Impact of the ionosphere on GPS-based precise orbit determination of Low Earth Orbiters

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D. Arnold[1], C. Dahle[1,2], A. Jäggi[1], G. Beutler[1], U. Meyer[1]

[1]Astronomical Institute, University of Bern, Bern, Switzerland
[2]GFZ German Research Centre for Geosciences, Potsdam, Germany

Introduction

Deficiencies in gravity fields derived from the orbital trajectories of Low Earth Orbiting (LEO) satellites determined by GPS-based Precise Orbit Determination (POD) were identified in recent years. The precise orbits of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission are, e.g., severely affected by an increased position noise level over the geomagnetic poles and spurious signatures along the Earth's geomagnetic equator. This is illustrated in Figure 1, showing the carrier phase residuals of a reduced-dynamic orbit determination for GOCE in meters, binned to the ionospheric piercing points at 450 km altitude (Jäggi et al., 2015a). The degradation of the orbits directly maps into the gravity fields recovered from these orbits.

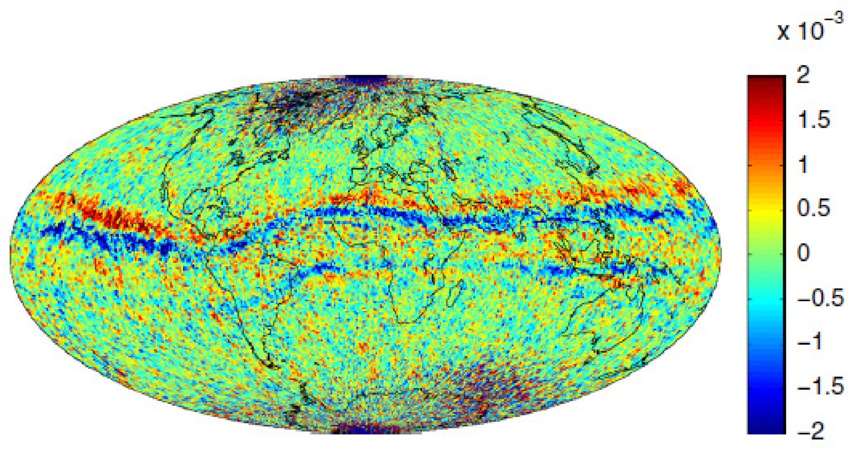

Figure 1: Carrier phase residuals of reduced-dynamic GOCE POD (in m). Systematic signatures along the geomagnetic equator are visible.

The same problems are evident, as well, for the on-going ESA missions Swarm and Sentinel. They are related to a disturbed GPS signal propagation through the Earth's ionosphere. While this might indicate that the GPS observation model and/or the data preprocessing need to be improved, there is now strong evidence that receiver-specific tracking problems under difficult ionospheric conditions play an important role.

GPS and ionosphere

The propagation of a microwave signal of frequency f emitted by GPS satellites is dispersively affected by the free electrons in the Earth's ionosphere:

$$\Delta\rho_{\text{ion}} = \pm\frac{C_X}{2} E f^{-2} + \mathcal{O}(f^{-3})\,, \qquad (1)$$

where $\Delta\rho_{\text{ion}}$ is the path delay due to the ionosphere, $C_X/2 \approx 40\,\text{m}^3\text{s}^{-2}$ and $E = \int N_e(\rho)d\rho$ is the line-of-sight total electron content (TEC), obtained by integrating the electron density N_e along the ray path. The negative sign in Eq. (1) refers to the phase advance (phase observations), the positive sign to the group delay (code observations), respectively.

- GPS satellites emit microwave signals at two frequencies ($f_1 = 1575.42\,\text{MHz}$ and $f_2 = 1227.60\,\text{MHz}$) and the ionosphere-free linear combination $L_{\text{if}} = (f_1^2 L_1 - f_2^2 L_2)/(f_1^2 - f_2^2)$ of the two original carrier phase observations L_1 and L_2 eliminates the ionospheric refraction proportional to f^{-2}.
- The terms $\mathcal{O}(f^{-3})$ are called higher-order ionospheric (HOI) corrections. They are not eliminated by forming L_{if}. Their modeling requires the knowledge of the electron density and the magnetic field along the ray path (Hoque et al., 2008).
- All orbit and gravity field solutions presented here were obtained by using only the ionosphere-free linear combination. In Jäggi et al. (2015a) some attempts were made to mitigate ionosphere-induced problems in GOCE POD by means of HOI modeling, but the success was marginal.
- The dynamics of the ionosphere can be directly derived from the GPS data by forming the so-called geometry-free linear combination $L_{\text{gf}} = L_1 - L_2$, which, up to a carrier phase ambiguity, corresponds to the ionospheric refraction.

