VGOS MEMO #061

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To: VGOS Group

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Subject: Nine years of monitoring the dependence of the GGAO12m phase calibration delay on antenna orientation

Introduction

To monitor the antenna orientation dependence of the phase calibration (or "phasecal") system, a monthly test is done for the 12-m-diameter VGOS antenna at the NASA Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, Maryland, hereafter referred to as GGAO12m. The test involves an automated procedure where phase calibration data are captured while the telescope slews quickly in azimuth or elevation. The captured data are then analyzed to produce estimates of group and phase delay. The end-product is a report on the variations in the phase calibration delay for band A over azimuth and elevation, and in the median delays for bands B, C, and D over azimuth and elevation. This memo includes plots of this information over time and orientation, and the results are used to determine if the 5-MHz cable or the band A cable exhibits excessive delay variation with orientation and should be replaced. This data analysis is necessary for geodetic VLBI systems that do not have a Cable Delay Measurement System (CDMS) that would directly measure the electrical length of the 5-MHz cable, such as GGAO12m. This memo provides a historical analysis of these measurements.

1. The measurement process and data analysis

Detailed information about the motivation behind the tests and about the data acquisition and reduction processes can be found in Corey (2024) [1]. Key points of that memo are summarized here.

The phasecal delay is comprised of two main parts: (1) the delay through the cable carrying the 5-MHz reference signal from the maser on the ground to the phasecal signal generator in the receiver on the antenna, and (2) the delay through the RF electronics in the receiver, the cables carrying the RF signal to the backend, and the backend itself. The latter delay affects both the phasecal delay and the delay from the VLBI radio source, and its measured values can be used to correct the radio source delay for instrumental delay. Because the 5-MHz cable delay affects phasecal delay but not radio source delay, its effect on phasecal delay must be removed when making the instrumental delay corrections. For a VGOS-compliant system, this delay is measured by a CDMS, but the GGAO12m, as the prototype VGOS antenna, could not be equipped with such a system due to lack of funding. In the absence of a CDMS, the monthly tests are designed to measure the dependence of the 5-MHz cable delay (and hence phasecal delay) on antenna orientation. If phasecal delay is not corrected for this dependence, the station position estimated from geodetic VLBI data may be in error.

During the tests, the antenna is moved rapidly in azimuth and elevation in a systematic pattern, and the delay through the system is measured using the phase calibration phases across all observed bands used for VGOS.

The output from the reduction of the phase calibration data consists of time series of one-second averages of group delay (derivative of phase with respect to frequency) and phase delay (phase divided by frequency at a reference frequency). Group and phase delay may differ due, e.g., to nonlinear dependence of phase on frequency or to drifts in local oscillator phase, which affect phase but not group delay. There is one time series per 512-MHz-wide frequency band and per polarization and for each type of delay. With four bands (designated A, B, C, and D) and two polarizations (horizontal (H) and vertical (V)), there are eight time series for each type of delay. For each band, the H and V data alternate every second, with H data recorded on even-numbered seconds and V on odd-numbered. The frequency ranges of the bands and the types of cable used to carry the signals from the antenna to the control room are listed in Table 1.

Table 1. RF frequency bands used in the cable delay monitoring.

Band	**RF frequency (MHz)**	**Cable**
A	2984.4–3496.4	coax
B	5224.4–5736.4	fiber
C	6344.4–6856.4	fiber
D	10184.4–10696.4	fiber

A valid scan is defined as a period in which the telescope rapidly moves either from 360° to -180° and back to 360° over azimuth while elevation is unchanged, or from 87° to 7° and back to 87° over elevation while the azimuth is unchanged. Only valid scans are used for analysis.

