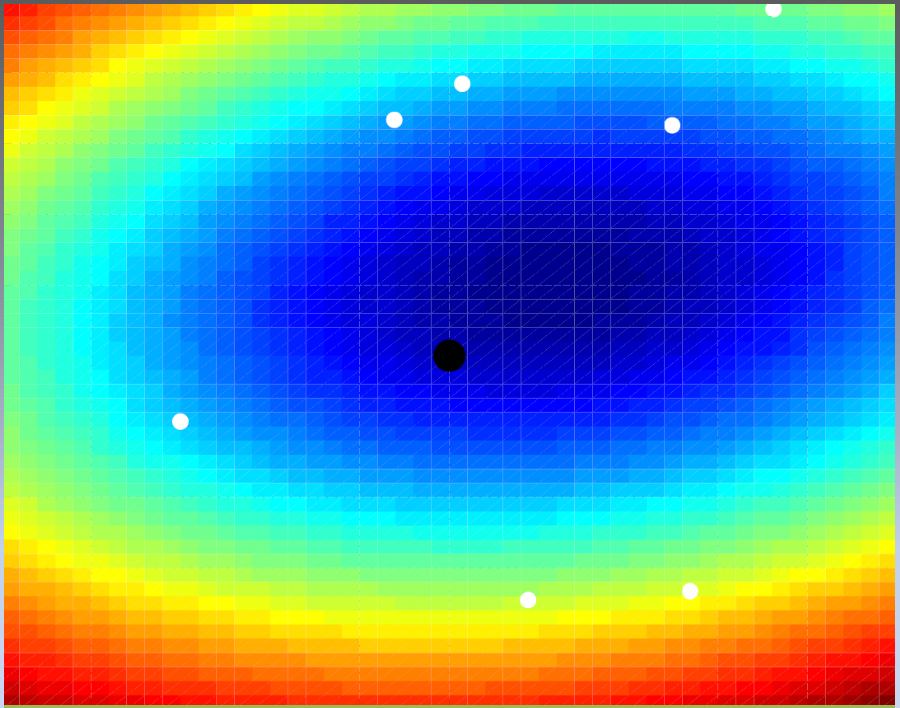
Single-baseline

$$\sigma_\iota = l\beta, \quad 0.3 \leq \beta \leq 3 \text{ mm/km}$$

β — uncertainty scaling factor

l — distance to reference station

σ_ι — uncertainty in iono correction

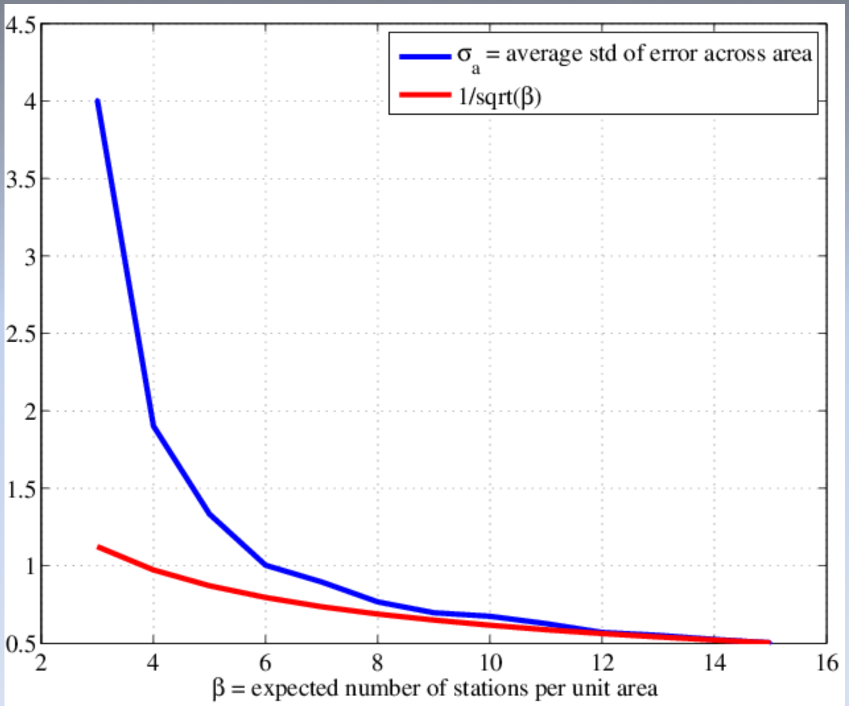


Network

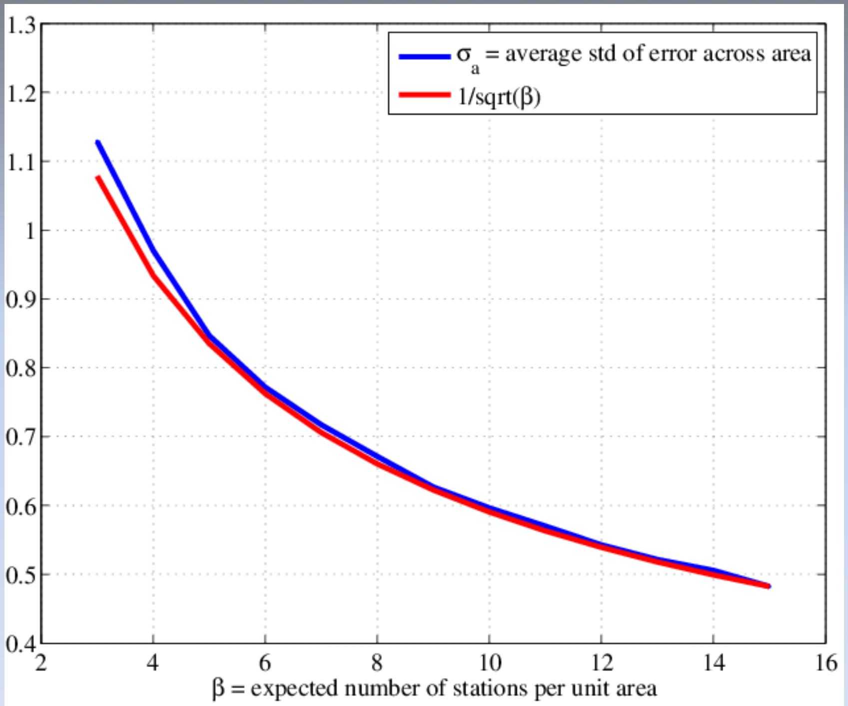
$$\nu = c_x dx + c_y dy + c_z dz + c_0$$

Uncertainty in DD corrections at any point depends on (1) interpolation model, (2) accuracy of interpolation model, and (3) location of point relative to master

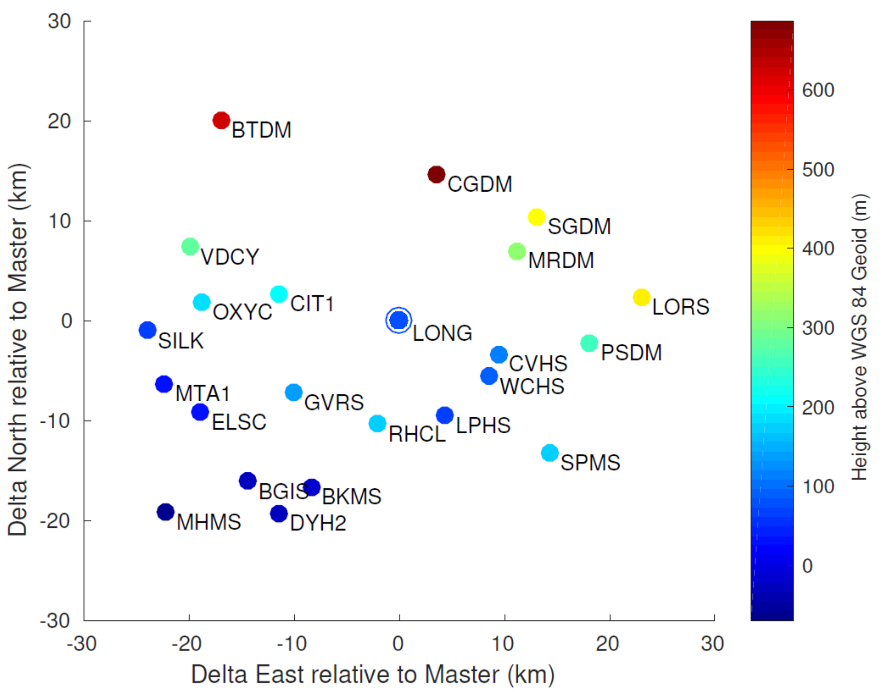
The theory of stochastic geometry shows the way to a closed-form relationship between network density and average uncertainty of corrections



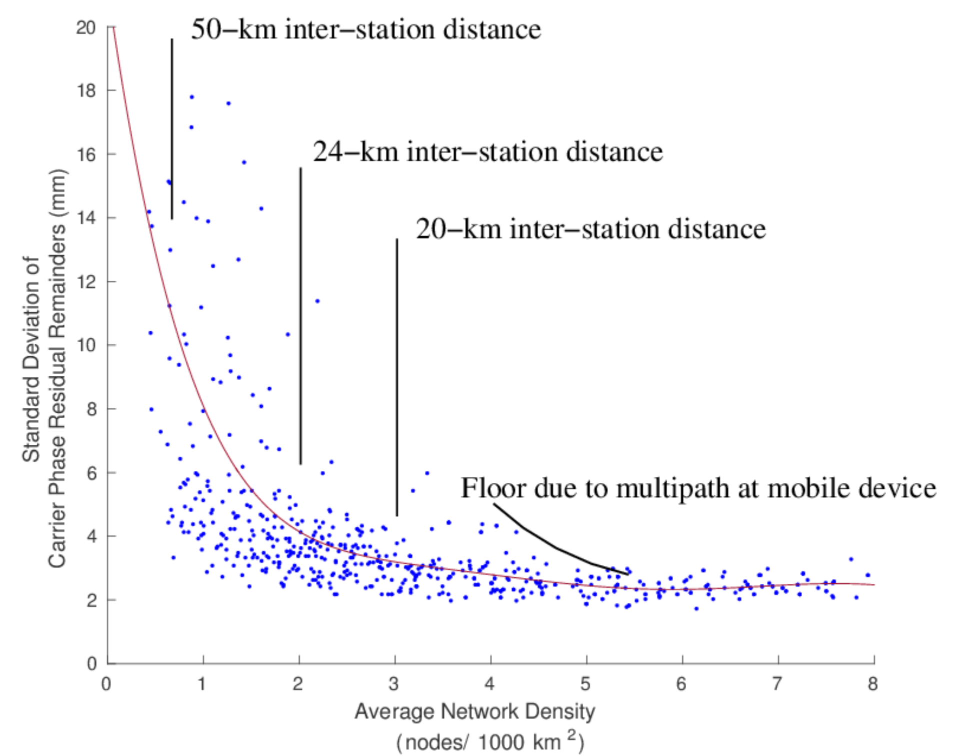
Average correction uncertainty when stations are distributed according to a Poisson point process



