Hogarth 2014 Supplementary note 2: Hawaiian Islands tide gauge data

Introduction

This note summarises work on extending regional tide gauge data from Hawaii and Oahu. It is intended as a supplementary reference and gives some of the regional context, data and sources underlying the global analysis of sea level acceleration in Hogarth 2014 (accepted for publication 12th Oct 2014). The data from this work extends the PSMSL annual time series by back by 13 years with robust datum connections and without gaps, and back by a further 15 years with a preliminary datum connection and significant gaps.

The tide gauges in the Hawaii islands, at Honolulu and Hilo, provide some of the longest tidal records from the central Pacific. A self-recording tide gauge was first installed at Honolulu in 1872 and worked for a few months (Alexander 1889). HTL (half tide level) derived from data from the short series from this gauge was used to establish a "mean sea level" datum of 16.50 ft (Lyons 1901) below a benchmark on the Judicial Building, known as tidal BM2. This datum became the accepted "city datum" for surveying in Honolulu (Lyons 1902) and still exists. Further gauges were installed in 1877 and then 1880 (Alexander 1889). Gaps exist from 1882 onwards, but tide gauge records from Honolulu at the time of the Krakatoa eruption in 1883 are often published in work on the effects of the related Tsunami, suggesting more records exist. A new gauge was installed in June 1891 and data from successive gauges was continuously recorded up to the present day.

Only some of this early data has been digitised. Some of the early (sparse) data from 1877 to July 1892 is available from the UHSLC (University of Hawaii Sea Level Centre) at daily and hourly resolution. Datum adjustments within the earliest data have previously been made by comparing to tide pole records (UHSLC station notes). The RLR and metric data from the PSMSL (Permanent Service for Mean Sea Level) is available from 1905 onwards and is essentially gap free. Precise connection between the datum for the older data set and the modern datum remains a challenge, and this research is ongoing at the UHSLC. This note provides a preliminary estimate for this datum connection, which allows an improved estimate of overall centennial scale sea level acceleration.

Research (Hogarth 2014) has recovered monthly MSL data from June 1901 to June 1904 (Lyons 1901-1904, table 1) which is referenced to 10.00 feet below the original city datum. Further recovered annual data from 1892 to 1909 (Monthly Bulletin of the Hawaiian Volcano Observatory, March 1928, table 2) referenced to the city datum allows the existing annual data series from 1905 (referenced to BM8 and BM2 in Honolulu) to be extended back by 13 years, and the datum values have been checked and connected using the temporal overlap with the modern series from 1905 to 1909 (figure 1). This data also allows confirmation of the datum connection for the monthly series from 1901 to 1904, giving low mm scale differences in the annual values (figure 1).