In the bottom two panels of Figure 1 the antenna orientation is shown for a representative measurement session. Over azimuth, scans 1, 2, 3, and 4 would be considered valid. Over elevation, scans 6, 7, 9, 11, 12, 13, and 14 would be considered valid. (Scan 8 is invalid because the pause is too long between the down and up slews.) There are occasional exceptions to this, such as interference of an unknown origin or variations caused by temperature changes in the control room, that are visible in plots like Figure 1, so even valid scans may have to be thrown out.

In addition (Figure 1), “rms” is the root-mean-square value of the tone phase residuals to a linear fit of tone phase vs. frequency, “phdly” is short for phase delay, and “grdly” is short for group delay, with units of picoseconds for both. The red, green, and blue lines in the 5th and 6th panels represent bands B, C, and D, respectively.

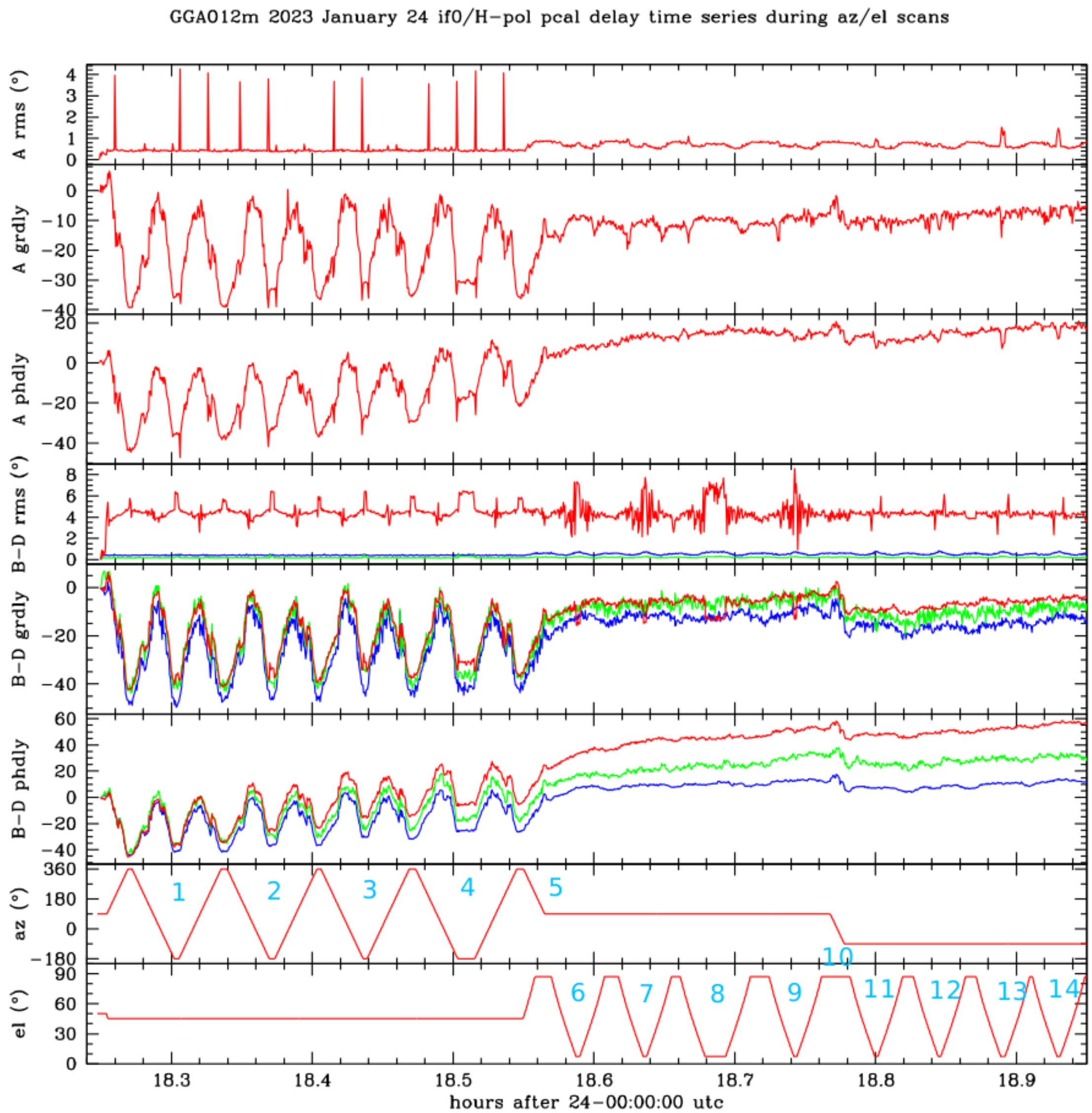

Figure 1. An example time series plot. (Further details of the plotted quantities are given in Section 9 of [1].)