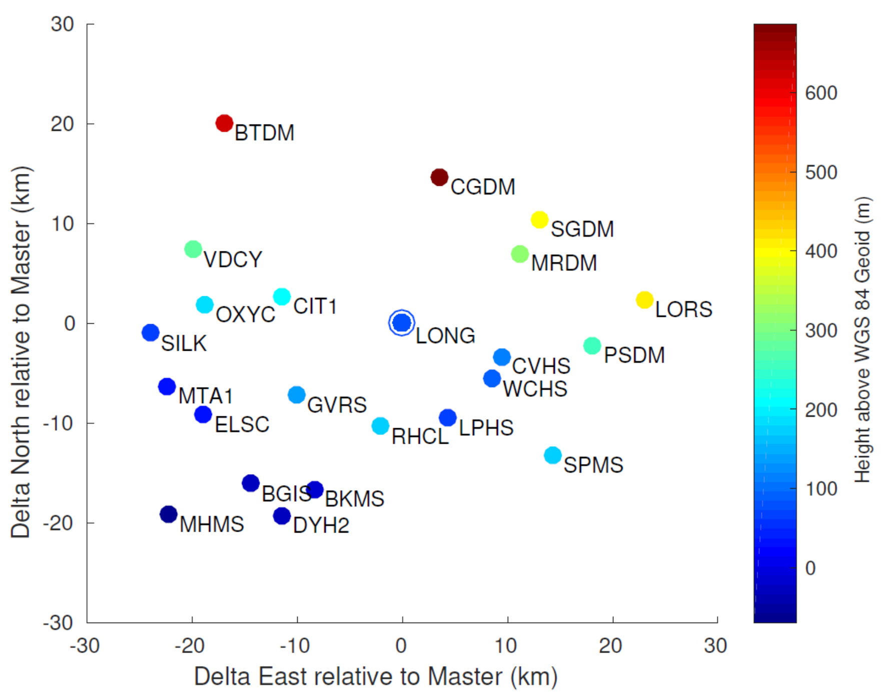
Average correction uncertainty when stations are distributed according to a repelling point process (e.g., determinantal)



Empirical data drawn from 23 stations in existing high-density public reference network in California



Corrections uncertainty is a highly nonlinear function of density. Floor due to multipath at mobile device reached only with < 20km inter-station distance.



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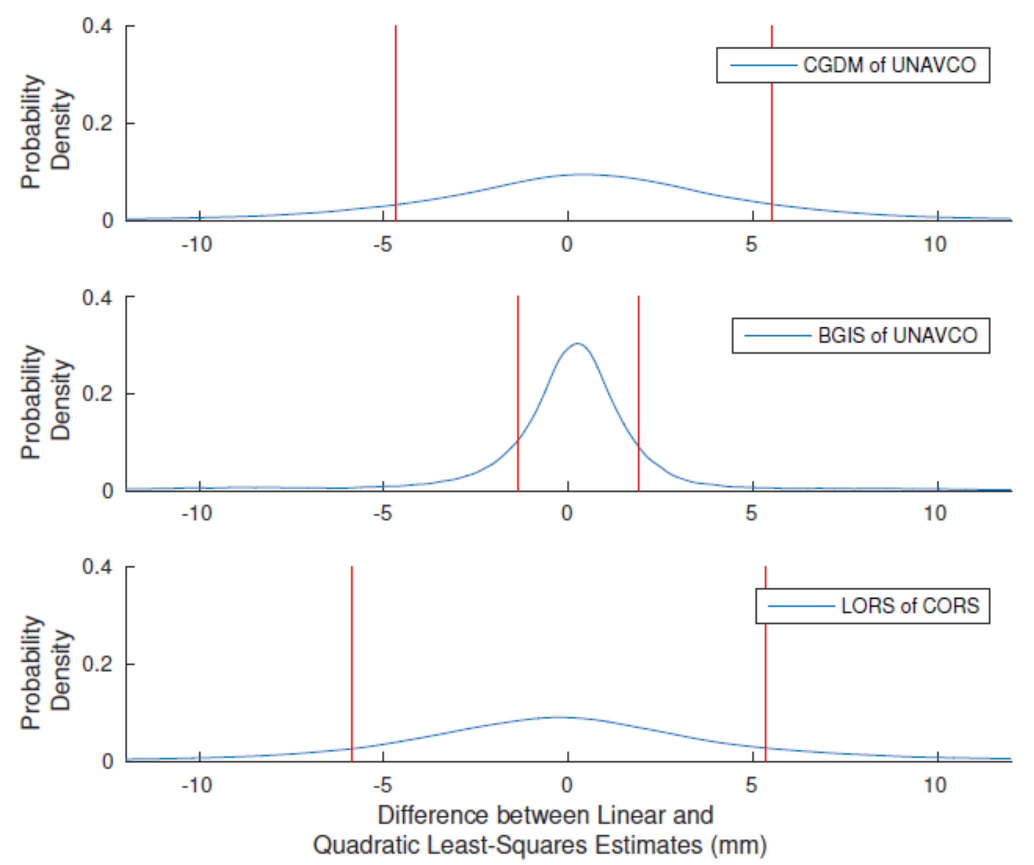
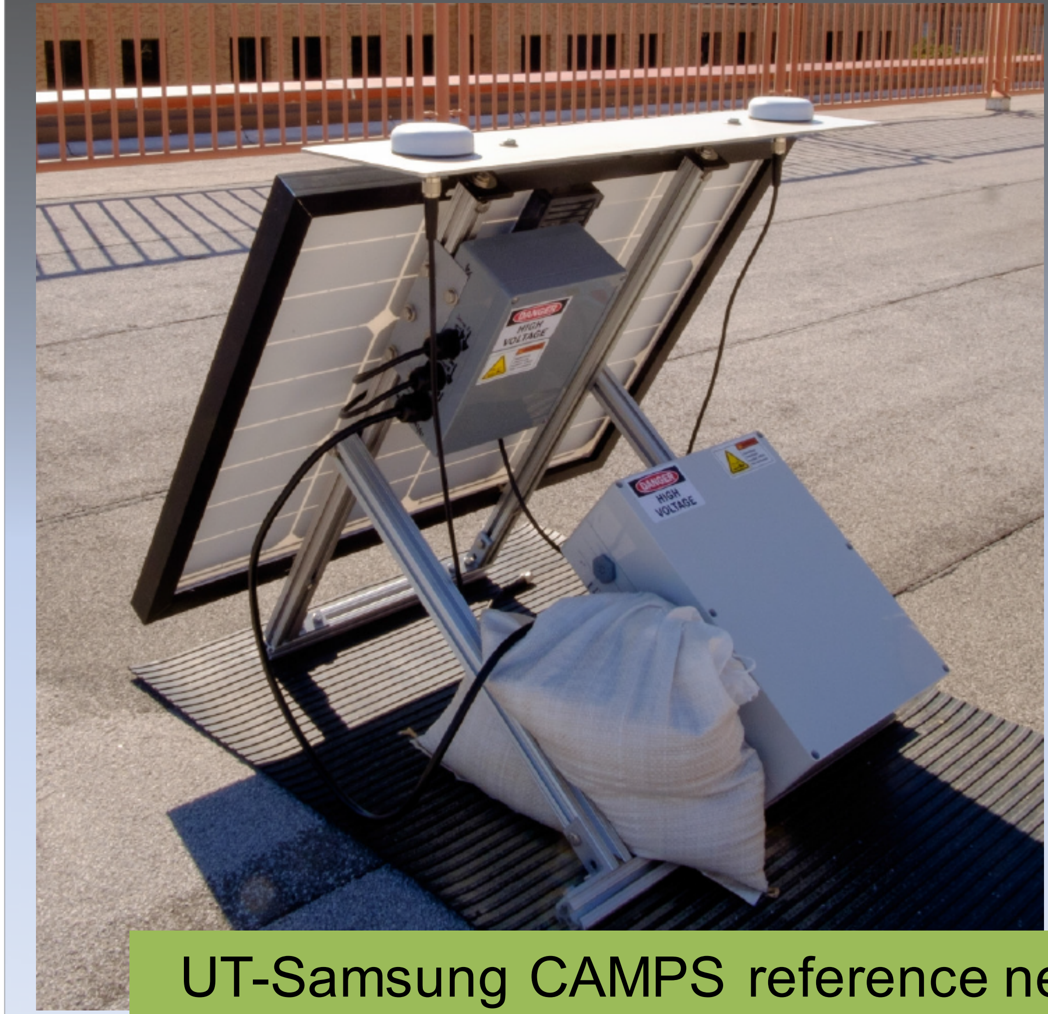
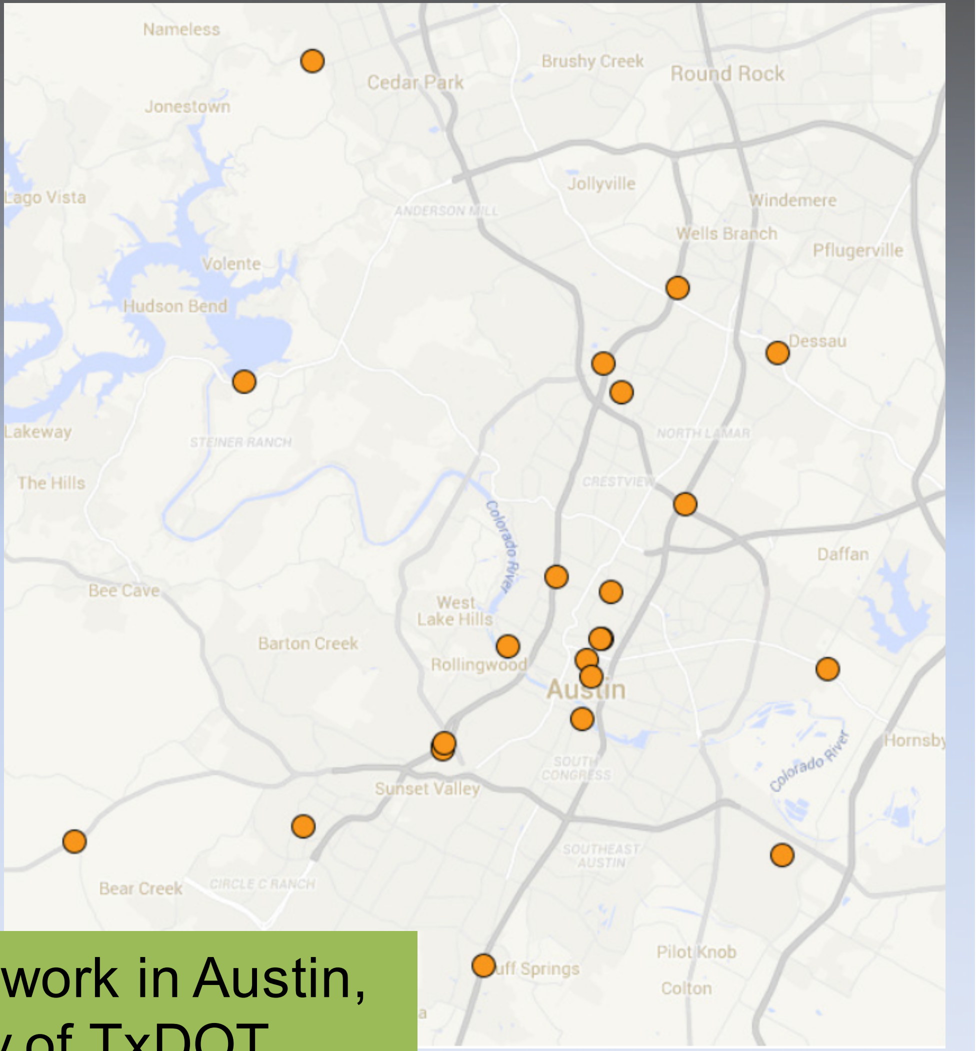
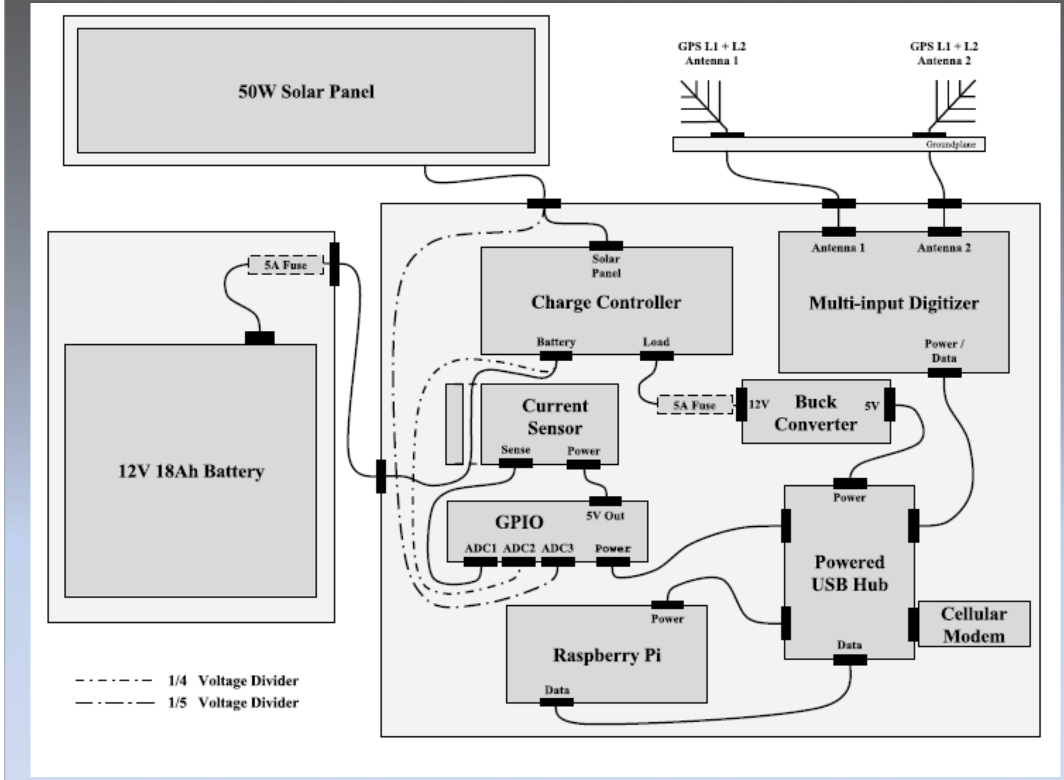