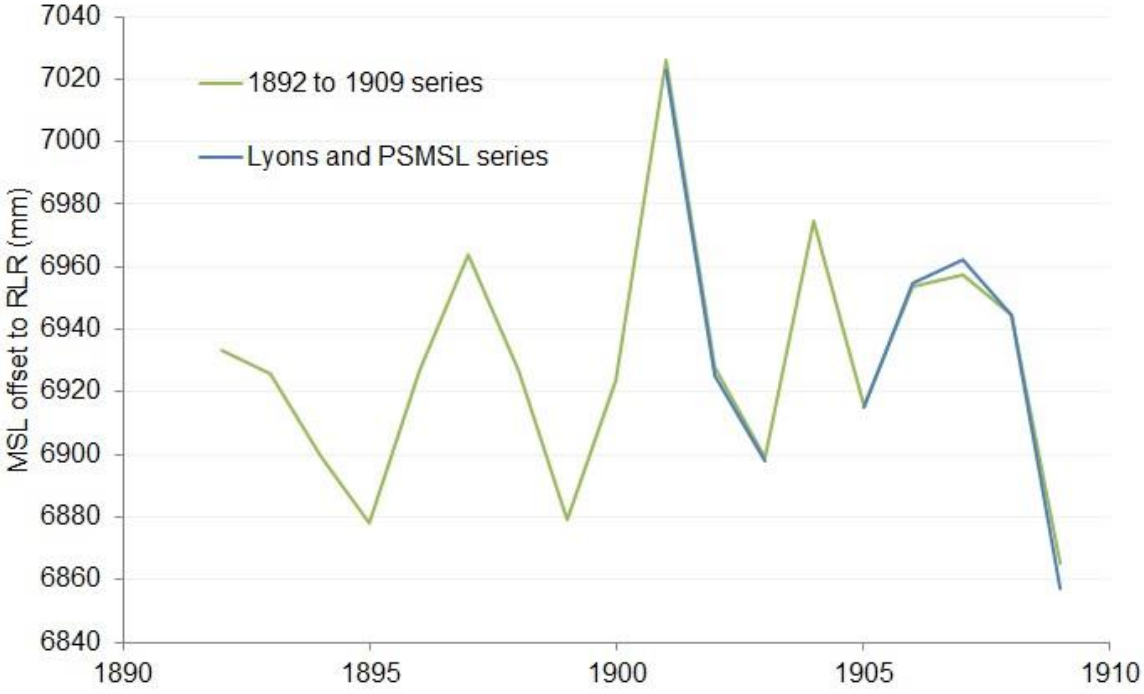

Figure 1: Extended annual MSL data from 1892 to 1909, and from Lyons 1901 to 1904, offset using benchmark data and overlaid on PSMSL data 1905 onwards.

The extended annual data now gives a continuous record back to 1892 referenced to known benchmarks. The 1892 annual value (-0.131 ft city datum, or 6933.5 mm RLR) can now be compared to the average of 6 months of overlapping data (ending July 12th 1892) from the older time series from UHSLC, which is 1.668 ft referenced to 1.803 ft below the 1891/2 mean sea level. To connect the datums we need to estimate the offset between the MSL used for the city datum and the 1891/2 MSL. Monthly and higher resolution data from June 1891 to June 1892 is also available referenced to average MSL over this one year period (Preston 1893). This year of data contributed towards the USCGS predicted tide tables of 1895 onwards, which states that the predicted tides are referenced to a MLLW datum 0.7 ft below MSL (0.7 ft is actually closer to the current accepted MLW value). Similarly, Lyons (1901) states that the hydrographic plane of reference is 1 foot below city datum. Additionally, from the accepted modern survey tidal planes (see link 1) for Honolulu:

MSL to MTL is +0.06 ft
MTL to MLW is -0.7 ft .
MLW to MLLW is -0.2 ft.

Therefore to reduce MSL relative values to the hydrographic (chart zero, MLLW) datum requires an offset of 0.84 ft. Clearly the early Honolulu data are referred to a datum about 1 foot below these low water datums.

The MSL datum was re-adjusted to 16.54 ft below BM2 in the precision levelling campaign of 1927 on Oahu based on 25 years of sea level observations (Rappleye 1929). This is very close to the original HTL of 16.50 ft below BM2 from 1872. This older half-tide level was stated to be only 0.02 ft lower than the average half-tide level for 1924–42 and 0.04 ft lower than the relative mean sea level (Colosi and Munk 2006). Lyons (1901) also mentions the relative stability of the sea level since 1872 when discussing the unusual sea level rise and flooding reported in 1901. This gives some confidence that no significant interannual changes in actual MSL occurred in the period of interest, but also highlights the significant and anomalous period of relative sea level rise recorded by the tide gauge in mid 1882. Although the hourly data does not reveal any clear evidence of a datum change in 1882 (UHSLC station notes) there is also no historical evidence of a temporary tidal rise of this magnitude, which as with the flooding of 1901would most probably have been reported in local newspapers. Therefore this mid 1882 section of data is excluded from the analysis of acceleration (it would positively impact the acceleration value) and it is possible that a localised subsidence of the jetty, tide gauge house or support structure may be responsible. It is assumed that the datum of the older data is otherwise stable, and that frequent levelling checks and bench mark connections were carried out, as was normal where harbour works were ongoing to meet increasing needs of traffic and trade from the late 19th century onwards.

The correction required to reduce the averaged 1892 UHSLC older data to city datum is 1.668 + 0.131 ft plus half the seasonal difference between the average of the first six months and the second six months of 1892. Without the monthly values for the second half of 1892 this difference can only be estimated. The long term average seasonal difference (NOAA values for Honolulu) between six month averages January to June and July to December is around +51mm or 0.167 ft. An estimate of the correction required to extrapolate an annual value from the first six months of 1892 is therefore 0.083 ft. This gives an estimated total correction of 1.668 + 0.131 + 0.084 ft, or 1.883 ft to reduce this data to city datum. The metric RLR offset to adjust the older Honolulu data and allow extension of the overall Honolulu time series is therefore estimated to be 6398.5 mm (table 3).