Figures 2 (band A) and 3 (bands B, C, and D) show the group and phase delays over azimuth and elevation angles for measurements made in horizontal (H) polarization on 2023 January 24. The dotted blue lines trace the measurements during motion in the clockwise (azimuth) or down (elevation) direction. The solid red lines are for the measurements during motion in the counterclockwise or up direction. For Bands B-D the median values for 20° bins in azimuth and for 5° bins in elevation are shown as solid dots. Because of potential hysteresis effects in the cable wraps, data are binned separately for the two directions of motion.

Coax cables are much more susceptible to delay variations caused by bending or twisting than fiber cables. At GGAO, the 5-MHz reference signal to the phasecal generator in the receiver is carried over coax from the control room, while the signals from the receiver for bands B, C, and D are carried over fiber to the control room. Any orientation-dependent delays in bands B-D are usually dominated by delay variations in the 5-MHz coax cable. Variations in bands B-D delay can therefore be ascribed generally to variations in 5-MHz cable delay.

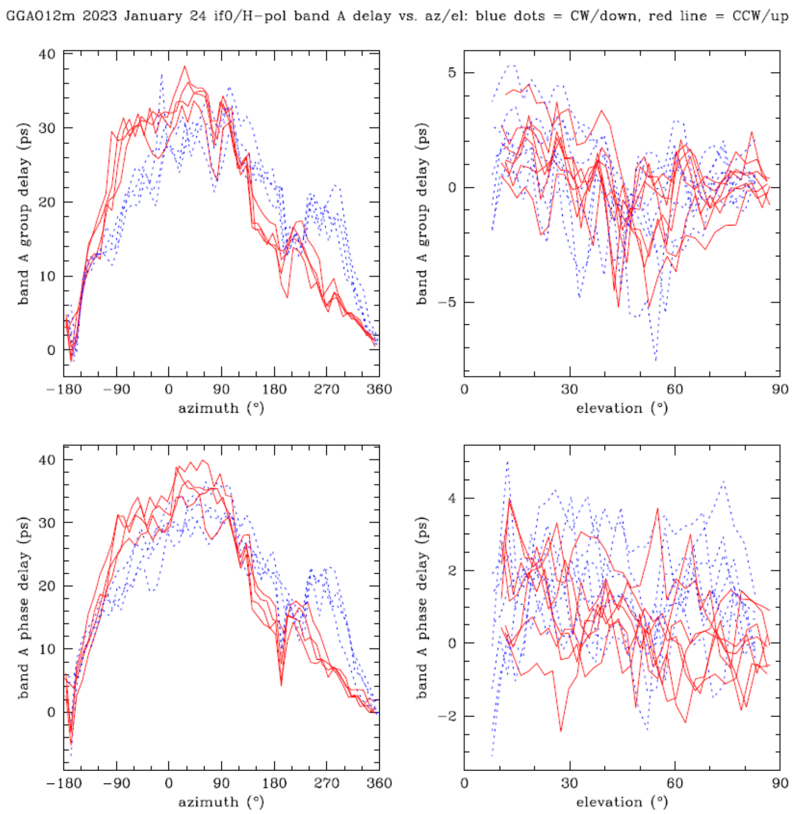

Figure 2. The band A, H-polarization group and phase delay over azimuth and elevation.