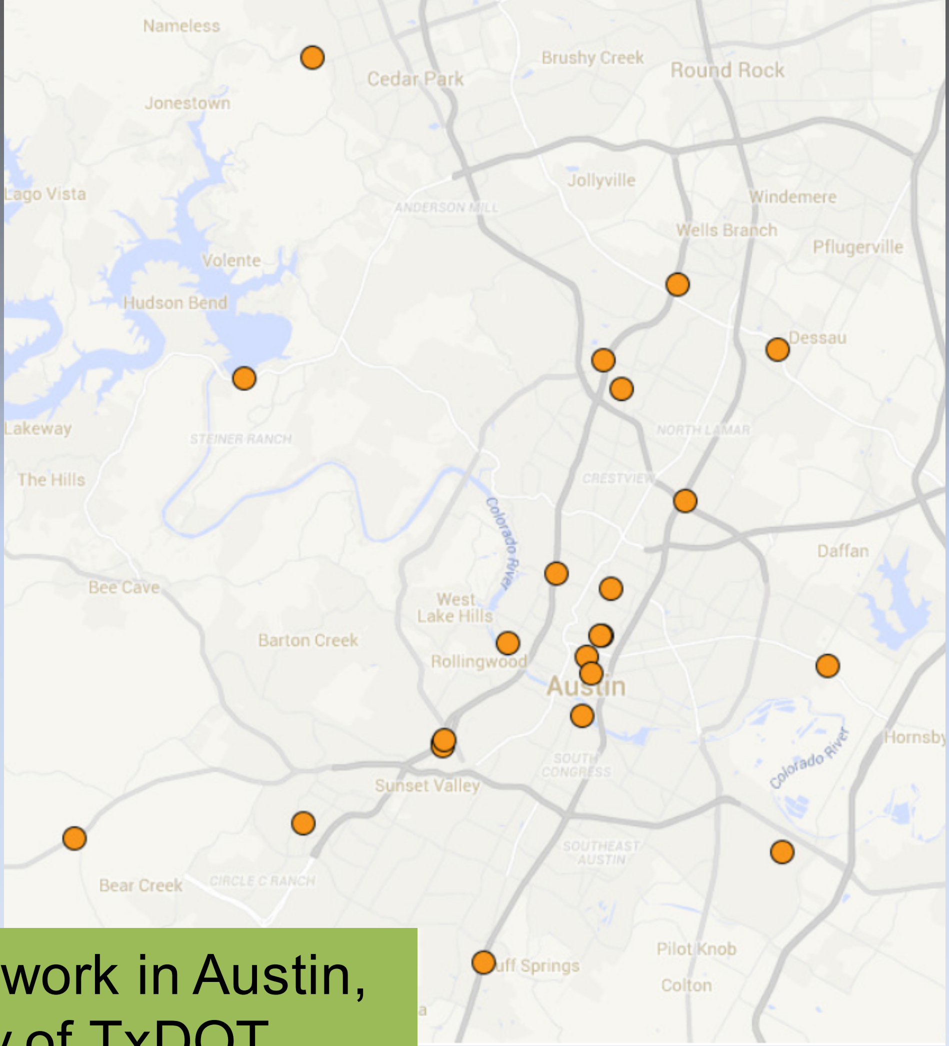
For the 30-km radius dense network studied, the difference between a linear and a quadratic interpolation model is near the multipath error level. Hence, the linear model is valid.





UT-Samsung CAMPS reference network in Austin, Texas, with site hosting courtesy of TxDOT





UT-Samsung CAMPS reference network in Austin, Texas, with site hosting courtesy of TxDOT

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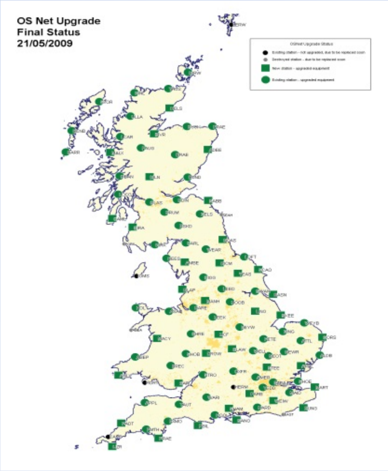


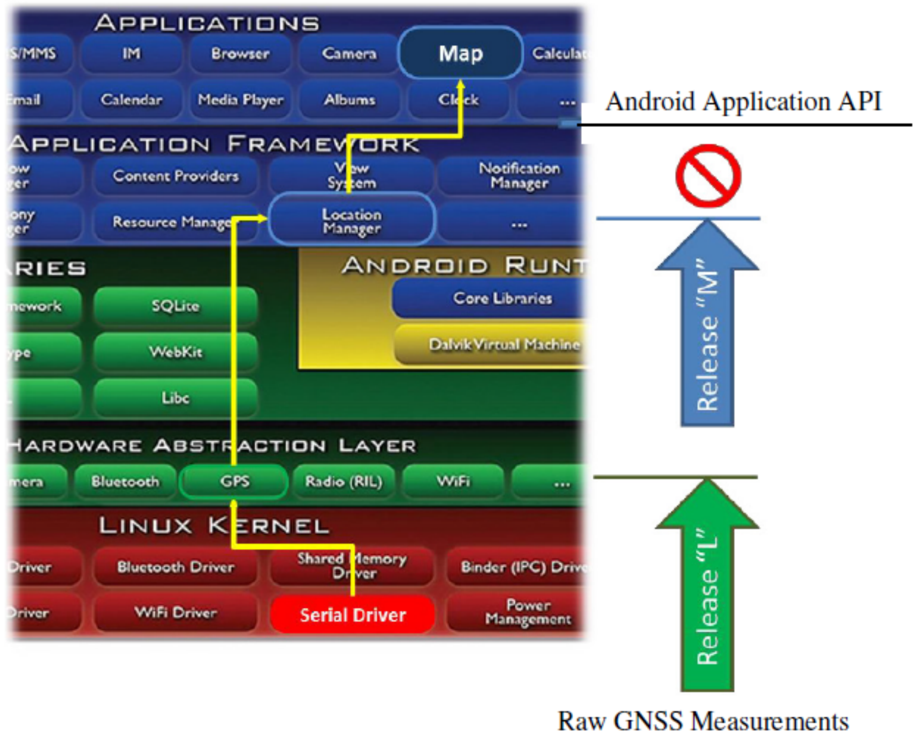
Existing permanent reference network: 70-100 km inter-station spacing