Considering the then common practice in tidal analysis and harbour work of adding an arbitrary fixed value (often a whole number of feet) to the MLLW referenced tide register readings in order to avoid negative peak low tide values, it appears that the early time series is referenced to around one foot below chart datum (MLLW), or approximately 1.84 ft below city datum (MSL).

Hilo

The PSMSL data from Hilo starts in 1927. The data from 1927 was recorded to give a datum for the geodetic levelling campaign (Wilson 1927, Rappleye 1929) and the gauge continued operating until 1932, when there is a gap in the record until late 1946. In a previous levelling campaign a complete year of tide gauge data was recorded and referred to known benchmarks at the same location from June 1911 to July 1912 (Marshall 1914). From levelling work the difference in MSL between 1911/12 and 1927 is +0.314 ft at bench mark F2 (Monthly Bulletin of the Hawaiian Observatory, Volume 16), and this has been cross checked for this note with the average difference in elevation above MSL of three other nearby bench marks over the same period of +0.316 ft. In isolation this value may seem anomalously high, but a comparison with the Honolulu tide gauge data (figure 2) shows the data series correlate well provided that estimated vertical land motion is accounted for.

In the 19th Century Professor Bache (USCS) had directed that a self-recording tide gauge be supplied to the Hawaiian Survey as early as 1862, but there is no evidence of it operating until Alexander took charge of it, when it was installed at Hilo around 1875 (USCS 1875). By 1889 this first gauge had been swept away by high waters and had already been replaced (Alexander 1889). No records have been found by this author from these early gauges, however the 1872 USCS report suggests that the Hawaii tidal regime is similar to that of the North Pacific (by comparison with early records from the North West Coast of the USA).

Vertical land motion

The relative land motion between Hilo and Honolulu, and tilting and volcanic movement on Hawaii have been the subject of much study (for example Caccamise et al 2005). In analysing absolute sea level rise it is necessary to account for land uplift or subsidence, and also assess whether such motion has been constant over the decadal or centennial time scales appropriate to the sea level analysis.

Caccamise et al concluded that the difference in SLR derived at that time of 1.8 ± 0.4 mm/yr was inconsistent with the then GPS derived relative land motion of -0.4 ± 0.5 mm/yr between Hilo and Honolulu. It was suggested this may have been due to interdecadal differences in upper ocean temperature. In Hogarth (2014) it is emphasised that longer periods of analysis can reduce bias caused by such localised differences.

If we use the extended data (back to 1911 with gaps for Hilo and 1892 for Honolulu), the relative MSL linear trend difference is:

3.143 -1.440 = 1.7 mm/yr.

Due to inter-annual differences there is a risk that the gaps in the Hilo data may bias the SLR trend. To avoid this bias and also remove further bias due to any sea level acceleration or deceleration in the longer Honolulu time series, the trends are compared over an identical 66 year period from 1947 to 2013. This gives a slightly lower trend difference.

2.909 – 1.285 = 1.624 (± 0.3) mm/yr.

Now looking at the CGPS results, corrected absolute geocentric vertical motion rate solutions from NASA (National Aeronautics and Space Administration) for Hilo and Honolulu respectively, both of which now have more than more than 12 years of data, give a vertical land motion difference between Honolulu and Hilo of:

-1.561 – (-0.426) = -1.135 (± 0.433) mm/yr

The ULR5 processed vertical motion solutions (University La Rochelle, Santamaría-Gómez et al 2012) for Hilo and Honolulu respectively also use over 10 years of data and give:

-1.92 – (-0.36) = -1.56 (± 0.52) mm/yr

The NASA solution from another longer term Hawaii based CGPS station (near the tide gauge at Kawaihae to the NorthWest of Hilo) gives a land subsidence rate of -2.113 mm/yr, although with larger uncertainty. This may indicate that the ULR5 solution may more accurately reflect the actual land motion at the Hilo tide gauge. Other CGPS stations on Hawaii do not yet have long enough term results to clarify matters.