Overall, these figures demonstrate that the delays can have a strong dependence on antenna orientation. From a geodetic point of view this variation is undesirable since, if uncorrected, it can introduce an erroneous estimate for the antenna position. This monitoring of the variation of delay with antenna orientation provides a measure of how large that effect might be and whether the cable or fiber is degrading. (To characterize the amount of variation in the delay, the term “variation” will be taken as the peak-to-peak range of the binned median values over azimuth or elevation.) Thus, monitoring the variation may provide advance notice of this.

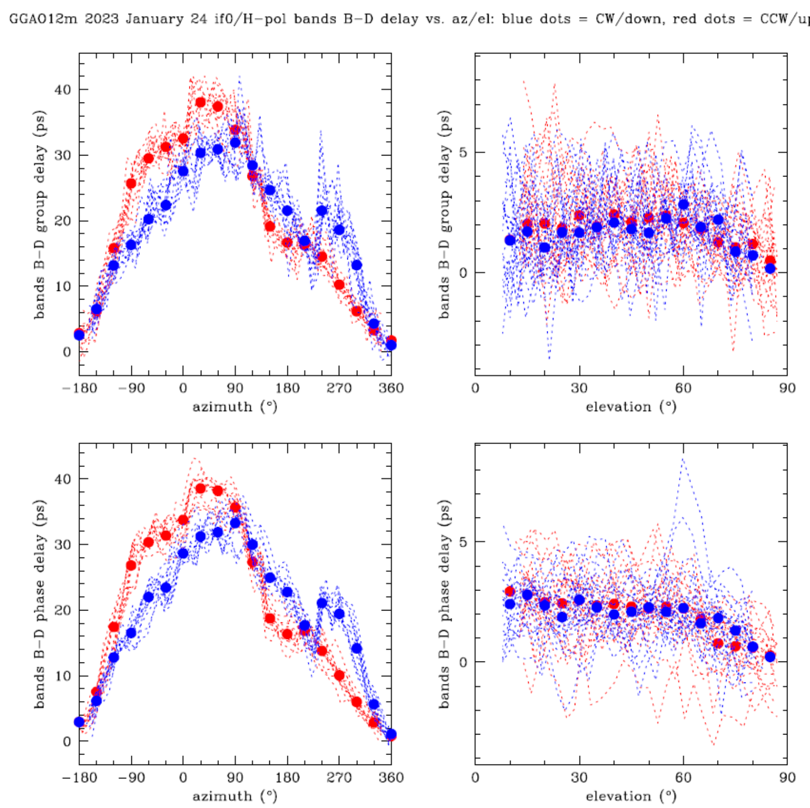

Figure 3. The bands B, C, and D, H-polarization phase delay and group delay values over azimuth and elevation. The median values for 20° bins in azimuth and for 5° bins in elevation are shown as solid circles.

2. Historical analysis

Figure 4 shows the variations in azimuth and elevation for the bands B-D median group delay and for the band A horizontal and vertical polarization group delays measured between the years 2015 and 2024. In this figure, “variation” is defined as the peak-to-peak range of the median values in azimuth or elevation bins, with the medians taken over all scans in each direction of antenna motion and, in the case of the B-D delay, over the three B-D bands. Because the B-D variations are dominated by delay variations in the 5-MHz cable, which are common to both polarizations, the B-D variations are typically the same for H and V polarization, to within 1 ps. If they differ by more than 1 ps, the reported B-D variation is the mean for the two polarizations.

Whenever the variations were deemed excessive, the 5-MHz cable, band A cables (both H-pol and V-pol), or all were replaced. The dots in the top panel in Figure 4 are color coded to indicate when and which cables were replaced. Notice the increase in variation prior to, and subsequent reduction after, the cable changes. The dates of the cable changes and the cable types used as replacements are given in Table 2. An “NC” cell means the cable was not changed. The optical fibers for bands BCD are “SMR-28e+,” and there is no record of those optical fibers having been changed after installation. The dates of the cable monitoring sessions and the measured values are given in the Appendix.