Mobile Device

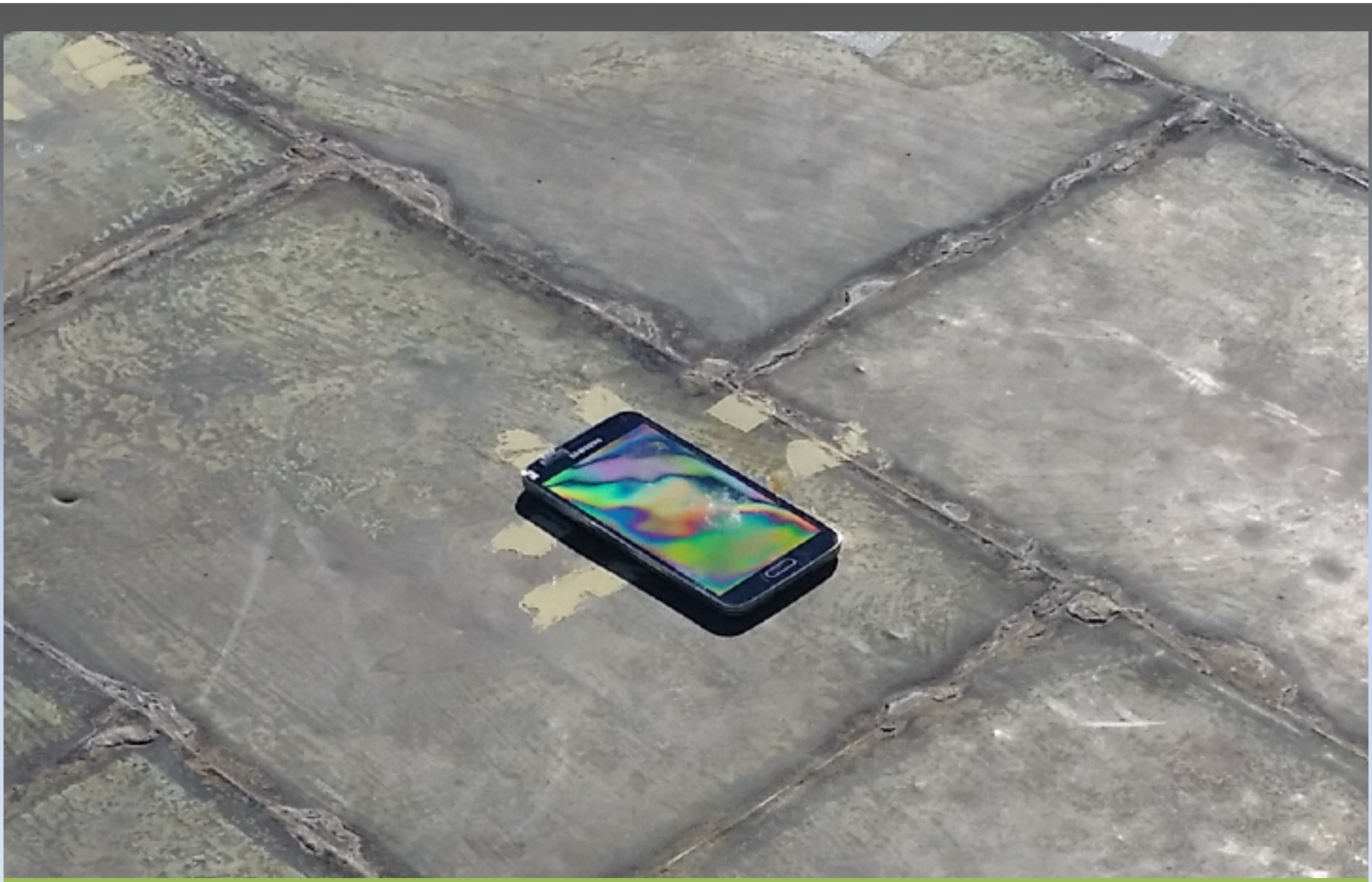
Q: How must we modify existing low-cost mobile devices – handsets, VR headsets, intelligent vehicle sensors – to enable these to achieve cm-accurate positioning?

Samsung Galaxy phone with internal <$1 Broadcom GNSS chip

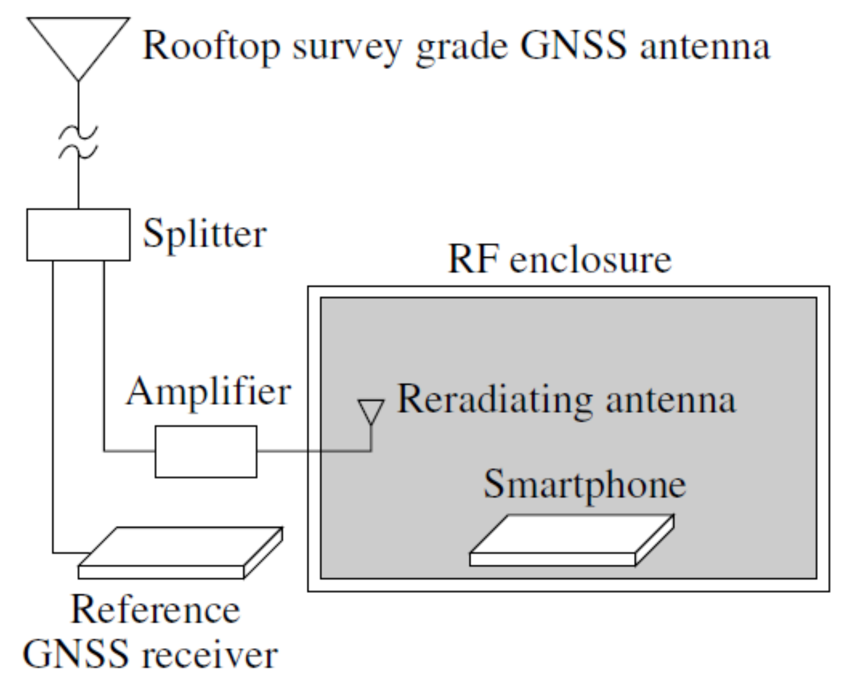
Q: We already know that (fragile) fixed-integer RTK is possible using a smartphone's internal antenna. But what about using its internal GNSS chip (and clock) for this purpose?

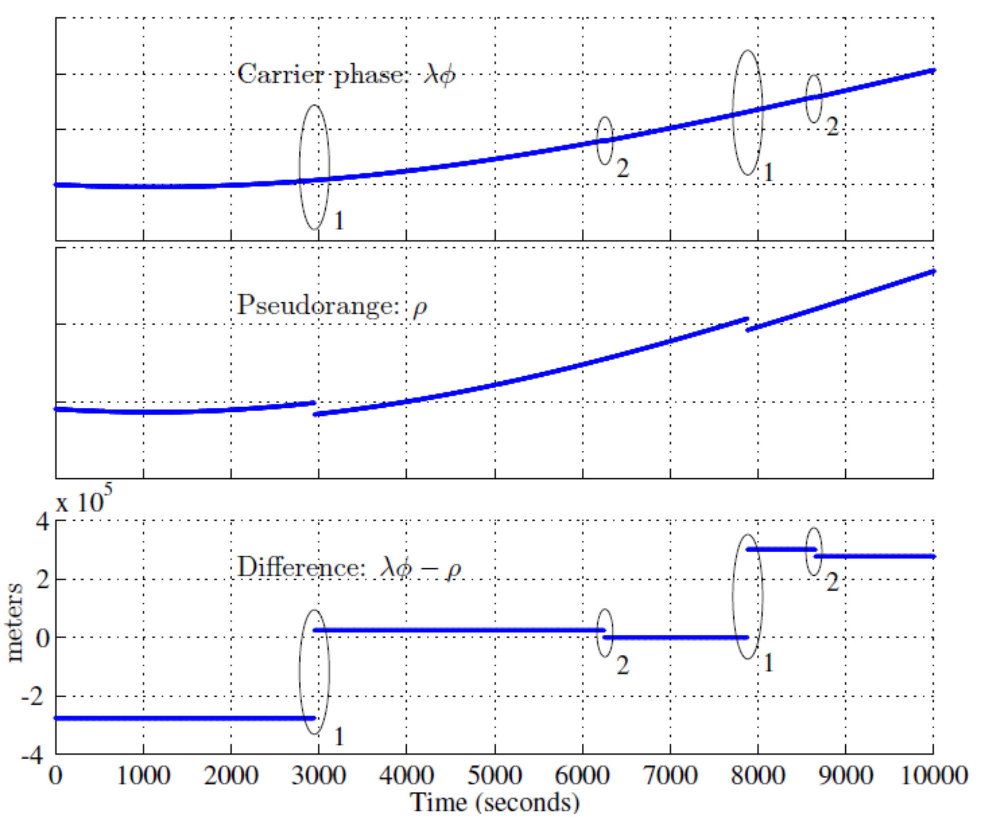


The Broadcom chip inside many smartphones produces pseudorange and carrier phase observables for all signals tracked (multi-constellation), but Android provides no access to these.

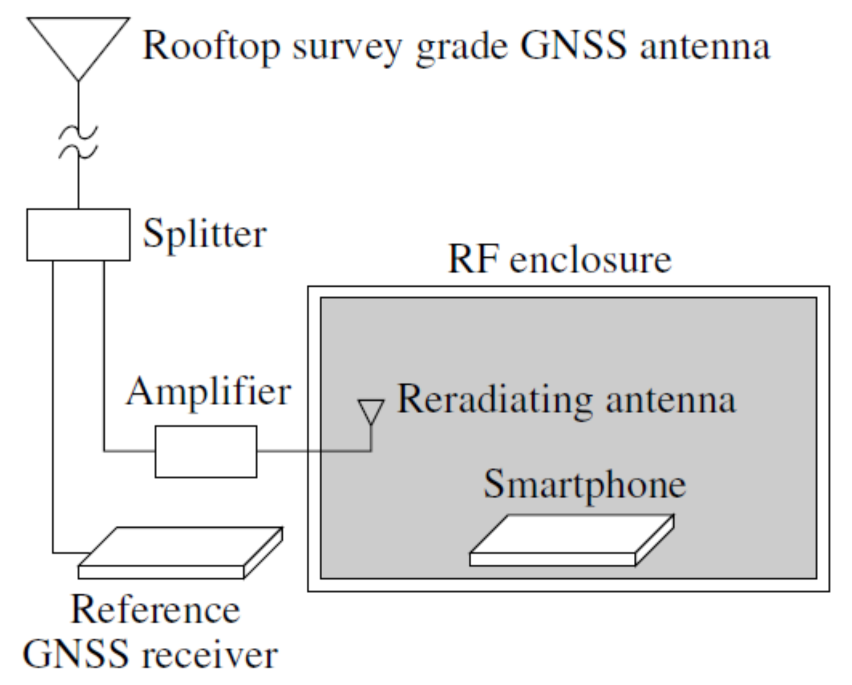


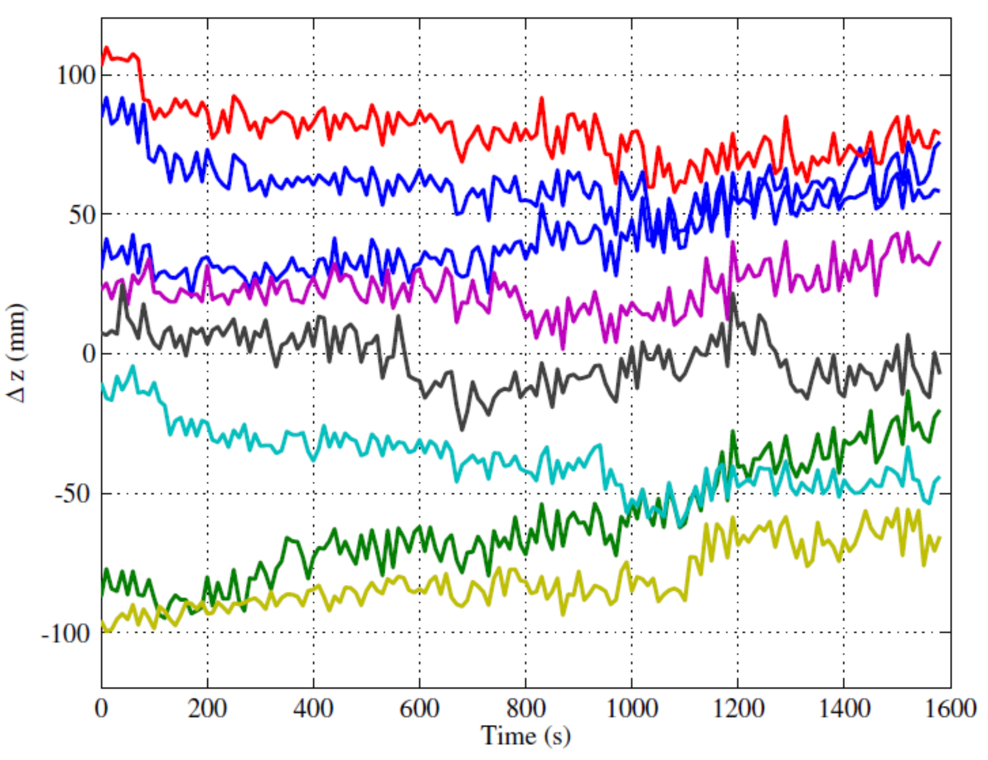
This Galaxy S5 produces RINEX files, thanks to Frank van Diggelen and Sergei Podshivalov (Broadcom).