Figure 2 (left) shows Swarm-A carrier phase residuals of two days with comparable orbit-Sun geometry (day 15/111: local time of ascending arc $\sim 17\,\text{h}$, day 15/233: local time of descending arc $\sim 18\,\text{h}$), but with substantially different mean TEC in die Earth's ionosphere, see Figure 2 (right). Note that the ionospheric disturbances are usually largest for the evening hours local time.

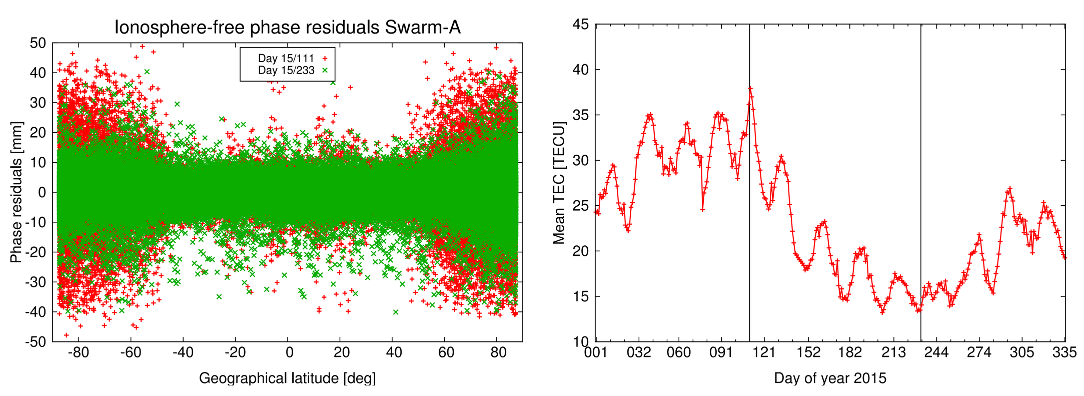

Figure 2: Left: carrier phase residuals of reduced-dynamic Swarm-A POD for days 15/111 (21-Apr-2015) and 15/233 (21-Aug-2015). Right: daily mean TEC as derived by the Center for Orbit Determination in Europe (CODE). The two vertical lines mark the days 15/111 and 15/233. 1 TECU $\equiv 10^{16}$ electrons/m^2.

Polar regions

Figure 3 (left) shows the time derivative dL_{gf}/dt computed from the observations of the Swarm-A receiver to one GPS satellite (G05) during 15.6 minutes when Swarm-A was at high latitudes ϕ (from $-60.0°$ to $-87.4°$ back to $-60.0°$). From minute 1304 ($\phi = -76.2°$) onwards the ionospheric refraction shows massive high-frequency variations, resulting in a higher noise also in the L_{if} phase residuals. They are most probably scintillation.