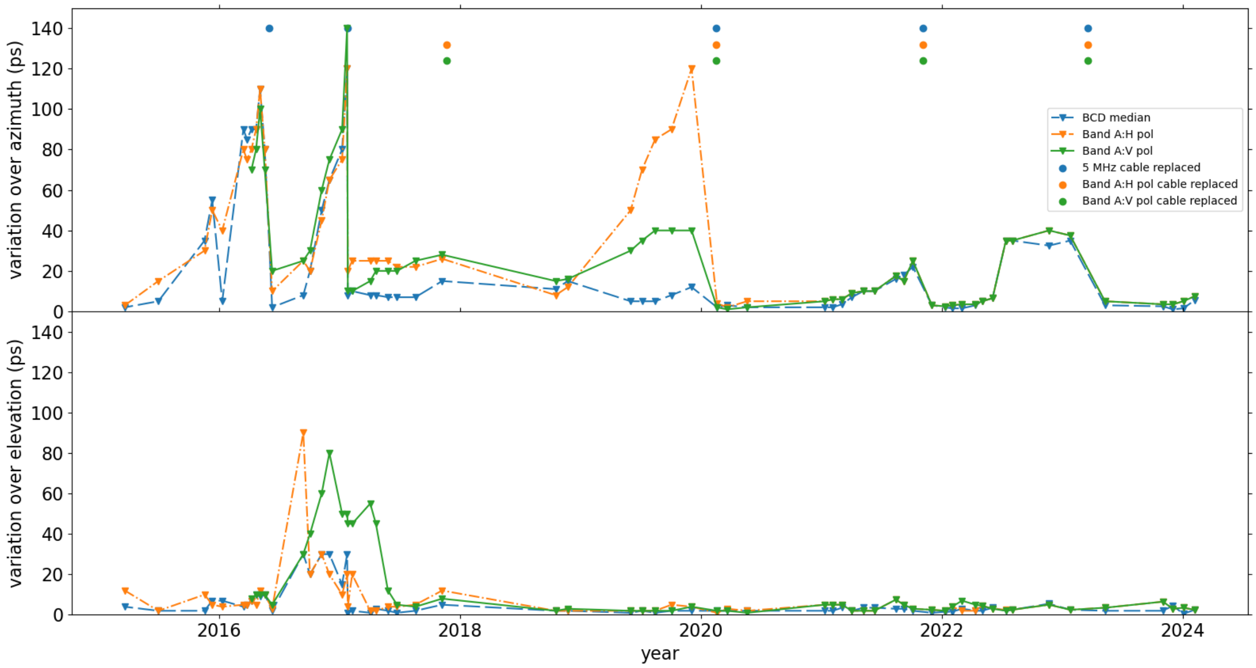

Figure 4. Variation of the phase calibration delay for 2014 December to 2024 February.

In some cases over the past nine years, the delay variations in all four bands are attributable primarily to the 5-MHz cable. Examples include the large peaks in variation over azimuth in 2016 and 2017, when the variations for both band A polarizations and for BCD median rose together to more than about 100 ps, then all fell sharply to below or equal to 20 ps after the 5-MHz cable was replaced. Similarly, in 2021 to early 2023, the three time series track each other closely; this will happen only if the 5-MHz variations dominate over the band A cable variations. (The orange band A:V points and line during 2021-2024 are generally not visible in Figure 4 because the H and V polarization time series are nearly identical during that time span, and the green A:H data overlie the A:V data in the figure.) On the other hand, there are instances when the three time series all differ from each other, e.g., the variations over azimuth in 2019 and the variations over elevation in 2016-2017. This behavior is to be expected, as different cables kink and twist differently in the cable wrap and hence develop different delay dependence on antenna orientation over time.