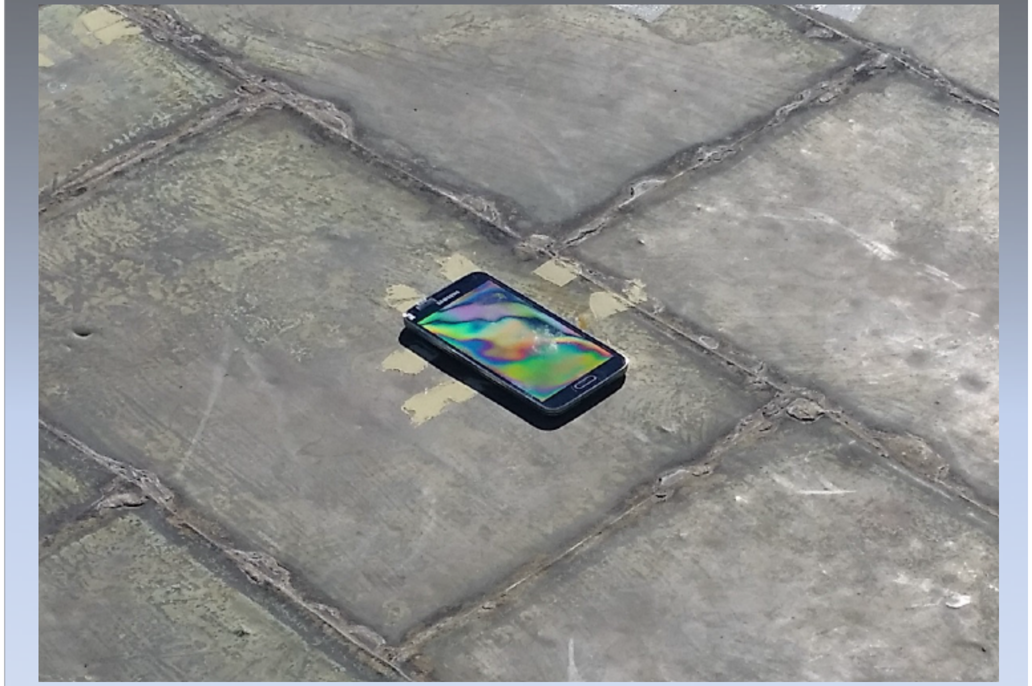


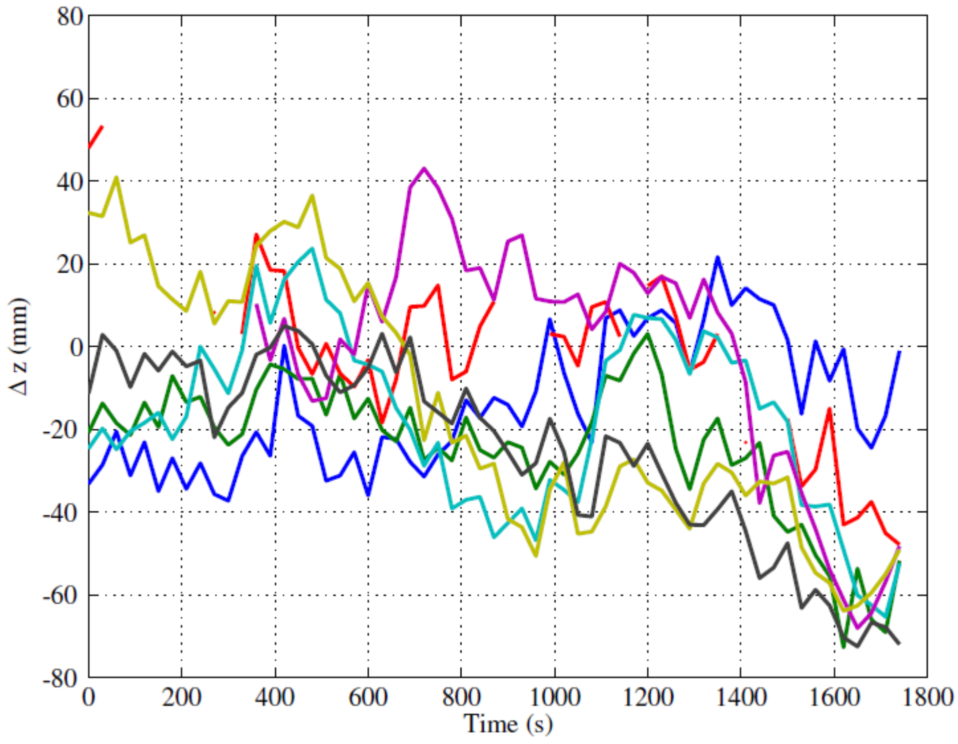
A zero-baseline test reveals excellent pseudorange but 5 phase anomalies, 4 of which are readily fixed in post-processing.





The 5th anomaly is a nonzero and drifting bias in the carrier phase measurements that prevents both float and fixed solutions

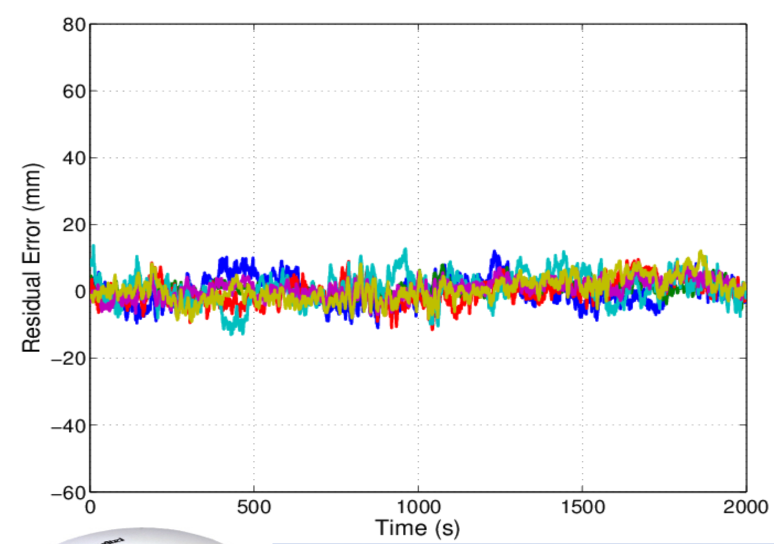




Phone produced cycle-slip-free carrier measurements for 9 GPS L1 C/A signals over a half hour interval.

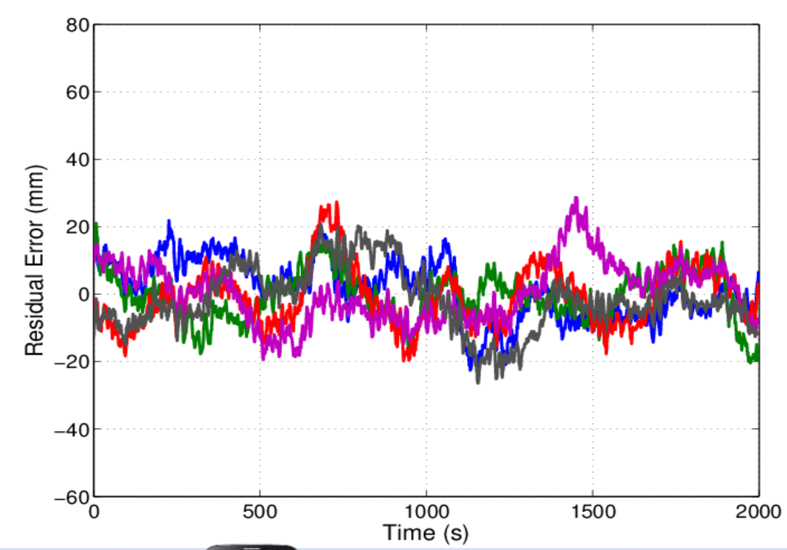
Primary Challenge: Large Time-Correlated Multipath Errors