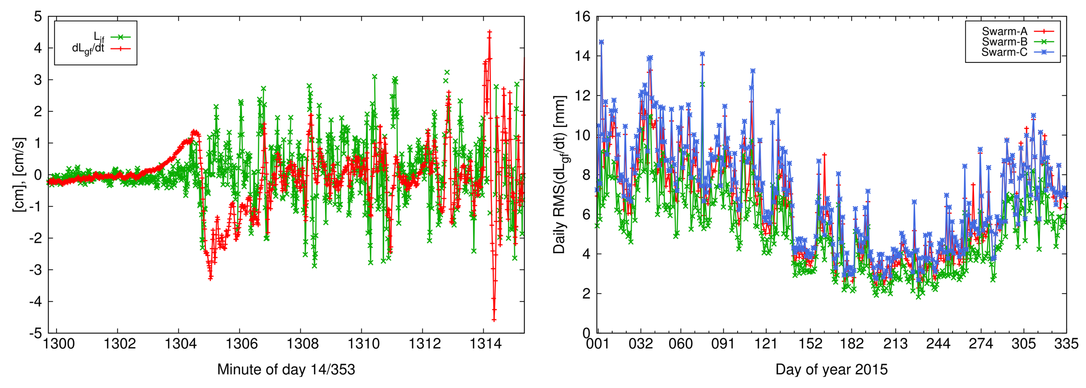

Figure 3: Left: time derivative of geometry-free linear combination L_{gf} (red, characterizing rate of change of ionospheric refraction) and ionosphere-free carrier phase residuals (green) for Swarm-A (kinematic POD) passing the south pole on day 14/353 (19-Dec-2014). Right: daily RMS of dL_{gf}/dt over all GPS satellites for polar passes ($|\phi| > 60°$).

Such passes are very common for GPS observations gathered by spaceborne receivers at high latitudes. Figure 3 (right) shows the daily RMS values of dL_{gf}/dt for all Swarm satellites and for polar passes. Note the clear correlation with the daily mean TEC in Figure 2 (right).

Equatorial regions

While scintillation-like features of dL_{gf}/dt do occur also at low latitudes, the more important phenomena are slower variations of dL_{gf}/dt with larger amplitudes. This is illustrated in Figure 4.

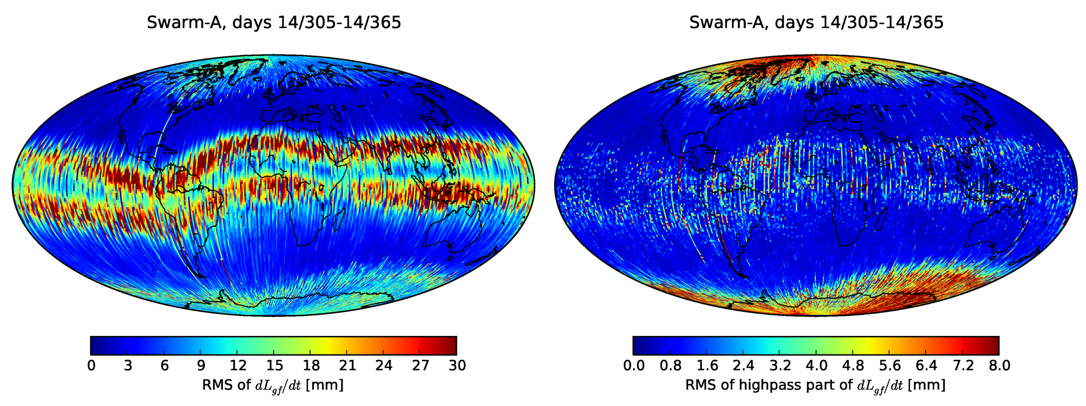

Figure 4: Geographically binned RMS of dL_{gf}/dt for Swarm-A. Left: the full signal dL_{gf}/dt is shown. Right: only the highpass part of dL_{gf}/dt is shown (a Gauss filter of width 100 s was used to filter each pass), indicating the geographical locations of scintillation-like features. The latter also appear for equatorial crossings, but the large RMS for low latitudes in the left plot is mainly due to the deterministic behavior shown in Figure 5 (left).

Figure 5 (left) shows an equatorial pass (from 30° to −30° geographical latitude) for Swarm-A on November 1, 2014.