A notable feature of the history is that the variations are generally lower during the past four years than in the first five. This change can be attributed to improvements that have been made to the manner in which the cables are supported in the cable wraps, so that they are subjected to reduced bending and twisting.

Table 2. Dates when the 5-MHz and band A (both H- and V-pol) cables were replaced, and replacement types.

Date	5 MHz	Band A
pre- 2014/03/27	LMR-400 UF	LMR-400 UF
2014/03/27	NC	LMR-400 UF
2016/06/02	LMR-400 UF	NC
2017/01/26	RG-214	NC
2017/11/21	NC	LMR-400 UF
2018/02/18	LMR-400 UF	NC
2020/02/17	LMR-400 UF	LMR-400 UF
2021/11/04	LMR-400 UF	LMR-400 UF
2023/03/17	LMR-400 UF	LMR-400 UF

3. Delay errors, recent anomaly

Delay estimates are subject to multiple error sources including thermal noise, thermally driven slow drifts in the electronics, and systematic errors of unknown origin. Errors from thermal noise and from slow drifts are reduced by using median values over multiple scans and/or bands. Rapid slewing of the antenna during data capture also reduces the effects of slow drifts.

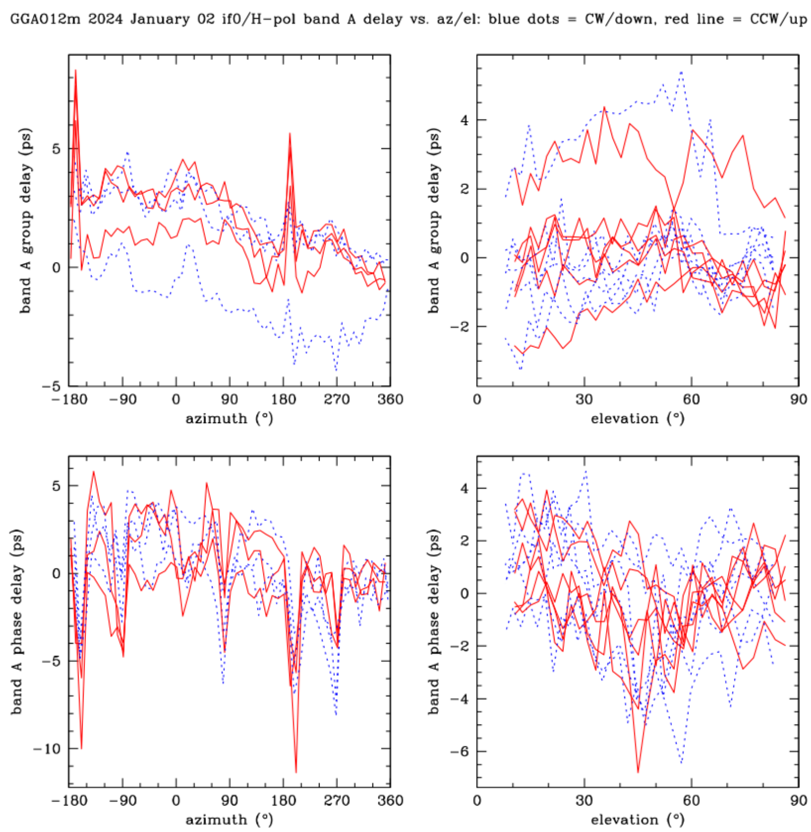

Figure 5. Plots of the band A H-polarization group and phase delay over azimuth and elevation with anomalies in the azimuth delays.

Recently, an anomaly in the band A data was noticed, which is shown in Figure 5. There are unusual spikes at about –170° and 190° in azimuth; these correspond to the same physical azimuth, 10° west of due south. The source of this interference is unknown but is thought to be caused by a signal coherent with the phase-calibration signal that is picked up by the antenna when it points in that direction. These variations, which amounted to about 5 ps in the session of 2024 January 2, can best be seen in the top-left panel of Figure 5.