Phase Residuals
Survey-Grade Antenna



Undifferenced std:
1.7 mm

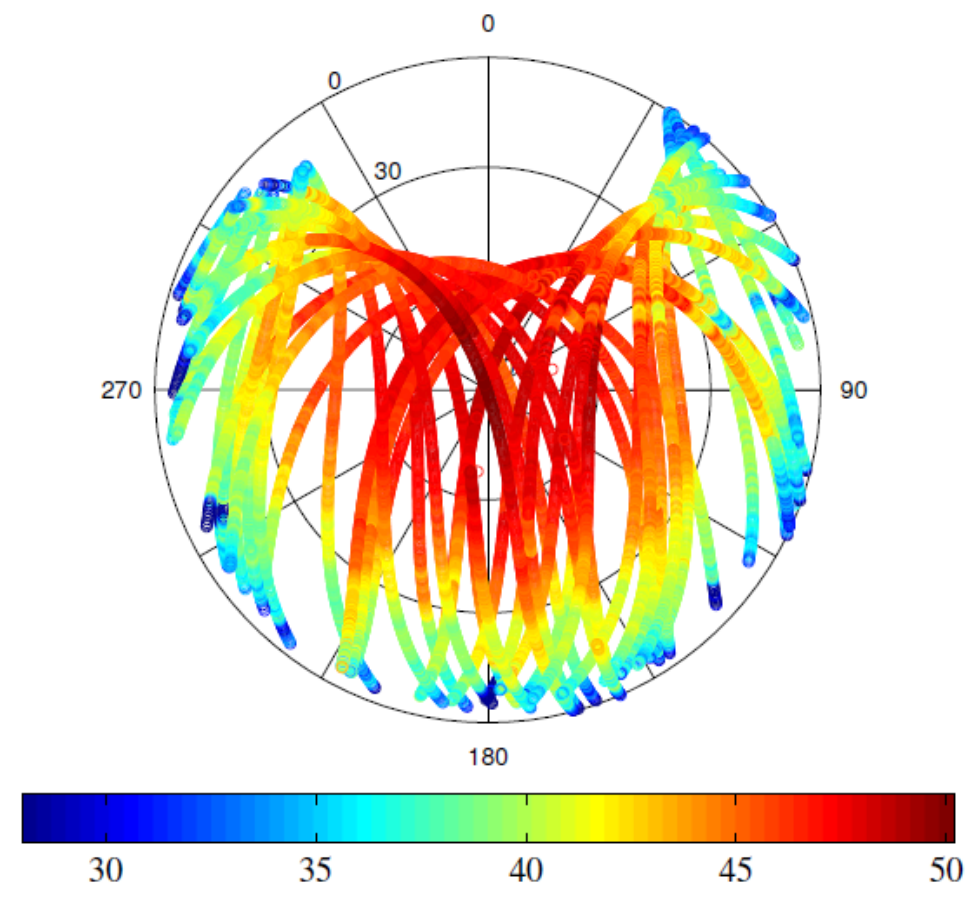
Phase Residuals
Smartphone Antenna



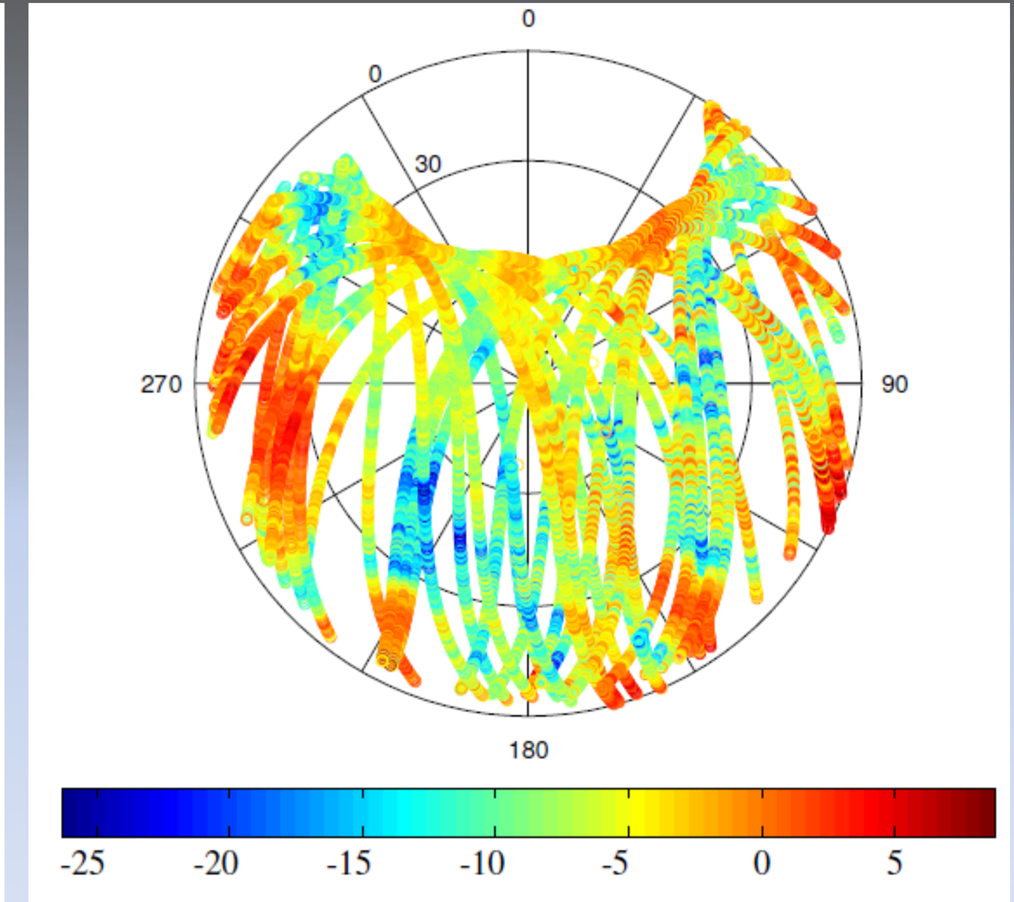
Undifferenced std:
5.3 mm
4.2 mm

Q: Is the phone antenna’s irregular gain pattern to blame for the outlier DD phase measurements?

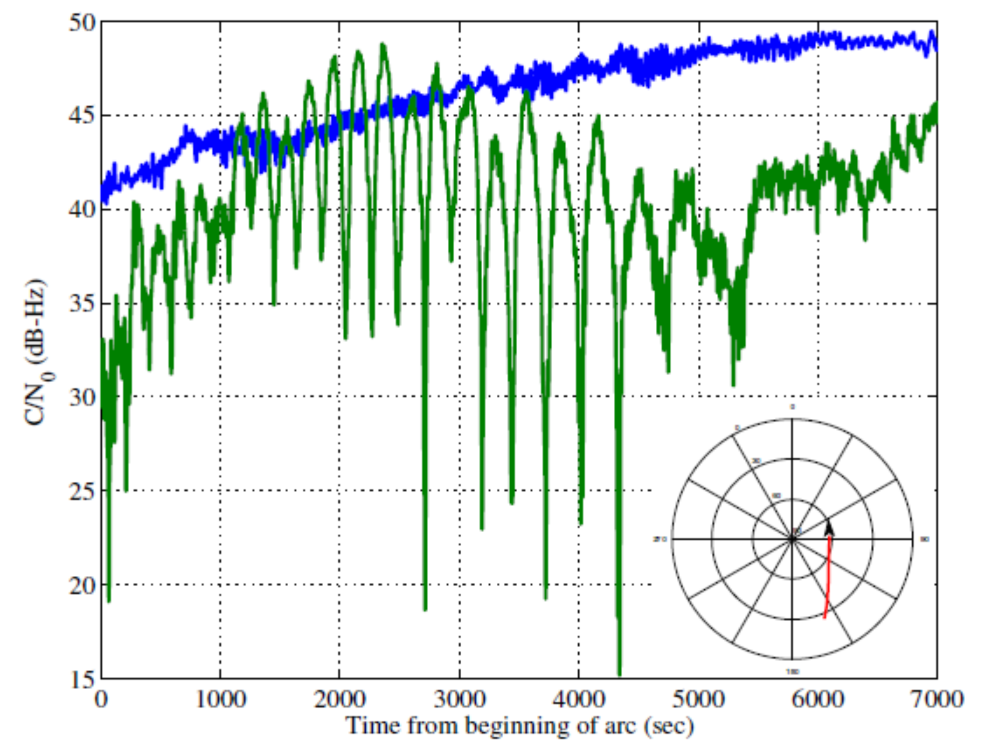
Experimental setup for Galaxy S3 gain pattern analysis