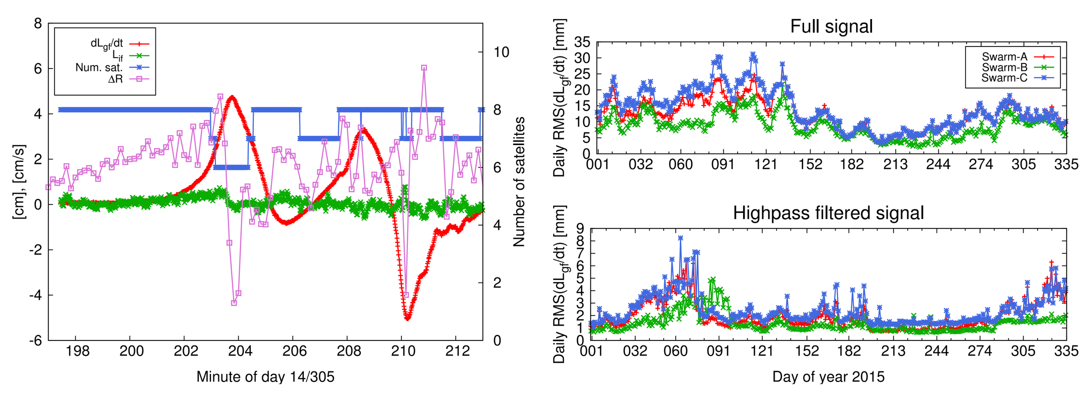

Figure 5: Left: Swarm-A passing the equator on day 14/305 (01-Nov-2014) west of South America. Red: time derivative of geometry-free linear combination L_{gf} (w.r.t. G04). Green: ionosphere-free carrier phase residuals of kinematic POD. Blue: number of GPS satellites used for kinematic positioning. Magenta: difference between reduced-dynamic and kinematic Swarm-A orbit in radial direction. Right: daily RMS of dL_{gf}/dt over all GPS satellites for equatorial passes ($|\phi| < 30°$). The top figure shows the full signal, the bottom plot only the highpass part.

On minutes 204 ($\phi = 4.9°$) and 210 ($\phi = -18.1°$) the difference between the reduced-dynamic and the kinematic orbit shows short deviations of several centimeters. Due to the stiffness of the reduced-dynamic orbit (6 minutes piecewise constant empirical accelerations were set up) these deviations have to be attributed to the kinematic orbit. They will be mapped into a gravity field solution recovered from these kinematic positions (see Fig. 8, left).

Figure 6 shows that the GPS receivers on the GRACE satellites behaves differently under similar ionospheric conditions.

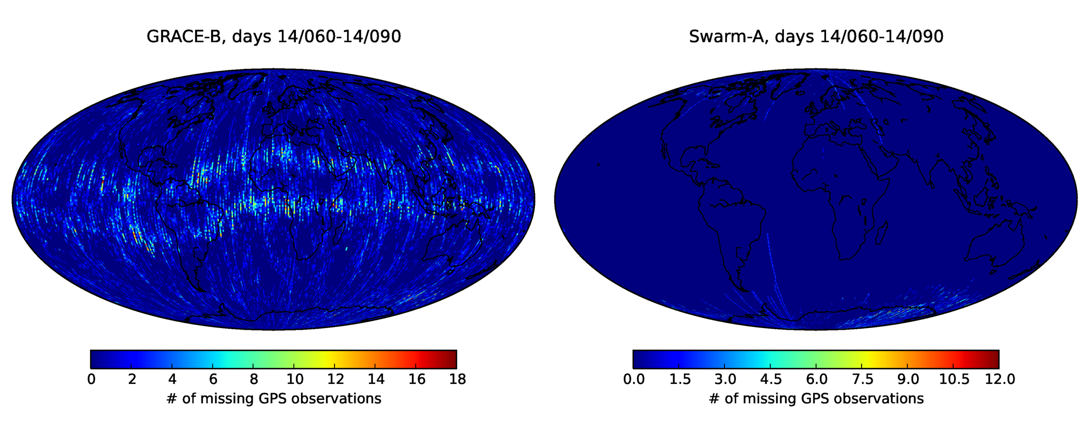

Figure 6: Number of missing GPS observations for GRACE-B (left) and Swarm-A (right) for March 2014. For these days the ascending arcs of GRACE-B and the descending arcs of Swarm-A passed the equator in the evening hours and the TEC was relatively high (38-44 TECU). While the Swarm receiver shows virtually no missing observations, the GRACE receiver skips a significant number of observations along the geomagnetic equator. This is presumably one of the reasons why GPS-only GRACE gravity fields show no, or at least very much reduced spurious signals along the geomagnetic equator.

Impact of tracking loop settings

The bandwidth of the L_1 carrier loop was increased by 50 % (from 10 to 15 Hz) and the bandwidth of the L_2 carrier loop by 100 % (from 0.25 to 0.5 Hz) for

- Swarm-C on 06-May-2015 (day 15/126)
- Swarm-A on 08-Oct-2015 (day 15/281)
- Swarm-B on 10-Oct-2015 (day 15/283).

Figure 7 shows that the tracking loop changes mainly decrease the carrier phase residuals at high latitudes (compare Swarm-A and -C between days 126 and 281).