Updating the Hilo and Honolulu results with nearly 10 additional years of MSL data and almost doubling the length of the CGPS records resolves the anomaly reported in Caccamise et al (2005) with reduced uncertainty levels. These solutions of course assume linear vertical land motion. Plotting both extended time series with corrections for vertical land motion (ULR5 estimates) allows direct comparison and shows high correlation. This gives some confidence in the extended MSL values at Hilo, as well as in the estimates of relative land motion.

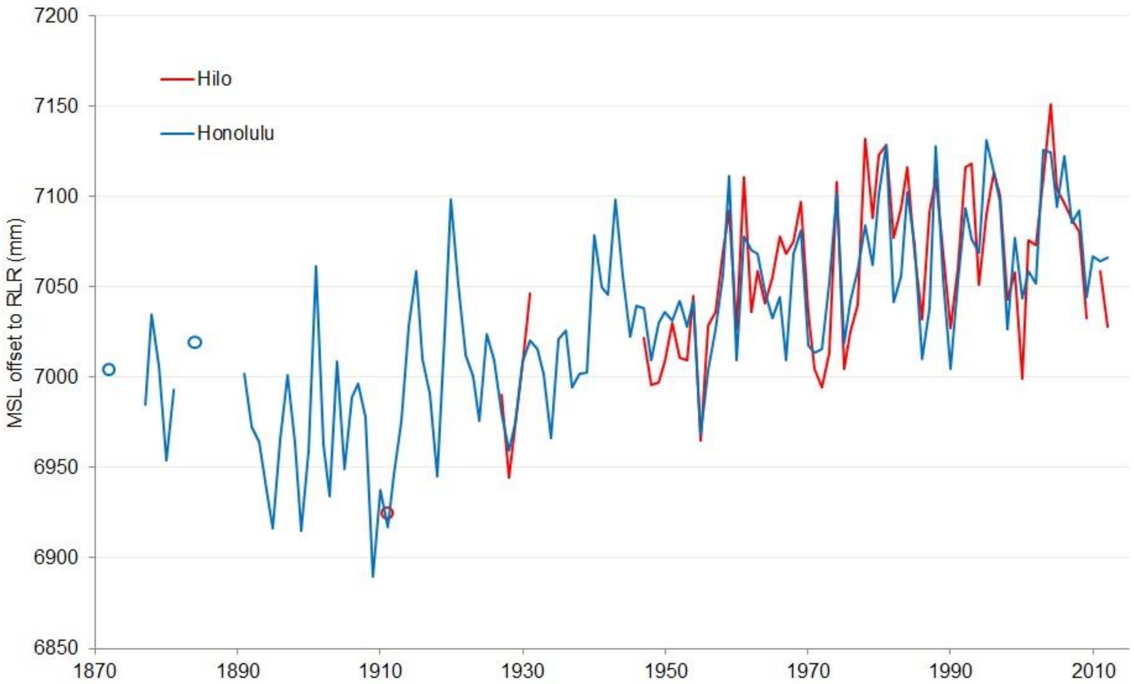

Figure 2: Extended annual MSL values for Honolulu and Hilo. Both are corrected for vertical land motion using ULR5 values (as at August 2014) and offset to Honolulu RLR value at year 2000.

It is difficult to verify the accuracy of the datum connections for the earliest data from Honolulu without corresponding early data from Hilo or other nearby tide gauges. Comparing tide gauge data from the North West Coast of the USA which is known to display similar multi-decadal variations to Hawaii, can give a course sanity check.

The CGPS records from the San Francisco Golden Gate area near the Presidio, Sausalito and Fort Point tide gauge sites are short. Therefore there is some uncertainty associated with the absolute vertical land motion at these sites. In general, a small long term subsidence is assumed (Ryan 2008). For the purposes of comparing with the Honolulu tide gauge data, an assumed vertical rate of -0.4 mm/yr for San Francisco gives good correlation of the respective tide gauge data sets over the post 1900 period when compared with Honolulu (also attempting to account for the El-Nino spikes), but the precise value for vertical land motion is not required in order to note the correlation between the available pre-1900 data at both sites (figure 3). This provides some evidence that if the gaps in the early Honolulu data were filled, then the overall SLR acceleration value derived from the available extended data (0.0033 mm/yr^2) would probably show increased convergence with the value estimated for San Francisco (0.0133 mm/yr^2).