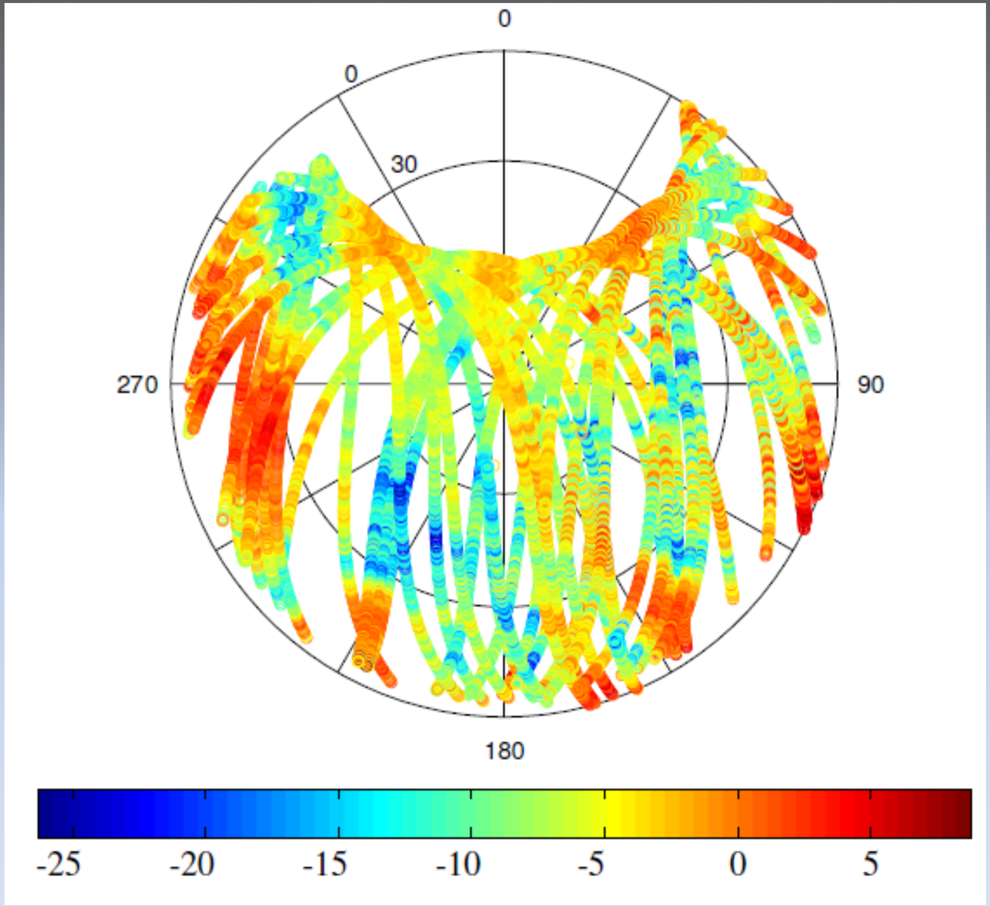
NovAtel Pinwheel C/N0 skyplot



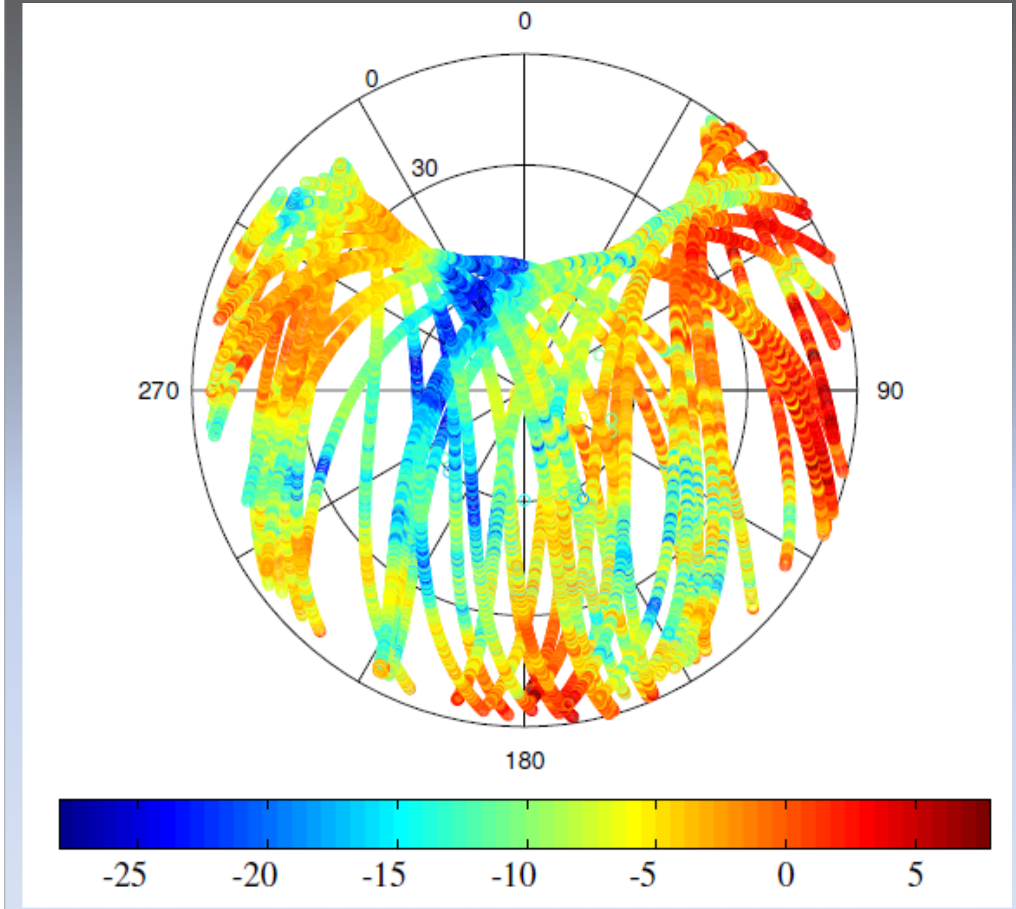
Galaxy S3 relative C/N0 skyplot



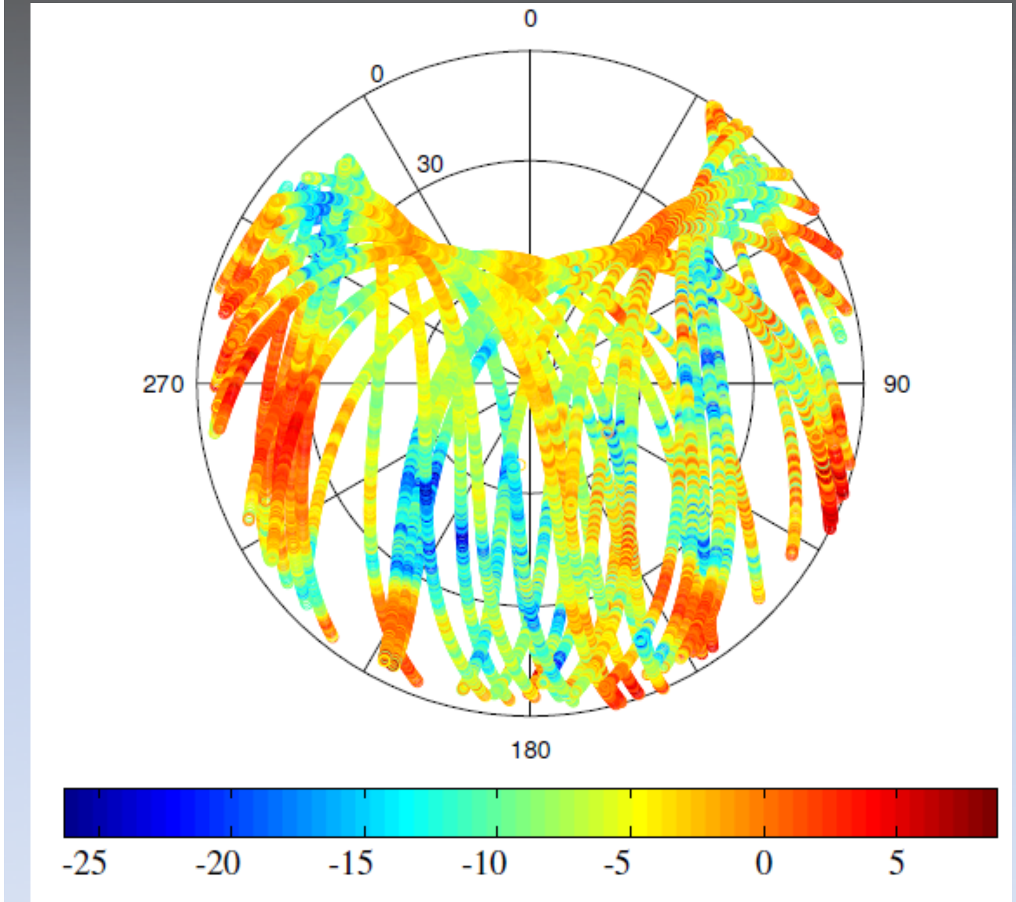
S3 (green) and Pinwheel (blue) C/N0 traces over the indicated arc



Galaxy S3 relative C/N0 skyplot



Phone moved a few cm to the east: relative C/N0 skyplot remarkably different, suggesting it's dominated by multipath

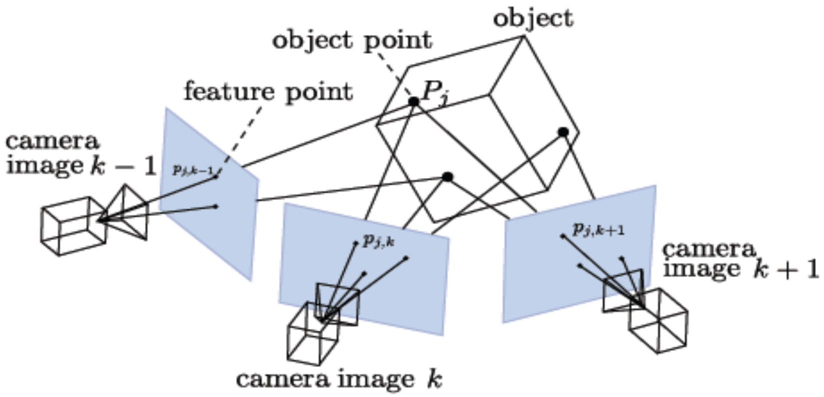


Galaxy S3 relative C/N0 skyplot

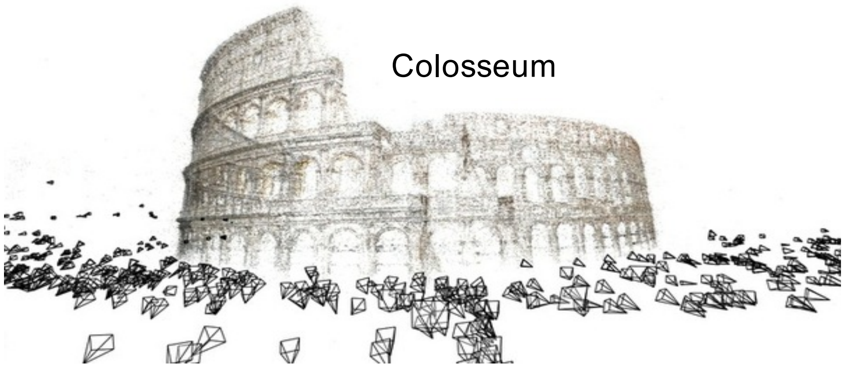
But our smartphone also has a camera ...

... what could we do with the camera?

Over the past 15 years, the computer vision community has made stunning advances in what is variously known as structure from motion (SFM), photogrammetry, and Vision-based Simultaneous Localization and mapping (VSLAM)



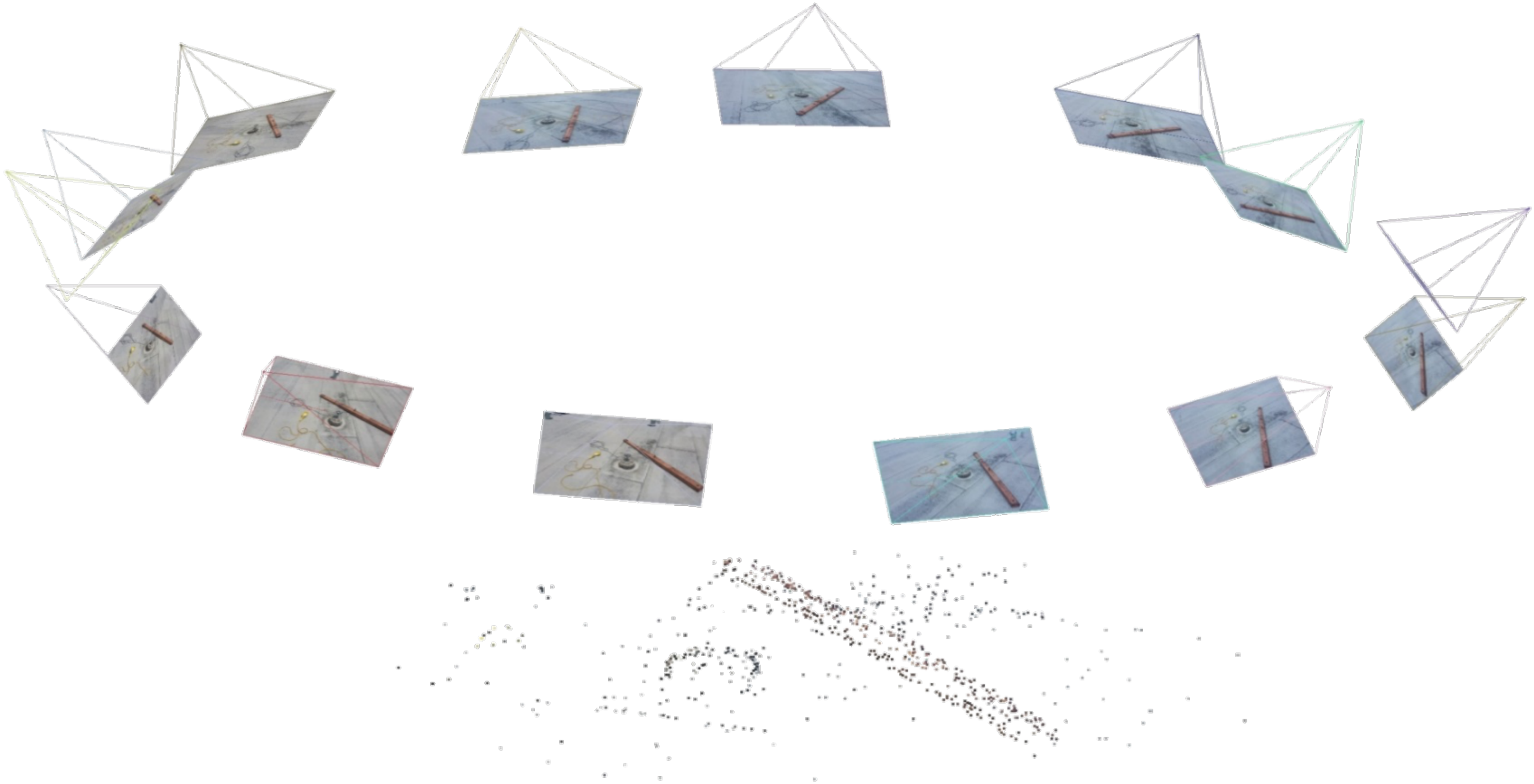
OpenMVG (2015)