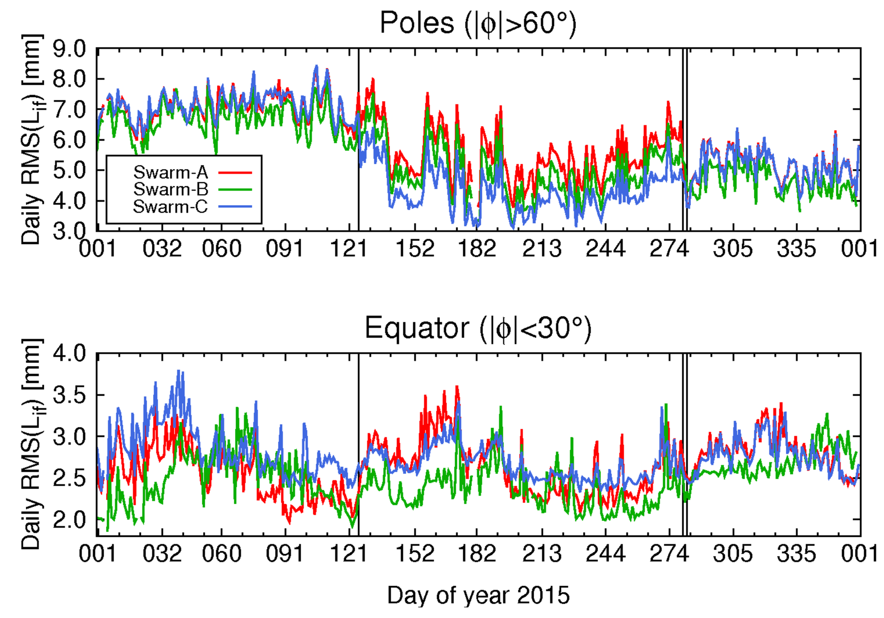

Figure 7: Daily RMS values of L_{if} phase residuals of kinematic POD for polar (top) and equatorial (bottom) passes. The three vertical lines indicate the days on which the tracking loop updates occurred.