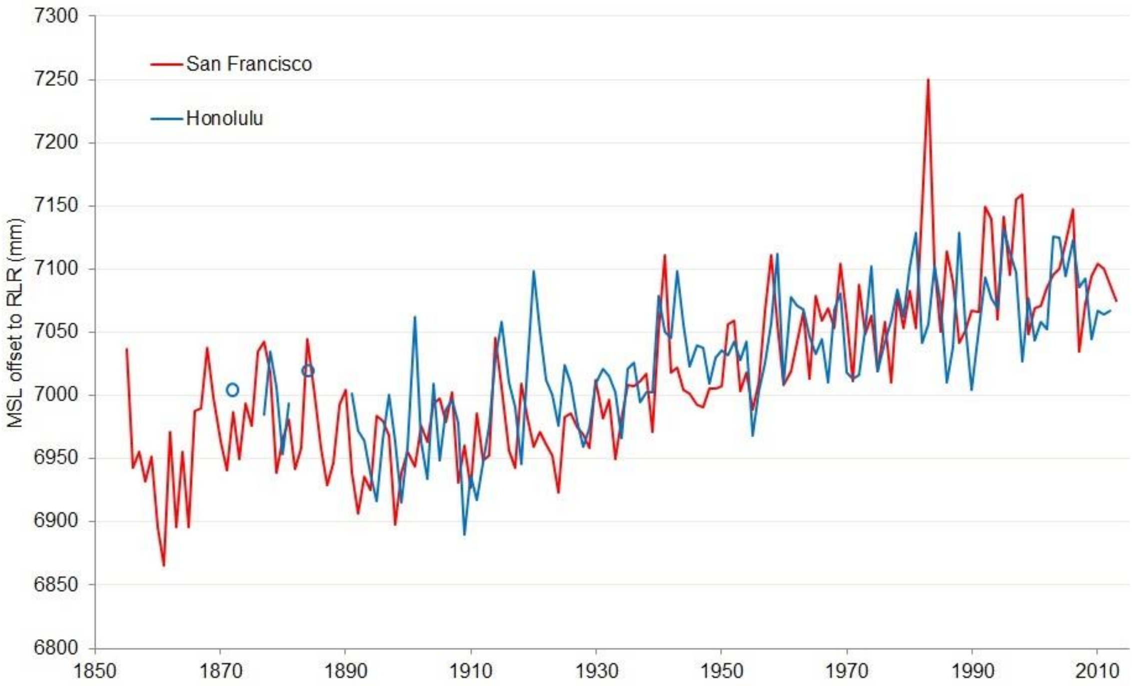

Figure 3: Extended annual MSL values for Honolulu, corrected for vertical land motion, compared with San Francisco MSL values with an assumed -0.4mm/yr linear subsidence.

Assuming variations at decadal scale do show low frequency correlation in the North Pacific, then the extended data from Honolulu may also provide tentative evidence that the “hump” in the early San Francisco data (here the Breaker 2012 corrected values are used) centred around 1880 represents a real regional sea level variation, rather than a localised datum issue, or seismically induced changes in land elevation.

The original and RLR data is presented in the following tables:

Month	ft	RLR mm
1901.458	10.50	7123.4
1901.542	10.42	7099.0
1901.625	10.23	7041.1
1901.708	10.46	7111.2
1901.792	10.37	7083.8
1901.875	10.21	7035.0
1901.958	10.26	7050.2
1902.042	9.90	6940.5
1902.125	9.89	6937.5
1902.208	9.85	6925.3
1902.292	9.75	6894.8
1902.375	9.76	6897.8
1902.458	9.75	6894.8
1902.542	9.86	6928.3
1902.625	9.78	6903.9
1902.708	9.68	6873.5
1902.792	10.05	6986.2
1902.875	10.13	7010.6
1902.958	9.87	6931.4
1903.042	9.71	6882.6
1903.125	9.66	6867.4
1903.208	9.59	6846.0
1903.292	9.65	6864.3
1903.375	9.65	6864.3
1903.458	9.78	6903.9
1903.542	9.77	6900.9
1903.625	9.70	6879.6
1903.708	9.64	6861.3
1903.792	9.94	6952.7
1903.875	9.99	6968.0
1903.958	9.90	6940.5
1904.042	9.77	6900.9
1904.125	9.88	6934.4
1904.208	9.77	6900.9
1904.292	9.79	6907.0
1904.375	9.70	6879.6
1904.458	9.84	6922.2

Table 1: Data from Lyons 1901 to 1904. Original data as reported in feet referenced to 10 feet below City datum (26.50 ft below BM2 in centre colum. The RLR offset to match the PSMSL data is 6971 mm.