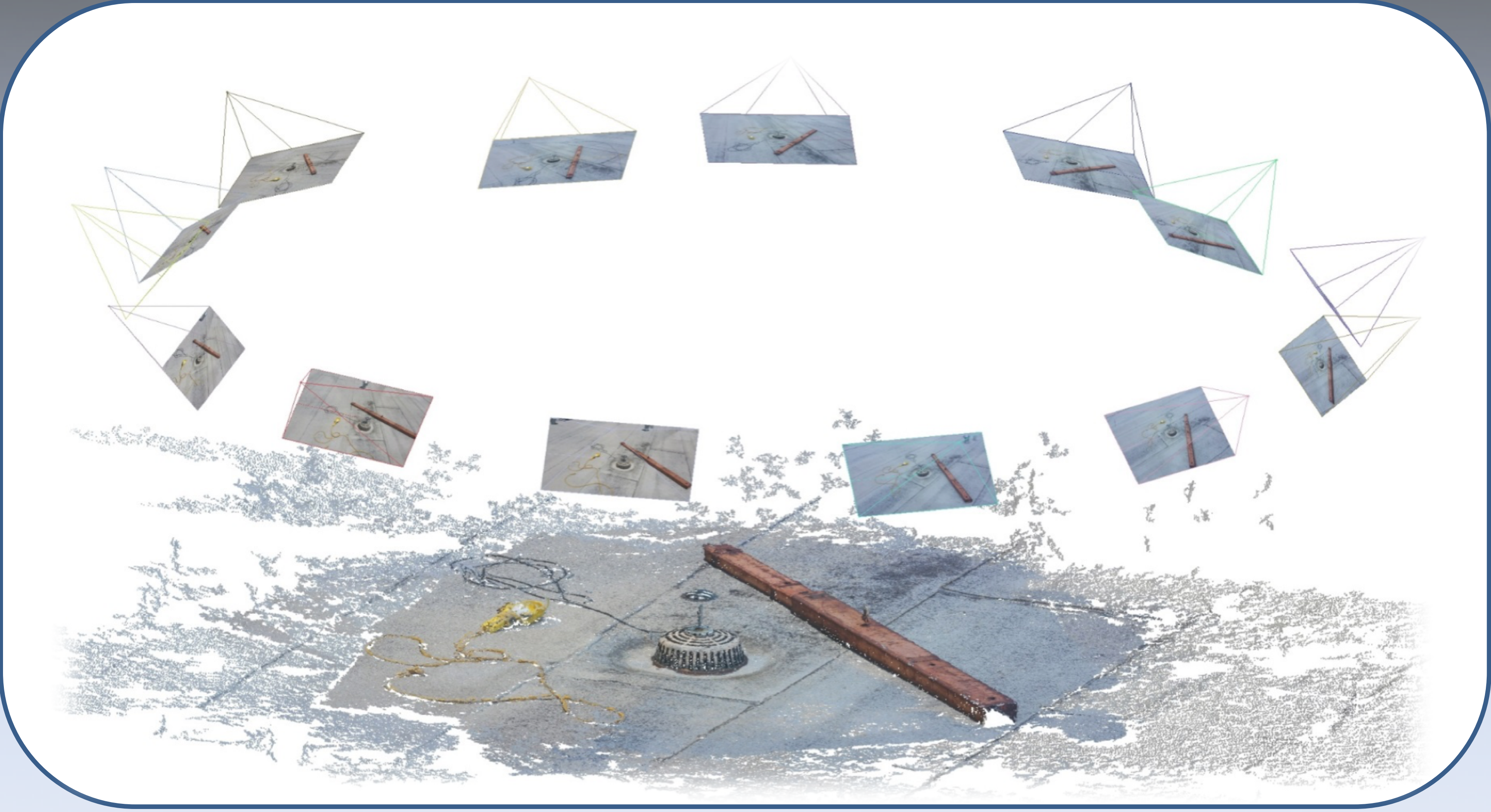
Agarwal & Snavely (2009)

Extending the SFM technique, we optimally fuse camera images and GNSS phase measurements to shorten time to fix *and* create geo-referenced 3D maps

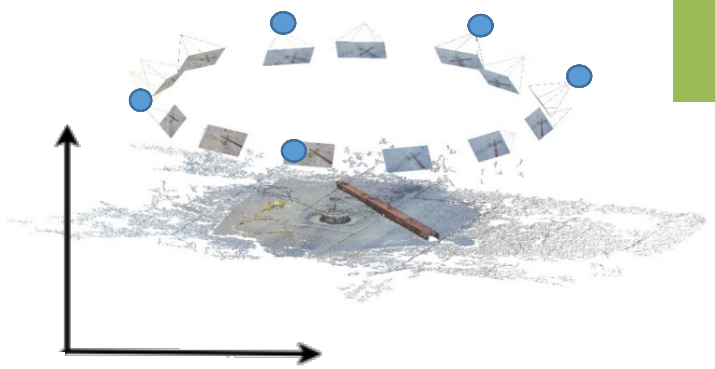
Sparse 3D Reconstruction



Dense 3D Reconstruction



Optimal ML solution



Resulting 3D point cloud is referenced to ITRF

Jointly fuse GNSS carrier phase and vision measurement in the same non-linear estimator:

CDGNSS Integer Ambiguities

Point Feature Positions

Vision Measurements

$$f_{\mathrm{NL}}\left(\mathbf{X}_{BA}\right) = \sum_{i=1}^{L}\left[\left\|R^{-1/2}_{y^k_{\phi,i}}\left(\mathbf{y}_{\phi,i} - \mathbf{h}_\phi\left(\mathbf{x}_{\mathcal{G}}^{\mathcal{C}_i}, \mathbf{q}_{\mathcal{G}}^{\mathcal{C}_i}, \mathbf{N}\right)\right)\right\|^2 + \sum_{j=1}^{M}\left\|R^{-1/2}_{\mathbf{y}_i^{\mathrm{p}_j}}\left(\mathbf{y}_i^{\mathrm{p}_j} - \mathbf{h}_y\left(\mathbf{x}_{\mathcal{G}}^{\mathcal{C}_i}, \mathbf{q}_{\mathcal{G}}^{\mathcal{C}_i}, \mathbf{x}_{\mathcal{G}}^{p_j}\right)\right)\right\|^2\right]$$

Phase Measurements

Camera Positions

Camera Orientations

Our technique preserves both the *sparsity* of bundle adjustment and the *integerness* of the carrier phase ambiguities


SAMSUNG

Point #392758

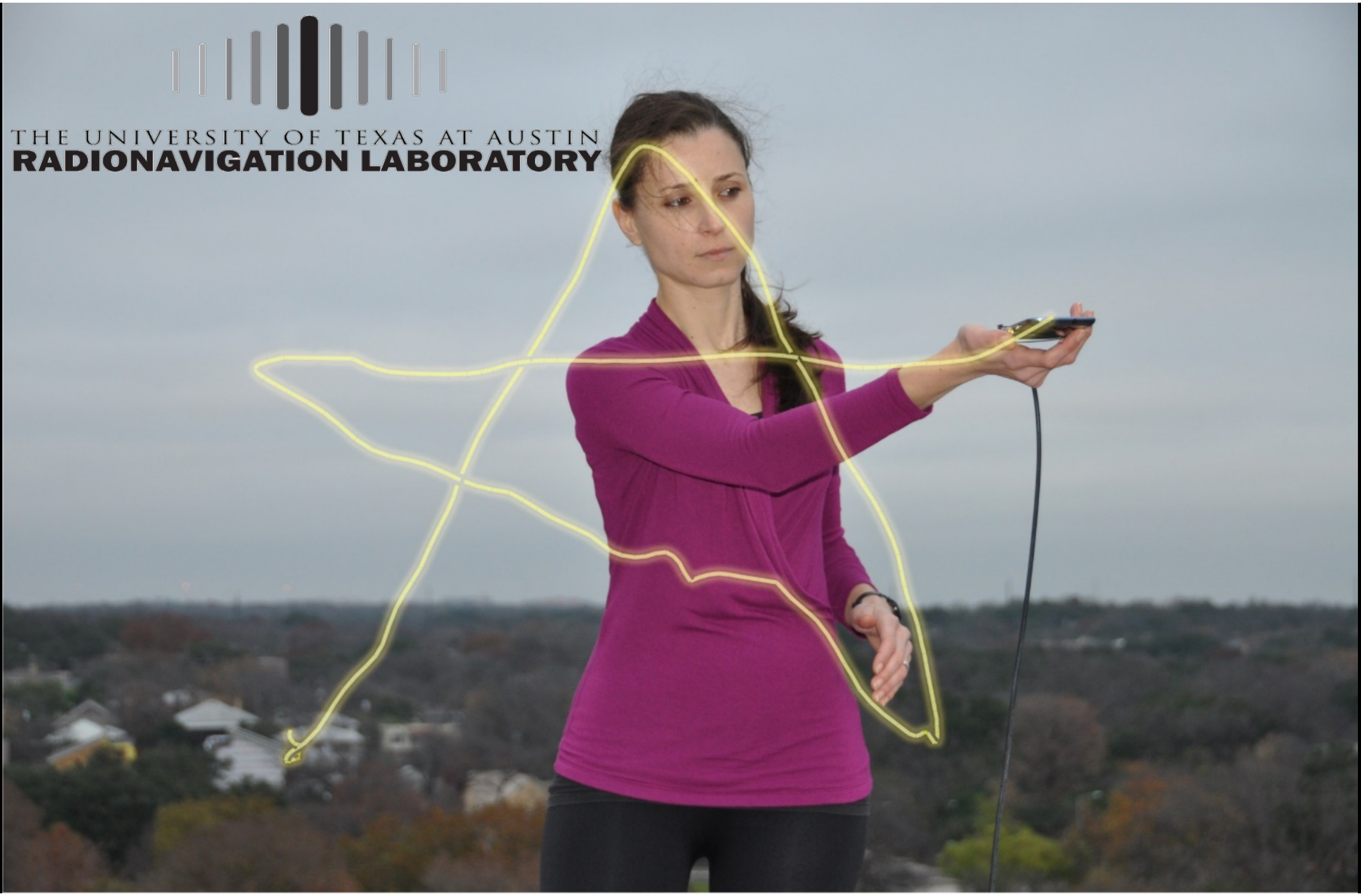
P#392758: (-24.280500;-3.722230;-7.438940)

Normal: (0.460726;0.513380;0.723998)

Color: (94;117;136)

Position	East	North	Up
VISRTK+MVS	-24.280	-3.722	-7.438
CDGNSS	-24.278	-3.721	-7.440
Difference	-0.002	-0.001	0.002
Expected Std.	0.004	0.008	0.005

Result: A globally-referenced 3D point cloud accurate to better than 1 cm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RADIONAVIGATION LABORATORY