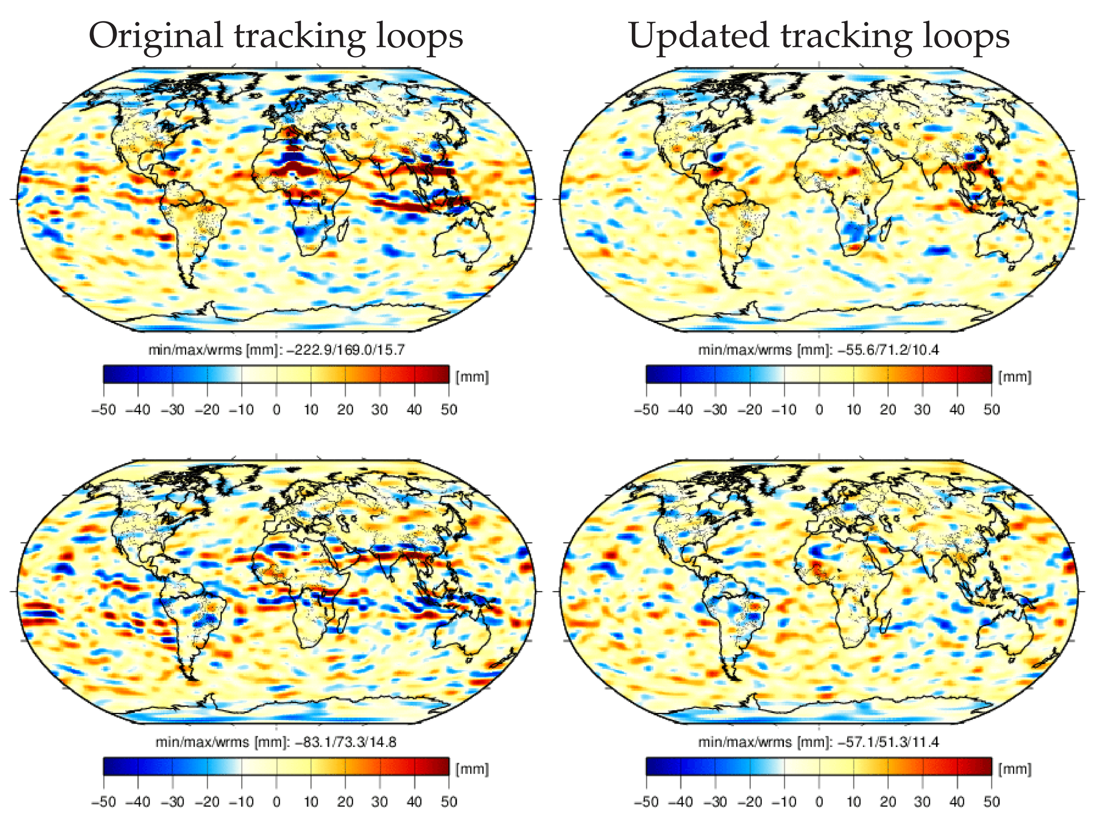

Figure 8: Monthly gravity fields recovered from kinematic positions of Swarm-A (left) and Swarm-C (right) for June (top) and September (bottom) 2015. Geoid height differences of degree and order 90 solutions w.r.t. GOCO05S are shown, a 400 km Gauss filter was applied.

Figure 8 shows that the tracking loop updates also help to substantially reduce the artifacts in the gravity field solution along the geomagnetic equator. In June and September 2015 Swarm-C had the updated settings, while Swarm-A was still at the old settings. Figure 9 shows that the tracking loop update did not cause the receiver of Swarm-C to reject the data along the geomagnetic equator. We therefore conclude that this data was "corrupted" prior to the tracking loop update!

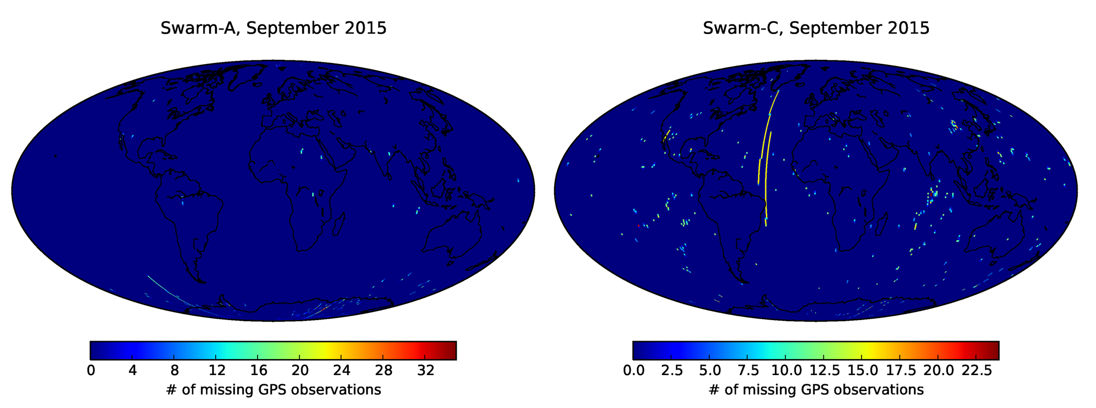

Figure 9: Number of missing GPS observations for Swarm-A (left) and Swarm-C (right) for September 2015. Similar picture for June 2015.

Conclusions

- Ionospheric disturbances have an important effect on GPS-based LEO POD and gravity field recovery, even when using the ionosphere-free linear combination.
- The first time derivative of the geometry-free linear combination L_{gf} is used to characterize the behavior of the ionospheric refraction. For Swarm, scintillation-like features of dL_{gf}/dt occur mainly at high latitudes, while the equatorial crossings are characterized by large, but deterministic changes of dL_{gf}/dt.
- The variations of the ionospheric refraction over the equator induce systematic biases in the kinematic positions. They map into gravity fields recovered from these positions. While unconsidered HOI modeling might play a certain role, *receiver-specific tracking problems are likely the main cause of the degradations.* An increase of the Swarm tracking loop bandwidths substantially reduces the traces of the geomagnetic equator in the gravity field solutions.
- The increased tracking loop bandwidths also result in smaller L_{if} residual noise at high latitudes. This might be in particular beneficial for space baselines determined for orbit and gravity field computations.

References

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Contact address

Daniel Arnold
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)
daniel.arnold@aiub.unibe.ch

AIUB
Poster compiled by Daniel Arnold, May 2016
Astronomical Institute, University of Bern, Bern
daniel.arnold@aiub.unibe.ch