Year	ft	mm	RLR mm
1892	-0.131	-39.9	6933.5
1893	-0.156	-47.5	6925.9
1894	-0.242	-73.8	6899.6
1895	-0.312	-95.1	6878.3
1896	-0.152	-46.3	6927.1
1897	-0.031	-9.4	6964.0
1898	-0.152	-46.3	6927.1
1899	-0.310	-94.5	6878.9
1900	-0.163	-49.7	6923.7
1901	0.173	52.7	7026.1
1902	-0.149	-45.4	6928.0
1903	-0.244	-74.4	6899.0
1904	0.004	1.2	6974.6
1905	-0.189	-57.6	6915.8
1906	-0.065	-19.8	6953.6
1907	-0.053	-16.2	6957.2
1908	-0.095	-29.0	6944.4
1909	-0.355	-108.2	6865.2

Table 2: Annual MSL data recorded in Monthly report of Hawaiian Volcano Observatory 1928. Original data in feet referenced to City datum (16.50 ft below BM2). The adjacent column is shown with mm conversion, and then RLR offset data to match PSMSL datum. RLR offset value is 6973.4 mm

Year	RLR mm
1871	
1872	6958.5
1873	
1874	
1875	
1876	
1877	6940.5
1878	6991.3
1879	6962.8
1880	6910.8
1881	6950.5
1882	
1883	
1884	6977.6
1885	
1886	
1887	
1888	
1889	
1890	
1891	6962.7
1892	6933.5
1893	6925.9
1894	6899.6
1895	6878.3
1896	6928.0
1897	6964.0
1898	6927.1
1899	6878.9
1900	6923.7
1901	7026.1
1902	6928.0
1903	6899.0
1904	6974.6
1905	6915.2
1906	6954.6
1907	6962.4
1908	6944.7
1909	6857.1
1910	6905.0
1911	6884.8
1912	6915.3
1913	6944.4
1914	6997.2
1915	7027.6
1916	6980.6
1917	6960.6
1918	6916.5
1919	6994.6
1920	7069.3
1921	7023.1
1922	6983.8
1923	6972.3
1924	6949.1
1925	6997.1
1926	6983.3
1927	6954.2
1928	6934.2
1929	6948.8
1930	6983.3
1931	6995.8
1932	6991.1
1933	6977.6
1934	6943.1
1935	6998.0
1936	7003.2
1937	6971.4
1938	6980.0
1939	6980.4
1940	7057.0
1941	7028.8
1942	7025.5
1943	7077.7
1944	7036.4
1945	7003.2
1946	7020.3
1947	7018.4
1948	6990.8
1949	7011.8
1950	7018.2
1951	7013.4
1952	7024.6
1953	7010.9
1954	7025.9
1955	6952.0
1956	6987.5
1957	7010.9
1958	7041.8
1959	7097.3
1960	6995.1
1961	7063.5
1962	7057.1
1963	7054.6
1964	7034.0
1965	7019.8
1966	7031.9
1967	6998.3
1968	7057.0
1969	7070.0
1970	7007.1
1971	7002.6
1972	7005.4
1973	7042.7
1974	7093.1
1975	7010.5
1976	7033.5
1977	7050.1
1978	7076.3
1979	7054.3
1980	7094.2
1981	7122.3
1982	7035.0
1983	7050.1
1984	7096.4
1985	7068.8
1986	7005.3
1987	7034.0
1988	7124.3
1989	7051.5
1990	7000.7
1991	7050.2
1992	7091.2
1993	7073.8
1994	7067.0
1995	7129.4
1996	7111.4
1997	7096.3
1998	7026.3
1999	7077.2
2000	7043.5
2001	7058.7
2002	7053.2
2003	7126.1
2004	7126.3
2005	7095.9
2006	7124.9
2007	7087.3
2008	7095.3
2009	7048.1
2010	7070.8
2011	7068.0
2012	7071.3
2013	7084.3

Table 3: Preliminary RLR values for Honolulu using older metric Honolulu A data set (red) and datum connection for overlapping six months of 1892.

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