Acknowledgements

We thank Katie Pazamickas and Jay Redmond (Peraton) for providing the information on the cable replacement.

References

[1] Corey, B., 2024; VGOS memo 60, https://www.haystack.mit.edu/wp-content/uploads/2024/02/VGOS_060.pdf

Appendix

Table A1. GGAO cable monitoring session dates and peak-to-peak group delay variations (see Figure 4 and text).

Date	Band A				Bands BCD	
	H-polarization		V-polarization			
	Azimuth	Elevation	Azimuth	Elevation	Azimuth	Elevation
	(ps)	(ps)	(ps)	(ps)	(ps)	(ps)
2015/03/20	3	12			2	4
2015/06/30	15	2			5	2
2015/11/18	30	10			35	2
2015/12/11	50	5			55	7
2016/01/11	40	4			35	7
2016/03/14	80	5			90	4
2016/03/25	75	5			85	5
2016/04/08	80	7	70	8	90	7
2016/04/22	90	5	80	10	90	10
2016/05/04	110	12	100	10	110	9
2016/05/18	80	10	70	10	80	10
2016/06/10	10	3	20	5	2	2
2016/09/13	25	90	25	30	8	30
2016/10/03	20	20	30	40	20	20
2016/11/08	45	30	60	60	50	30
2016/12/01	65	20	75	80	65	30
2017/01/09	75	10	90	50	80	15
2017/01/24	120	20	140	50	120	30
2017/01/26	20	4	10	45	8	1
2017/02/09	25	20	10	45	10	2
2017/04/03	25	2	15	55	8	1
2017/04/20	25	2	20	45	8	3
2017/05/26	25	4	20	12	7	2
2017/06/23	22	4	20	5	7	1
2017/08/18	22	5	25	4	7	2
2017/11/08	26	12	28	8	15	5
2018/10/17	8	2	15	2	11	2
2018/11/23	12	2	16	3	15	2
2019/05/31	50	2	30	2	5	1
2019/07/05	70	2	35	2	5	2
2019/08/14	85	2	40	2	5	1

2019/10/03	90	5	40	2	8	2
2019/12/03	120	4	40	4	12	2
2020/02/19	4	1	2	2	2	2
2020/03/19	2	3	1	2	3	2
2020/05/19	5	2	2	1	2	2
2021/01/11	5	5	5	5	2	2
2021/02/05	6	5	6	5	2	2
2021/03/02	6	5	6	5	3.5	3.5
2021/04/02	9	2	9	2	7	2
2021/05/06	10	2	10	2	10	3.5
2021/06/09	10	2	10	2	10	3.5
2021/08/13	17.5	7.5	17.5	7.5	16	3
2021/09/07	15	5	15	5	18	3
2021/10/04	25	3	25	3	22	2
2021/12/01	3	2.5	3	2.5	3	1
2022/01/10	2.5	2	2.5	2	2	1.5
2022/02/01	3	4	3	4	1.5	1.5
2022/03/01	3.5	2	3.5	7	1.5	3
2022/04/11	3.5	2	3.5	5	3	2
2022/05/01	5	4.5	5	4.5	5	2
2022/06/02	6.5	3	6.5	3	6.5	3.5
2022/07/12	35	2.5	35	2	35	2
2022/08/01	35	2.5	35	2.5	35	2.5
2022/11/21	40	5	40	5	32.5	5.5
2023/01/24	37.5	2.5	37.5	2.5	35	2.5
2023/05/08	5	3.5	5	3.5	3	2
2023/11/01	3.5	6.5	3.5	6.5	2.5	2
2023/12/01	3.5	3	3.5	3	1	4.5
2024/01/02	5	3.5	5	3.5	1.5	0.5
2024/02/06	7.5	2.5	7.5	2.5	5.5	2.5